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Improvements in Dielectric Strength of Polymers for Electrical Insulation and Energy Storage Applications

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Abstract : This review discusses developments in dielectric strength (DS) of polymers used for electrical insulation, transmission cables and capacitors used for devices operating over a wide range of frequencies. Traditional products like epoxy are still used in electrical insulation, XLPE for cable insulation, and BOPP in capacitors. Occasionally, reports on additives like voltage stabilizers or nanofillers and interesting chemical modifications are seen for improvement in DS of these polymers. Relatively more active research areas are polymers with higher DS for devices operating at higher temperatures or in MHz to GHz frequency range. They must overcome various tradeoffs to qualify. We have discussed promising examples of PEI, PI and other polymers. Complementary changes occurring in fundamental polymer properties like free volume, crosslinking, interface during these improvements are discussed. Ageing under different conditions is a significant parameter that influences changes in DS of insulation, and this is also discussed briefly in this paper.

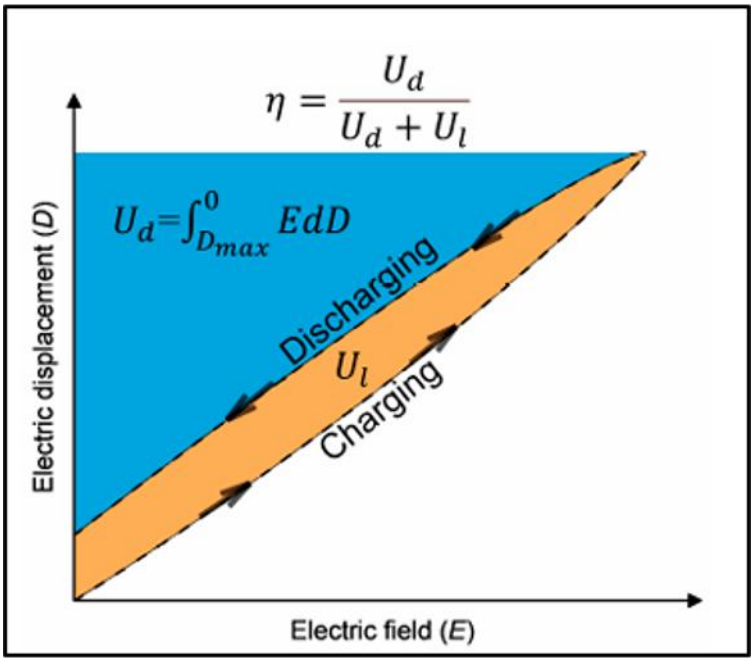
***Index Terms* – electrical insulation, capacitor, dielectric properties, dielectric strength, energy storage**

Abbreviations - bi axially oriented polypropylene(BOPP), crosslinked polyethylene(XLPE), poly ether imide(PEI), poly imide (PI), polyether ether ketone) (PEEK), poly tetrafluoro ethylene (PTFE), polyphenylene sulfide(PPS), epoxy resin of bisphenol A (DGEBA), Dicyandiamide(DICY), 3, 3’, 4, 4’-Benzophenone tetracarboxylic dianhydride (BTDA), KV/mm (Kilovolts/millimeter)

I. INTRODUCTION

Electrical insulation using polymers is essential in power generation, transmission, and end-use equipment. The global electrical insulation market, including polymeric materials, is projected to reach 17 billion USD by 2030, while the polymer film capacitor market is expected to reach about 2 billion USD by 2030 [1, 2]. The wire and cable market, largely based on XLPE and PVC, is expected to exceed 55 billion USD by 2030 [3]. Polymeric dielectrics are widely used in motors, transformers, power cables, capacitors, high frequency devices for communication, defense, medical systems etc. Key dielectric properties include dielectric strength, dielectric constant, and dielectric loss, with this paper focusing on dielectric strength. Often expressed as breakdown voltage, dielectric strength represents the maximum electrical stress insulation can withstand before sudden failure. Unlike gradual degradation, breakdown is catastrophic and can halt equipment operation, making prevention and early detection a major research focus. Dielectric properties help explain breakdown mechanisms and mitigation strategies [4-9]. A recent comprehensive review discusses polymer dielectrics, their advantages and challenges [5]. The challenges have also motivated efforts to develop predictive methods for breakdown in insulation, although the field remains at an early stage [10]. Polymer films used for insulation or capacitors absorb electrical energy, induce polarization, and release the stored energy over time, and this happens in cyclic manner during the lifetime of an insulation film(Scheme 1). The applied electric field displaces bound charges within atoms and molecules, and this process occurs repeatedly during operation. Energy release is accompanied by losses due to heat, defects, and leakage currents, increasing the separation between the polarization and depolarization curves. Higher electric fields (values on the abscissa in Scheme 1) that can be sustained over many cycles indicate better insulation performance. Residual displacement remains small but non-zero because depolarization is imperfect. Dielectric strength (E_b) is the maximum field the film can withstand without failure, for charge-discharge cycle loops, and corresponds to the highest value of the Field value on abscissa for the loop shown in Scheme 1. Another parameter which is important is efficiency of charge-discharge cycles (η) which is indicator of unwanted losses in stored energy per cycle and ideally it should be 100% (Scheme 1).

The reduction in dielectric breakdown strength (E_b) is associated with insulation failure caused by four major mechanisms: electric (intrinsic), thermal, electromechanical, and chemical breakdown. These mechanisms are often complex, overlapping, and dependent on material properties such as composition, Tg, electrical and thermal conductivity, operating temperature, and electrical stress conditions [11, 12]. Electric breakdown occurs under very high electric fields (10^7 to 10^8 V/m), causing electron avalanches and rapid conduction within ~10^{-8} seconds; its relation to electron excitation and bond breakage has been recently studied [12]. Thermal breakdown results from increased charge conduction and localized heating due to poor heat dissipation. Electromechanical breakdown is common in thin films (submicron to a few microns), where electrostatic pressure can damage the insulation. Chemical breakdown occurs when moisture, contaminants, and electrical stress create surface cracks and conductive paths. Practical examples of situations wherein these breakdown mechanisms are functional, are summarized in Table 1.



Scheme 1 Typical displacement -electric field (D-E) graph for insulation film (reproduced from reference of Liu, L.et al., Polyimide-Based Dielectric Materials for High-Temperature Capacitive Energy Storage. Electron. Mater. 2024, 5, 303-320. https://doi.org/10.3390/electronicmat5040019 [173])

Table 1 Practical examples of four major types of breakdown mechanisms in dielectric strength polymeric insulations

Type of breakdown	Examples
Electrical (intrinsic) breakdown	Pulsed power capacitors used for faster communication, radar, particle accelerators, or defense systems
Thermal breakdown	DC link capacitors in electric vehicles fail prematurely due to thermal runaway at elevated operating temperatures
Electromechanical breakdown	Flexible capacitors and dielectric elastomers used in actuators
Chemical breakdown	Outdoor composite insulators in industrial or coastal areas fail due to tracking and erosion rather than bulk breakdown

The dielectric strength can be expressed as breakdown strength for short term, and voltage endurance for long term exposure to high voltage. The breakdown strength in polymeric insulations is measured using a destructive test wherein a polymeric insulation is tested with increase in applied voltage till the material fails as an insulation and begins to conduct electricity. The corresponding voltage is expressed as voltage per unit of film thickness (usually KV/mm) and termed as breakdown voltage. In the voltage endurance test, the time to failure (t) under constant or stepwise applied voltage (V) is determined, and it can be represented as V–t (voltage vs life) curve. Voltage endurance testing is frequently used in high-voltage rotating machines

The dielectric strength of polymeric insulation depends upon several factors (Table 2). The probability of breakdown as an event is much less than other more probable but less catastrophic events like partial discharge, electrical treeing or corona discharge that happen at much lower voltages than E_b. However, the combined effect of these less harmful reasons for reduction in quality of insulation can also increase probability of breakdown. Hence, though concept of dielectric strength in terms of breakdown value is very useful, its value can keep changing with ageing of the insulation, and it is complex to comprehend. It may be noted that research papers in the literature usually report breakdown voltage values for pristine (unaged) insulation samples. As shown in a recent paper, the useful life of electrical insulation for a power cable is related to applied electrical stress by inverse power law and it can be considered valid for polymeric insulations used in most of the equipment [13]. Since the lifetime drops exponentially with field, design engineers tend to give ratings for equipment far below breakdown voltage value of pristine insulating material.

Table 2 Factors that control dielectric strength of electrical insulation

Factor	Characteristics associated with the factor
Material properties	Chemical structure, Composition, polarity (non-polar material like PP has better dielectric strength).
Physical structure and morphology	High crystallinity, low free volume, and absence of voids improve dielectric strength; rough surfaces reduce it.
Thickness of insulation	Higher insulation thickness generally lowers dielectric strength.
Environmental conditions like humidity and temperature	High humidity and temperature can reduce dielectric strength; contaminants such as dust and oil promote leakage and breakdown
Electric field characteristics	High and non-uniform electric fields increase breakdown risk due to localized stress.

Frequency of applied voltage	Higher frequency increases dielectric losses, heating, and insulation degradation.
Ageing related factors	Electrical ageing (PD, corona, treeing), thermal ageing (oxidation, hardening), radiation exposure, and mechanical stress (cracks, deformation) reduce dielectric strength

Though several factors affect life of insulation and hence that of an expensive device, proper control of these factors has enabled electrical machines, especially oil-filled transformers with long service life.

Before discussing developments in improving dielectric strength of insulating materials, it is important to consider the effects of aging on dielectric properties and equipment life. Ageing of polymeric insulation is considered as the process of irreversible, and progressive change in the properties of the polymers used to make the insulation, over time. Aging of polymers used in electrical insulation has been extensively studied [14, 15]. IEC has also developed several standards to systematically evaluate insulation aging for different applications (Table 3). These standards help assess and document changes in the insulation properties, including dielectric strength, to ensure safe operation throughout equipment life.

Table 3 Various IEC Test methods used to study ageing in polymeric insulations and its effect on dielectric properties

IEC Standard	Parameter Reported	Remark
IEC 60216	Temperature index of insulation	Evaluates thermal ageing of insulation.
IEC 60243	Dielectric strength of solid insulation	Measures high-voltage breakdown resistance.
IEC 60247	Dielectric constant, dielectric loss, DC resistivity of liquid insulation	Assesses insulation quality and condition.
IEC 60250	Dielectric constant and dielectric loss	Evaluates dielectric properties over a wide frequency range.
IEC 62631	Volume and surface resistivity	Measures electrical resistivity of insulating materials.
IEC 60270	Partial discharge (PD) signals	Measures and evaluates partial discharge levels.
IEC 60505	Estimated service life of insulation system	Estimates insulation life under multiple stresses.
IEC 60587	Tracking and erosion voltage	Evaluates resistance to tracking and erosion.
IEC 60112	Proof tracking index (PTI) and comparative tracking index (CTI)	Assesses tracking resistance and material performance.
IEC 61251	Voltage endurance coefficient (VEC) and Electrical Threshold Stress (E_0)	Supports long-term insulation life prediction.
IEC 62068 & 60216	Measures retention between voltage stress and time-to breakdown	Insulation materials are tested for accelerated electrical, voltage and thermal stresses to check AC voltage endurance over time
IEC 60422	Transformer oil condition parameters	Classifies oil condition for maintenance decisions.
IEC 60060	Peak voltage, withstand voltage, sparkover voltage	Assesses insulation performance under high voltage.
IEC 60851	Winding wire insulation properties	Evaluates electrical, mechanical, and thermal performance of winding wires.
IEC 61857	Laser video disc characteristics	Defines compatibility and performance requirements for videodiscs.
IEC 60505	Ageing and service life of insulation systems	It covers electrical ageing as combined effect of partial discharge, electrical treeing, space charge accumulation and tracking/erosion and thus adds effect of thermal, mechanical and environmental factors

Following are important features of this review paper: (i) discussion on the reports on commonly use insulating polymer systems and test methods (ii) analysis of new developments focused on polymers having high temperature dielectric properties using variety of approaches like use of new monomers, grafting, blending of polymers, crosslinking by thermal or UV/Gamma rays, use of nanofillers, multi-layer fabrication (iii) we show importance of changes associated in fundamental properties of insulating polymers like crosslinking density, free volume content, shallow and deep traps, and interfaces formed in polymer blends or nanocomposites, that accompany the improvement in breakdown strength. Further, we highlighted examples of these changes in insulation suitable for high temperature and high frequency applications.

This paper briefly discusses literature in the last five years on improvements in dielectric strength of the polymeric materials used for electrical insulation for rotating motors and transformers, high and medium voltage transmission cables and capacitors used in power devices. We briefly discussed insulations films for high temperature-high frequency applications. Insulation degradation mechanisms mentioned in Table 3 including PD, electrical treeing, and corona discharge, are beyond the scope of this paper. Some interesting recent papers can be referred to on these topics[16,17].

The ensuing discussion is divided into following subsections: (i)improvement in dielectric strength of polymeric electrical insulations for different applications namely, motors, transformers, and power transmission cables (ii) Test methods for dielectric strength and related phenomena (iii) improvement in dielectric strength of polymeric materials used in power storage devices like capacitors for a wide range of frequencies (iv) conclusions and future work different applications

2. Improvement in dielectric strength of polymeric insulation for different applications

Polymeric insulation is widely used in motors, transformers, cables and capacitors. Small motors and capacitors typically require insulation with high dielectric strength at ambient temperatures, generally thermal class 120 or 155. Common materials include alkyds, polyester, polyester imides, polyurethane, and epoxy. Higher-power motors operating at elevated temperatures require thermal class 180 polymers such as specially designed epoxy, poly(ester imide), poly(amide imide), and unsaturated polyesters. Demanding applications including traction motors, power electronics, electric mobility, aerospace/defense, renewable energy, grid infrastructure, industrial high-temperature equipment, and RF systems require class 200 and 220 insulation materials. Polyimides, silicone resins, PEEK, PTFE, PPS, and specially formulated epoxy and unsaturated polyesters are used in these applications and are expected to maintain good dielectric strength at temperatures above 150 ˚C. In India, development of high-voltage insulation products is expected to accelerate, following the Government's announcement of a Rs 53,000 crore investment in nine 1100 KV AC transmission lines and ten substations over the next decade [18]. The impressive continuous progress in developing polymeric insulations for emerging applications is underlined by two recent reviews: one for advanced communication technologies [19] and the other for discovery of new polymers using AI technology that allows saving time and efforts for avoiding roadblocks like tradeoff between dielectric strength and dielectric constant [20].

Epoxy, polyurethane (PU), and unsaturated polyesters are the most widely used insulating materials in motors and transformers. They protect windings, coils, stators, rotors, core plates, and bushings[21-23]. PET, polyamide, and polyimide films are commonly used for slot insulation in rotating machines. Epoxy resin casting is well established for dry-type transformers up to 15 KV AC [24], while higher-rated outdoor transformers typically use mineral oil along with epoxy-coated insulation paper. Silicone resins are preferred for heavy-duty rail applications requiring thermal class 180 or 200 insulation and are often combined with ultra-thin mica tapes for main-wall insulation in high-voltage motors [25]. Recent literature indicates greater focus on dielectric strength for linear polymers such as PEI and PI than for cross-linked polymers such as epoxy. This trend may be due to the established thermal stability of crosslinked polymers in insulation applications, whereas linear polymers are increasingly optimized for high dielectric strength in high-energy-density capacitors. The following discussion considers cross-linked polymer insulation systems followed by systems using linear polymers.

PU resins are popular in low voltage devices for home appliances, power tools, low voltage transformers, solenoids/ignition/Radio frequency coils and recently in flexible electronics. The review by Choi et al discussed research trends of PU-based composites containing polymeric conducting fillers for EMI shielding, sensors, coating, films, and foams from last decade[26]. Many flexible PU resins are used in highly stretchable polyurethanes and applications needing biocompatibility and biodegradability for emerging applications in biomedical applications [26]. Samad et al reported comparison of AC and DC dielectric strength for three samples of hard PU with shore hardness 40, 70 and 90 (PU40, PU70, PU90). They noted an increase in both AC and DC breakdown strengths as hardness increased from PU40 to PU90 (from 24 to 56 KV/mm for DC breakdown strength). However, DC dielectric breakdown strength data for PU70 and PU90 samples exhibited significant difference, unlike the overlapping Weibull plots observed in the AC breakdown. This was attributed to heating and dielectric loss caused due to reversal of electric field causing different charge distribution in AC breakdown strength test than in DC breakdown test [27]. An interesting development in application for PU elastomer as synthetic muscle involved adding covalently bound voltage stabilizer molecule in hard segment during elastomer synthesis. This improved breakdown strength from 32 to 59 KV/mm and helped actuation performance of the elastomer[28]. A polyurethane insulating and water repellant protective coatings for porcelain insulators that improved Flashover voltage and reduced electric field in presence of high moisture was reported [29]. A recent review discussed more applications for flexible and high dielectric constant PU elastomers for soft electronic devices [30].

Epoxy-based systems are versatile insulating materials typically formulated as either two-pack systems (resin plus hardener) or one-pack systems (resin with a boron trichloride-based latent curing agent). Dielectric strength is influenced by resin and hardener structure, functionality, crosslink density, and glass transition temperature (Tg). Cycloaliphatic epoxy resins are preferred over DGEBA when higher rigidity, Tg, and outdoor yellowing resistance are required. Common hardeners include aromatic diamines, anhydrides, and boron trichloride adducts. Anhydrides generally provide lower dielectric loss, while aromatic amines offer higher Tg and better dielectric strength retention. Proper vacuum processing minimizes voids and moisture, improving long-term insulation performance. Typical epoxy-anhydride insulation can show DC breakdown strength of 50 KV/mm and AC breakdown strength of 30 KV/mm. Epoxy/mica tapes are also widely used in vacuum pressure impregnation (VPI) systems for motor insulation. More details are available in the useful reviews [31, 32].

Improving epoxy dielectric strength remains an active research area. Epoxy composites containing 1% ceramic filler have demonstrated up to 130% higher dielectric strength at 110 ˚C compared with neat epoxy, attracting significant research interest [33]. Bio-based recyclable epoxy composites have also been reported for triboelectric nanogenerators used in clean energy generation [ref 34**]**. Bezdek et al. proposed a porous mica tape insulation system as an alternative to conventional epoxy-anhydride VPI varnishes for large HV windings [35]. Partial discharge (PD) is a major cause of epoxy insulation degradation. Simulation studies showed that PD activity increases with excitation frequency [36]. Experimental work confirmed that discharge repetition rates increased by 1220% at high frequency of 100 KHz, while cumulative discharge amplitude rose by 41.8%, causing significant thermal and chemical degradation of insulation [37]. Humidity-aging studies on epoxy-anhydride insulation predicted a service life of 33.16 years at 25˚C and 95% relative humidity based on comparative study of changes in FTIR spectra of samples tested at different ageing time, indicating good moisture resistance in power transmission environments under chosen testing conditions [38]. Trend of increasing use of higher voltage and wider applications is driving research on improved polymer composite insulation properties and longer lifetimes [39].

Recent studies show that voltage stabilizer molecules as additive with high electron affinity create deep charge traps in epoxy matrices, improving dielectric strength by approximately 30% at additive contents below 5% [40,41]. Calisir et al. reported epoxy composites containing 15% stearic acid-coated aluminium flakes with dielectric loss below 0.01 and dielectric constant around 5 at

10 GHz, making them suitable for high-frequency applications [42]. For power electronic transformers operating under high-frequency square waves, increased PD activity in epoxy film was found to accelerate degradation as noted by increase in surface concentration of atomic carbon and oxygen [43]. The grafting of epoxy resin with only 0.5 wt% maleic anhydride increased dielectric breakdown strength from 61.5 to 73.4 KV/mm, improved electrical resistivity 17-fold, reduced dielectric constant by 30%, and enhanced tensile strength [44]. Sustainability is becoming increasingly important in epoxy insulation research. Bio-based Magnolol-derived epoxy composites containing alumina filler achieved a breakdown strength of 35 KV/mm and thermal conductivity of 1.19 W/(m.K) for high-voltage insulation applications [45]. In another study, density functional theory was used to select polyhedral oligomeric Silsesquioxane (POSS) type silicone-based additives for bio-based Eugenol-derived epoxy. The resulting composite exhibited DC breakdown strength of 81 KV/mm, AC breakdown strength of 40 KV/mm, and dielectric loss of only 0.002 [46].

Unsaturated polyester resins (UPR) are widely used for electrical insulation in rotating machines and high-voltage applications because of their low viscosity, low dielectric loss, and low electrical conductivity [21]. The dielectric strength of UPR insulation depends on factors such as vinyl monomer content (e.g., vinyl toluene), backbone unsaturation, crosslink density, curing conditions, thermal stability, and shrinkage-induced defects, and vary between 15 to 25 KV/mm. Compared with epoxies, UPR exhibit higher curing shrinkage, which can generate voids and reduce dielectric strength. They are also more susceptible to hydrolysis in moist environments and may suffer dielectric deterioration due to metallic accelerators at elevated temperatures. In inverter-fed motors, impregnating resins must provide high partial discharge inception voltage (PDIV), especially near the glass transition temperature where permittivity increases and electric field enhancement can occur. Rumi et al. showed that PDIV is influenced not only by UPR permittivity but also by factors such as thermal expansion, suggesting need for more studies [47]. Fetouhi et al. reported significant changes in complex permittivity and DC conductivity after thermo-oxidative aging, attributing these effects to competing oxidation and crosslinking processes for UPR insulation [48]. Wrobel et al. demonstrated that resin impregnation, slot liner selection, and assembly design strongly affect winding heat transfer and motor reliability [49]. Yang et al. found that although breakdown strength remained largely unchanged under high-humidity aging conditions, dielectric loss and tan delta varied significantly, suggesting these parameters are more suitable for monitoring insulation aging [50]. While reports on voltage stabilizers in UPR insulation are scarce, improved dielectric endurance has been observed with nanofillers such as Zinc borate and nano-alumina in polyester resins [51].

Silicone resins are used for vacuum pressure impregnation of high-power motors by curing at about 200 ˚C for several hours. High curing temperature is necessary for completion of curing and to flush out traces of moisture. The curing involves dehydrogenation reaction that liberates water by reaction of mixture of methoxy silane compounds containing organic groups (methyl, phenyl etc.) in the presence of catalyst and typically show DC breakdown strength in the range 25 to 40 KV/mm [52, 53]. Sun et al have reported a simulation study of an improvised Silicone rubber used in cable accessory insulation wherein a novel voltage stabilizer molecule, 3-amino-5-chlorophenyl 3-fluorophenyl methanone (ACFM) was grafted on the resin. The theoretical analysis of properties for the material after modification indicated that it would suppress space charge accumulation and electron avalanche breakdown. It also showed improvement in heat capacity in the temperature range 300–600 K temperature range, which can enhance insulation strength against thermal–electric breakdown for the out-door exposure of the material [54]. Anthracene grafted polydimethylsiloxanes (1% anthracene) extruded cable material showed 57% increase in voltage required for initiation of electrical treeing, increase in AC breakdown strength and reduction in DC conductivity due to effective role of anthracene as voltage stabilizer [55].

Improving dielectric strength in linear polymer insulation films for low frequency applications is possible by following approaches[16]: (i) designing the polymer film with intrinsically high breakdown strength (ii) reducing free volume or by introducing deep traps in the polymer and using principles that help for tighter chain packing (iii) by preventing the rapid rise in electrical breakdown. Recent examples of these approaches are as follows: (a) controlled reaction induced phase separation produced a morphology that improved breakdown strength. Crosslinking of benzoxazine added to PEI induced physical interpenetration of chains as well as generated deep traps to give breakdown strength of ~ 750 KV/mm at 25 ˚C and ~ 650 KV/mm at 200 ˚C[56] (b) The significant reduction in free volume content of 50/50 blend of PEI/PI was proposed for record high value of breakdown strength of 1000 KV/mm [57] (c) very compact chain packing due to better miscibility in two amorphous polymers, polystyrene and PPO, produced long range disordered microstructure that helped to suppress charge mobility and gave impressive energy density of 5.5 J cm^{-3} with >90% efficiency at 600 KV/mm and 150 ˚C[58] (d) Polyamide modified with silicone resin to give high BDV of 726 KV/mm, energy density 6.5 J cm^{-3} at 150 ˚C with excellent tensile strength of 321 MPa. Silicon containing groups can sacrificially degrade under harsh conditions of exposure to high voltage to create silica like structures that resist corona discharge and protect the film [59].

Few miscellaneous reports are as follows: (i) Choe et al proposed recycling waste PET to synthesize high acid value PET oligomers via glycolysis. The resulting resin showed good water miscibility and, when cured with a water-miscible methylated melamine crosslinker, produced insulation films with Tg around 160 ˚C, dielectric strength of about 50 KV/mm, and volume resistivity of 7×10^{15} Ω cm [60] (ii) Ahmed et al reported a 25% increase in breakdown strength for solvent-based polyester varnish modified with 0.4% surface-treated TiO_2 nanofiller [61] (iii) A general review on polymeric insulations for high-voltage applications discussed various breakdown cases [62] (iv) Zhou et al reported a styrene-based unsaturated polyester impregnating varnish containing up to 20 % vinyl-terminated hyperbranched polysiloxane as a reactive additive, resulting in improved thermal stability, 30% better bond strength, and 40% lower dielectric loss than the control sample [63] (v) A comparative study of three commercial unsaturated polyester resins showed low dielectric loss across a wide frequency range, indicating their suitability for insulation in high-power induction motors fed by pulse width modulator (PWM) inverters [21].

One more type of resin containing product used extensively for electrical insulation of motors is resin rich mica tapes. These are ready to use products. They offer consistent quality and convenient ways to manufacture various motors parts like stator coils and bars of medium and high voltage ratings. The tapes consist of mica paper, glass fibers as reinforcement and impregnating resin (usually epoxy) for different thermal class insulating tapes. The tapes made this way allow curing without use of separate vacuum pressure impregnation (VPI) process. Recently lot of work has been reported on new tapes, e.g., tapes containing a thermally conducting filler, and understanding of the deterioration of insulating tapes used in various rotating motors [64-68]. A new calendaring method is reported by Liu et al to fabricate very low thickness Silicone rubber sheet containing spherical alumina filler (about 0.08 mm thick sheet) with high thermal dissipation that allows 30˚C decrease in temperature of Light emitting diode (LED) device in working temperature as compared to control experiment [69].

The insulation tapes and their performance can be characterized by the following International Electro Commission (IEC) tests: IEC/TS 60034-18-33 (multifactor thermal-electrical endurance), IEC 60034-18-32:2022 (electrical endurance qualification of form-wound windings) and IEC 60034-18-1 : 2022 (general qualification framework). The Table 4 below provides references that are complementary for improving dielectric strength in polymers for electrical insulation.

Table 4 Recent reports on new polymeric materials with better dielectric properties

Important result	reference
To improve breakdown strength, dielectric constant, and other vinyl polymer properties, two polymerization techniques were explored in the last two decades: controlled free radical polymerization (CRP) and ring-opening metathesis polymerization (ROMP). The review presents key examples.	70
Incorporation of 4,4'-dihydroxy diphenyl (DHDP) increased epoxy chain rigidity and formed ordered nanostructures, leading to improved thermoset performance.	71
Addition of 0.02 wt% TU3 (a zwitterion voltage stabilizer with deep traps) significantly improved epoxy resistivity and breakdown strength, with enhanced performance up to 120 ˚C.	72
Recycling of crosslinked polymers while retaining insulation performance is rarely reported. An epoxy vitrimer retained dielectric strength after first recycling. Tg was 113 ˚C, and recycling required 10 MPa pressure at 200 ˚C.	73
Manufacturing-induced voids in epoxy switchgear insulators were studied. Combination of high-energy X-ray computed tomography (HE-XCT), partial-discharge (PD) testing, and multi-physics phase-field simulations was used. The thermal expansion mismatch between resin and metallic inserts, and cure shrinkage created 40-50 µm interfacial voids, reducing tree inception threshold by ~12% and increase tree-branching complexity.	74
Li et al compared solution coated vs electrostatically sprayed films of Epoxy cured with DICY. The latter allowed film of about 37-micron hierarchical microstructure with significantly reduced porosity and interfacial defects. This film also showed better dielectric strength of 589 KV/mm, high energy density and high dielectric constant of 6 at 1 GHz frequency.	75
A branched anhydride derived from TDI isocyanate trimer and 3,3′,4,4′- diphenyl ketone tetracarboxylic dianhydride (BTDA) provided improvement in dielectric properties of epoxy-anhydride systems, with ~25% higher dielectric strength at 20% branched anhydride content	76
A bio-based benzoxazine resin from guaiacol and vanillyl alcohol showed dielectric constant 2.99, dielectric loss 0.019 at 3 GHz, and breakdown voltage of 27.2 KV/mm.	77
A new Class C silicone impregnating varnish with optimized combination of D-T structural units based on two condensation processes was developed using computational simulation for better properties	78
A fluorinated active ester curing agent for Novolac resin composites yielded dielectric constant 2.67, dielectric loss 0.006 at 20 GHz, and thermal decomposition temperature of 385 ˚C, suitable for robotics and 5G applications.	79
Many epoxy resins with silicon or fluorine containing groups are reported in this work, aimed at electronic packaging application. Further, Fu et al discussed strategies useful to get suitable epoxy materials with dielectric constant below 3 at 1 MHz and some suitable for higher frequency.	80
Epoxy resin cured with a hardener containing combination of alicyclic amine and a phenalkamine made with polyether amine creates an asymmetric molecular chain structure in crosslinked network that is more polarizable and hence improves energy density to 9.12 J cm^{-3} at higher field of 550 KV/mm and also shows energy density of 1 J cm^{-3} at 120 ˚C.	81

We will briefly discuss the polymer insulation used in cables below. An important polymer used in cable protection for medium and high voltage (MV and HV) power transmission is crosslinked polyethylene (XLPE). These products are expected to last more than a decade, with proper maintenance. XLPE materials are made by crosslinking extruded polyethylene using peroxide catalyst at higher temperature around 120˚C for few hours and then degassed under vacuum for many hours to remove harmful impurities like ketone. Two recent reviews discussed (i) reports that can circumvent presence of harmful impurities and some reports on recyclable cable insulations based on covalently adaptable bonds and (ii) developments in XLPE nanocomposites to improve dielectric properties and lifetime of cable [82, 83]. Bjurstrom et al have reviewed reports on modeling and predictive work on dielectric properties of polyolefins used for HVDC cables. They also discussed test methods for dielectric strength of various cable insulation and capacitor films[84]. Some more examples of reports related to improving the dielectric strength of XLPE are shown in Table 5.

Table 5 Different approaches for improvements in dielectric strength of XLPE

Important Results	Reference
4,4′-Diaminobenzophenone enhanced XLPE, boosting DC breakdown strength by 16% (30 ˚C) while lowering conductivity. DFT analysis linked this improvement to balanced charge trapping and transport arising from synergistic donor and acceptor groups.	85
Peroxide-crosslinked XLPE modified by grafting maleic anhydride or allyl chloroacetate created deep charge traps, suppressing conduction and improving dielectric strength by ~15%.	86
A diimide (BVM) acted as voltage stabilizer, space-charge inhibitor, and crosslinking aid. Dielectric strength increased ~30% while reducing peroxide content by 27%, and crosslinking was not affected	87

Review of XLPE modifications. Nanofillers improved dielectric strength and electrical treeing resistance through large interfacial regions.	88
XLPE/polystyrene blend (200 ˚C) improved dielectric strength by >25%. Polystyrene forms a separate phase that reduces voids and helps to create more charge traps.	89
Slow cooling of crosslinked XLPE increased crystal size (6 to16 μm) and improved breakdown strength by ~10% (from 80 to 100 KV/mm)	90

Notwithstanding the problems in dispersion of nanofillers, nanocomposites of various resins mentioned above have also attracted lot of attention in past few years due to possibility of achieving high dielectric strength. The new studies not only report data on improvement in dielectric strength but also provide complementary evidence based on deep trap energy level values. Few interesting reviews are available in recent times on this topic [5, 91, 92]. Few more recent reports (with most of them using epoxy resin) are shown in Table 6 below:

Table 6 dielectric strength and other properties of recently reported nanocomposites

Important Results	Reference
Aslam et al found that 2.5% epoxy-functional POSS improved DC dielectric strength (236 KV/mm, >15% gain over control) by introducing deeper traps (2.15 eV vs 1.8 eV in neat epoxy). Similar behavior reported for nano-silica modified Kraft paper by Chen et al (ref 94).	93, 94
Zn/Al-LDH nanoclay epoxy for gas insulated switchgear (GIS) showed stable permittivity, low dielectric loss, suppressed DC conductivity (10^{-15}-10^{-12} S/cm), and higher breakdown strength (from 30.1 for control to 37.4 KV/mm at 5 wt%).	95
1-7% Nanosilica containing Silicone resin composites were tested. Results showed that nanofiller content of 7% gave about 10% improvement in dielectric strength to reach 13.7 KV/mm, and about 25% increase in PD inception voltage was noted at 5% nanosilica content	96
Use of 2-4% nanofiller derived from silane and Zinc salts in epoxy improved dielectric strength (~10%) with simultaneous reduction in dielectric loss and dielectric constant .	97
1 wt% boron nitride coated with polydopamine (h-BN@PDA) gave epoxy composite with optimum performance: deeper traps (1.078 eV), higher DC breakdown strength (217.9 vs 201.9 KV/mm). Higher loading (3-5 wt%) reduced performance due to interfacial polarization.	98
0.5% of the magnetic filler $SrFe_{12}O_{19}$ in PP multilayer composite increased breakdown strength to 283 KV/mm and reduced leakage current by ~82%.	99
Use of 20% methylated porous silica filler in PI achieved low dielectric constant/loss at very high frequency of 10 GHz and breakdown strength of 96 KV/mm. Filler also increased inter-chain spacing suggesting increase in free volume.	100
Recyclable epoxy vitrimer with 0.5% alkyl-modified montmorillonite retained low dielectric loss (0.008 at 120 ˚C) after recycling.	101
TiO_2 nanofiller improved dielectric strength in epoxy composite by ~10% at 413 K. Optimization of free volume and nanoparticle content enhanced high-temperature breakdown strength.	102
3-5% nano-alumina in 1K epoxy showed excellent breakdown resistance with no emission-current reduction at 6 kV. Nano-silica performed better than neat epoxy but worse than nano-alumina.	103
Epoxy/TiO_2 breakdown mechanism changes with temperature: charge transport dominates below Tg, while free-volume expansion governs breakdown above Tg.	104
<1% silica nanoparticles provided modest dielectric-strength improvement in polyester insulating varnishes.	105
Graphene was preferred as a nanofiller due to better heat dissipation at higher frequency, while nano-silica delivered the best dielectric properties in epoxy composite for high-frequency transformers.	106

Predicting dielectric strength at breakdown is difficult. However, this information is desired to avoid expensive downtimes and save time lost in electric supplies and other manufacturing operations. Some interesting reports in this direction are available, but more work is required [10 ,107]

3. Test methods for dielectric strength and related phenomena

In this section, various standard tests for insulation and related properties as well as other features like traps and free volume are discussed. The most widely used methods for evaluating dielectric strength are IEC 60243 and ASTM D149. Dielectric strength is determined from the breakdown voltage of a polymer film. Electrical breakdown in polymers follows a weakest-link mechanism, where failure is triggered by the most severe defect, such as a void or impurity. Since such failures represent low-probability events, breakdown data are better described by the Weibull distribution than by a symmetric Gaussian distribution. Because of this statistical behavior, breakdown strengths vary among identical samples. IEC 60243 and ASTM D149 therefore require testing multiple specimens to generate a Weibull distribution and determine the dielectric strength (KV/mm) corresponding to a 63.2% probability of failure. Breakdown strengths at other probability levels can also be calculated.

When voltage is applied to an insulating film, electrons shift slightly and remain in a higher-energy equilibrium state. Since no insulation is defect-free, a small leakage current is always present. Prolonged voltage application (ageing) or higher electric stress can disturb the equilibrium, eventually leading to conduction and breakdown. Charge traps present in insulating materials restrict charge movement and retard deterioration. Table 7 summarizes phenomena occurring below breakdown voltage in materials that influence insulation performance. Standard test methods for lab made or freshly made industrial scale materials for dielectric strength, partial discharge, and space charge resistance are listed in Table 8. At present, no standard test methods exist specifically for deep and shallow traps in solid insulation materials.

Table 7 Phenomena closely associated with changes in dielectric strength

Phenomenon	Effects of Phenomenon	Reference
Electrical ageing	Charge injection, recombination, and bond scission occur below breakdown stress, reducing insulation lifetime under prolonged electric fields.	108
Space charge accumulation	Trapped charges distort the internal electric field, accelerating insulation ageing and causing field non-uniformity in the film.	109,110
Partial discharge (PD) initiation	Local discharges at voids, interfaces, or defects initiate insulation degradation. PD being repetitive, creates hot spots, promotes polymer damage, and leads to corona discharge, electrical treeing and eventual failure.	111

Table 8 Standard Test methods for Dielectric strength and associated phenomena

Test method	Type of insulating material
IEC 60851-5	Wire enamel (magnet wires)
ASTM D149/ IEC 60243	Epoxy potting compounds
IEC 60464	Varnishes in rotating motors (tested as solid films)
IEC 60243-1	Slot insulation films like Mylar and for capacitor films
IEC 60243	Paper insulation in oil transformers
IEC 60156	Transformer oil
IEC 60243/IEC 60371	Resin rich Insulating tapes
IEC 60664-1	Partial discharge test
IEC 62758:2012	Space charge distribution in high voltage insulation materials

The methods in Table 8 are primarily destructive. Kaziz et al [111 in above Table 7] reported a non-destructive, non-contact method for detecting partial discharge activity. More recently, Sui et al. developed a non-destructive approach for estimating breakdown voltage in XLPE cable insulation [112]. XLPE samples thermally aged at four temperatures (105, 135, 155, and 180 ˚C) showed a strong correlation between dielectric strength and NIR absorption peaks at wavenumbers 1730 and 1763 cm^{-1}, which are associated with crystallinity changes. Surface potential decay (SPD) measurements further indicated that breakdown strength is influenced by deep-traps having energy levels correlated with these absorption peaks. A backpropagation neural network was then used to predict the breakdown strength of XLPE cable samples subjected to six service periods. Qi et al. proposed another non-destructive method for predicting DC breakdown strength of polyethylene (PE) and PE nanocomposites using a bipolar charge transport (BCT) model and trap-energy analysis from isothermal surface potential decay (ISPD). Trap distributions measured in 110-micron films containing 20 nm silica-filler were used to determine intrinsic breakdown strength, and the predictions were validated experimentally [10].

Characterization of thermal properties(Glass transition temperature and thermal stability in terms of weight loss), and crystalline morphology using X-ray diffraction study are particularly important for semicrystalline polymers such as PP and PVDF. A fundamental study on PVDF and vinylidene fluoride copolymers showed that (i) all-trans conformation and (ii) polar β-phase are not favorable for capacitor energy-storage applications. Instead, copolymer having TTTG conformation (T for trans and G for Gauche) with small polar γ- phase and Curie transition near ambient temperature provided more balanced properties [113].

Two additional factors strongly influencing dielectric strength are charge traps and free volume. Charge traps are beneficial localized defects that temporarily capture charge carriers and improve dielectric strength. Traps with energies below 0.6 eV are generally classified as shallow, while those above 0.6 eV are deep traps. Deep traps retain the charges longer and more effectively restrict charge transport [114]. Although there is no dedicated IEC standard for trap characterization, researchers commonly use IEC 62631 guidelines together with specialized techniques such as (i) Thermally Stimulated Depolarization Current (TSDC) and (ii) Space Charge Decay Analysis. TSDC is widely used for determining deep-trap energy distributions and densities. The polymer is polarized under a high DC field at elevated temperature, rapidly cooled to retain trapped charges, and then reheated while monitoring depolarization currents corresponding to different trap depths [115-117]. Space Charge Decay Analysis evaluates the dissipation of trapped charges after removal of the applied field and is also used to estimate deep-trap distributions [118].

Free volume refers to microscopic voids between polymer chains and is commonly characterized using positronium lifetime measurements. The positronium lifetime depends on cavity size, allowing determination of hole radius, volume, and free-volume distribution [119]. Increased free volume generally reduces dielectric strength, although exceptions occur in nanocomposites where free volume may act as charge traps and slightly improve dielectric strength [120]. In some high-Tg polar polymers, marginally increased free volume can reduce charge-transport and enhance dielectric strength and energy density. A recent study on 17 different PI polymer structures aimed at reducing dielectric constant (k) confirmed that k is correlated with free volume content in terms of the measurable parameter (I_3) in positronium lifetime measurement[121]. A recent FTIR-based Restricted Orientation Anisotropy (ROA) method identifies the shape and orientation of free-volume elements. Unlike conventional methods that assume isotropic spherical cavities and report only average free volume, ROA provides a more realistic description of polymer morphology and better correlates with dielectric strength, charge transport etc [122]. A less discussed topic is interfaces present in the insulation. For very high energy-density capacitors, interfacial effects must also be considered. Interfaces generated by additional polymers or fillers influence mobility, crystallinity, and chain conformation, and more importantly, provide more traps to reduce leakage current and charge transport [123]. More work is required to systematically define the interfaces that help to improve dielectric strength and other performance parameters. This is getting evident from recent reports related to insulation for high power application[5, 8].

IEC 61558 standard covers safety of power transformers using high frequency. High-frequency transformers are increasingly used in power electronic transformers because of their compact size and efficient energy conversion. The insulation systems operating under high-frequency stress (10-40 kHz) are prone to premature failure. A recent study proposed a method for determining equivalent test voltages between power-frequency and high-frequency operation using partial discharge measurements and dielectric-strength equivalence analysis which helps to identify this problem by detecting immediate dielectric and PD effects of higher-frequency testing [124].

4. Improvement in dielectric strength of polymeric film capacitors used in power storage devices

For polymer films used in capacitors, energy density and charge-discharge efficiency are key requirements, whereas films for electrical insulation require high thermal stability and dielectric strength. As mentioned earlier, dielectric strength represents the maximum electric field a capacitor film can withstand. Dielectric strength therefore provides guidance for safe and efficient capacitor operation by preventing use beyond E_b [125].

The most widely used capacitor insulation films are still based on BOPP due to their low dielectric loss, which enables excellent performance up to 85 ˚C at reasonable cost. A recent breakdown strength study reported an optimum film thickness of about 9 µm for insulation film, with both breakdown strength and volume resistivity declining outside the 9-12 µm range [126]. Several modification strategies have been explored to enhance performance of polymers used in capacitor films. Annealing of BOPP film at higher temperature of 140 ˚C is reported for improved performance of corresponding metallized film that showed energy density of 2.7 J cm^{-3} with 12.7% improved dielectric strength to 67 KV/mm. Further, reduction in free volume content of amorphous phase as well as increase in crystallinity was also obtained [127]. Plasma-fluorinated MMT/TiO_2/SiO_2 nanohybrids introduced deep charge traps and improved breakdown strength by up to 33% at 75 ˚C [128]. UV-induced reconstruction of laminated PP films increased dielectric constant, polarization, and energy-storage capability [129]. The C-F bond activation strategy enabled poly glycidyl methacrylate (PGMA) grafting onto fluoropolymer side chains of a copolymer. This improved dielectric properties, breakdown strength, and charge trapping. The resulting polymer (4.5 wt% PGMA) achieved a high discharge energy density of 10.0 J/cm^3 (82.1% efficiency) at room temperature and maintained 8.1 J/cm^3 (71.9% efficiency) at 125 ˚C [130]. A recent review highlights grafting, crosslinking, blending, and nanofiller incorporation as effective approaches for improving breakdown strength and energy density in BOPP at 85-120 ˚C [131]. These studies may provide useful guidance for developing higher-temperature insulating polymer systems.

The global power electronics market, including EV inverters, renewable energy converters, and industrial drives, is expected to approach 97 billion USD within the next decade [132]. Consequently, high-temperature and high-frequency polymeric dielectrics will remain an active research area [133]. To give an example, future insulation films in battery operated vehicles must operate near battery-engine temperatures of 140 ˚C and electric fields of 200 KV/mm. Requirements for underground oil and gas exploration and electrified aircraft may exceed 200 ˚C and 250 ˚C, respectively [134]. In addition, wide-bandgap semiconductor-based power electronics require capacitors capable of operating above 150˚C [133]. The following discussion briefly covers (i) developments for temperatures above 140 ˚C and (ii) advances in high-frequency insulation films, along with key background concepts.

The main goals of developing capacitor films for high-temperature operation are (i) to reduce charge injection (ii) to reduce dielectric loss since heat generated due to loss increases exponentially as tan δ increases (iii) to improve dielectric strength (iv) enhance thermal stability through high-Tg polymers (v) maintain energy density and charge-discharge efficiency at high temperatures. Current trend in designing to control losses in dielectric performance at high temperatures and high frequency applications are showing new concepts that are hitherto not reported. According to Wang et al., above ~200 ˚C, phonon-assisted interchain tunnelling dominates charge transport in dielectric polymers, and suppressing it enables high-energy-density dielectrics for high-temperature applications [135]. Wan et al. showed that π- π stacking between imide and phenyl rings in ordered PEI domains enhances charge transport but restricts energy density. Here, controlled crosslinking stabilizes desired packing conformation which suppresses π- π stacking and charge transfer, resulting in a high energy density of 3 J cm^{-3} at 250 ˚C [136]. Thus, changing polymer topology can play important role for the new applications. Yet another report that shows important role of topology of chains that favours high energy density at high temperature was by Li et al, who found good relation between dielectric properties, chain flexibility, and substituents on aromatic rings of monomers used to synthesize PEI films [137]. Unlike the various models on topic of polymer insulations for low frequency and low working temperature [16, 138- 140], probably the insulations for higher operating temperature and higher frequencies are in the phase of generating required experimental data to support basic models. One example that illustrates this gap is: π- π bonding that significantly obstructs high energy density at high temperatures in PEI insulation films is not active at lower temperature and lower frequency as seen from energy density of 8.48 J cm^{-3} at field of 678 KV/mm for very carefully dried PEI film [141].

The following Table 9 gives a brief correlation between first seven parameetrs affecting polymeric insulation and corrective actions with corresponding references for high temperature capacitors. The same factors are also relevant for insulation used in high frequency capacitors, in addition to the factors discussed in the last three rows of Table 9.

Table 9 Parameters affecting insulation and corresponding corrective actions for high temperature performance

Parameter affecting insulation	Corrective Strategy	Reference
High charge injection rate from electrode at high temperatures	Create electrode/interface barriers by either modifying interface with ultrathin layer of conducting filler or by incorporating special nanofiller (ceramic filler coated with metal)	133, 142
Exposure to high carrier concentration that increases leakage current	Wide-bandgap polymer matrix	143, 144
High carrier mobility that can cause rapid charge transport and energy loss	Incorporate deep-trap forming additives or blend catalysts in polymer to change its conformation to create deep traps	55, 145, 146
Space-charge accumulation that causes field distortion and local electrical overstress	Introduce deep traps as well as interface barriers	147, 148
High polymer chain mobility at elevated temperature favouring charge transport	Restrict mobility by use of high Tg polymer or introduce controlled crosslinking	11
Charge hopping through interchain gaps creating disorder	More ordered molecular structures by increased chain packing density	149
Presence of Electric-field non-uniformity	Use thinner top layer to redistribute electric field to help base layer to improve its performance	150
Self-heating/thermal runaway	Thermal management by improving thermal stability	11
High dielectric loss that leads to Energy dissipation and lower energy efficiency	Use low-polarity polymer matrices like cyclic olefins, fluoropolymers	80, 100
High dielectric constant causing RC delay that can cause Signal distortion and reduced frequency response	Design or modify polymers to get films with low dielectric constant	80, 151

In the last few years, several promising high-temperature polymeric dielectric films have been reported. Selected examples are highlighted to illustrate different approaches for achieving high dielectric strength (DS) and energy density (ED) at elevated temperatures. Approaches used include new monomers, blending, use of nanofiller, interlocking of polymer chains, adding deeper traps using interface formed in phase separated morphology etc. For convenience, the results are grouped according to test temperatures of 150, 200, and 250 ˚C (Table 10). The report on self-healing insulation with extended working life is promising development in applied chemistry for power engineering (see ref 163 in Table 10). Most of the results in Table 10 and 11 need to be confirmed at pilot or larger scale.

Table 10 Examples for performance parameters of high energy density insulation used at high temperatures

Temp (˚C)	DS (KV/mm)	ED (J. cm^{-3}) and (efficiency)	K*	Important reasons for improvement[reference]
150	474	5.07	4.2	PI copolymer with bulky/polar diamines [152]
150	NA	5.93 (90%)	NA	PEI with CF_3 and OH groups in monomers; reduced π-π conjugation [153]
150	709	7.1 (90%)	NA	PEI/BMI interpenetrating blend; created deep traps [56]
150	550	4.6 (92%)	NA	Crosslinked PEI with 5% benzoxazine; stable for 50,000 cycles at 400 KV/mm [154]
150	605	3.7 (90%)	4.1	PU/PEI blend; hydrogen bonding induced deep traps [155]
200	200	6.5 (90%)	NA	PEI/polythiourea blend containing1.5% BN filler; 10^5-cycle durability at 200 ˚C [156]
200	549	6.5 (90%)	4.2$^{\$}$	Bulky POSS groups containing PEI; POSS increased inter-chain spacing and introduced deep traps [157]
200	648	8.1(84.9%)	4.3$^{\#}$	Blend of PEI/poly(sulfonated) aramid; uses interfacial deep traps [158]
200	400	5.5 (90%)	6.51	PEI/PPEU blend; higher free volume content and presence of deep traps [159]
200	NA	3.49 (90%)	NA	N, S -doped carbon-dot/PEI nanocomposite [160], with good cycling ability of 10^5 cycles
200	437	1.58	NA	Corona-treated PEI with internal charge layer fabrication to restrict charge movement [161]
200	617	4.68 (90%)	NA	Metal-complexed crosslinked PEI for better thermal stability and recycling possibility, metal ions serving as deep traps[162]
200	NA	6.06 (90%)	NA	A self-healing dielectric enhanced insulation life at 200˚C because it worked for additional 80000 cycles after breakdown [163]
250	NA	4.31	NA	Twisted-conformation PI; suppressed intermolecular interaction [164]
250	NA	4.1 (90%)	NA	Mechanically bonded PI with threaded cyclic polyether [135]

250	450	3.5 (90%)	NA	Si-containing alicyclic PI copolymer with self-healing under breakdown condition [165]
250	NA	8.6	13	Nanoscale phase-separated dipolar polymer blend [166]
NA- not available, *K is dielectric constant, $- measured at 150˚C, # measured at 200˚C				

The insulation films operating at higher frequency face little different problems. In addition to requirements shown in Table 9 as well as high thermal stability and high Tg polymers, they need the materials that must show as low dielectric loss and polarization relaxation as possible. Some recent reports show the achieved performance level(Table 11).

Table 11 developments in polymeric insulations suitable for high temperature and high frequency applications

Key Results	Reference
A platform has been developed to predict dielectric properties of different polymers by varying the structure of monomers used. This work shows machine learning technique can correlate desired dielectric constant with the structure of polymer for a wide range of frequencies.	167
Fluorinated Parylene-F dielectric film (CVD) showed improved charge trapping, low conduction loss, and thermal stability up to 150 ˚C, achieving 2.92 J cm^{-3} energy density at >90% efficiency.	168
Sulfonyl-modified polyimide with HfO_2 nanofiller achieved 2.71 J cm^{-3} energy density and 95.7% efficiency at 150˚C and 200 KV/mm	169
This is rare study on dielectric breakdown behavior of PI thin films from room temperature to 400 ˚C (20 KV/mm at 400 ˚C), showing strong temperature dependence of breakdown strength.	170
Blend containing 40% porphyrin-based PI achieved dielectric constant 6.68, dielectric loss <0.05, and energy density 2.87 J cm^{-3} at 250 ˚C.	171
Controlled crosslinking in PEI synthesis using tri-functional amine monomer allowed dielectric constant of 3.2 and dielectric loss of 0.003 at 10 GHz, with Tg 350 ˚C	172
Review summarizes high-temperature PI dielectric performance, including breakdown strength, leakage current, energy density, efficiency, Tg, and gives examples of AI-assisted material design.	173
Ester/ether linkages containing linear polyimides showed ultra-low dielectric loss (0.0015-0.0024 at 10 GHz) and retained performance under humid and high-temperature conditions.	174
High-frequency stress accelerates partial discharge damage in PI films; experiments and simulations confirmed local electric field concentration drives degradation under high frequency sinusoidal voltage.	175
Adding 5 mol% silicon-based additives to polyimide improved dielectric strength, despite a frequency-dependent drop from ~160 KV/mm (5 kHz) to ~100 KV/mm (20 kHz), likely due to reduced polarization losses and deep-trap formation.	176
A polyimide with carefully chosen comonomers allows polymer chain that has isomers as comonomers that also serve to create units of chain with different energy levels. This helps to significantly restrict movement of charges at higher temperatures. The copolymer film showed energy density of 1.1 J cm^{-3} at 300 ˚C with 90% efficiency.	177
PI-based aerogels were recognized by IUPAC as one of the top ten emerging technologies in 2022. A co-gel synthesis route combining polyamic acid imidization with silica sol-gel transition produced aerogels with low thermal conductivity, low dielectric constant (<3 at 180 ˚C), tensile strength of 5.7 MPa, and high thermal stability, making them suitable for flexible thermal insulation and demanding aerospace applications	178
Soluble, recyclable fluorinated polyimide films with porosity of 33-71% and pore sizes of 1-10 μm were prepared using a solvent/non-solvent method. A film with 48% porosity exhibited a dielectric constant of 2.48 at 10 GHz, highlighting porosity as an effective parameter for high-frequency insulation applications.	179
Epoxy composites with carefully selected nanofillers are useful for high frequency solid state transformer fabrication. Higher thermal stability, better thermal conductivity and reduction in electrical conductivity at higher frequencies are seen for nanocomposites	180
A very recent review analysed filler design, interface design and multiphase structure design as core requirements for high temperature polymeric dielectric to get synergistic advantages	181
Appropriate monomer substituents promote dense packing, delivering a dielectric constant of ~2.6 and dielectric loss of 0.007 at 10 GHz without relying on porosity for poly (aryl ether ketone ketone)	182
Epoxy functionalization of POSS modified cyanate ester allows dispersion of nanofillers to provide adhesive films for high frequency application with strength of 39 MPa (55% of this value retained at 200 ˚C) and dielectric constant of 2.82 at 10 GHz	183

5. Conclusions and future work

To conclude, the above discussion first introduced effects of aging on dielectric strength and other dielectric properties and briefly discussed various IEC tests for this study. The later discussion included polymeric insulations used in conventional applications (epoxy, unsaturated polyester, silicone resins, PU resins), cable insulations based on XLPE and resin rich mica tape insulation. We then covered various test methods for polymeric insulation properties like thermal stability, free volume, and shallow/deep traps. The very active research area in polymeric film insulations for capacitors is discussed in the last section, starting with BOPP and then focusing on improving insulation properties for use at high temperatures and high frequency. Although PEI are excellent materials for many applications, polyimides appear to be used in very demanding temperatures and high frequency applications. In future, one can expect more use of polymeric dielectrics operating under high voltage in high frequency devices and higher operating temperatures. The currently used polymeric dielectrics used in high-voltage, high-frequency systems face key limitations. For example, defects such as electrical treeing, partial discharge, and space-charge accumulation, which reduce reliability under high electric fields. These dielectrics also exhibit high dielectric loss at elevated frequencies and because they usually have poor thermal conductivity, this leads to overheating and efficiency loss. Further, they face conflicting trends in improvement for permittivity, breakdown strength, and thermal stability, which results in restricting energy and power density improvements. Use of nanofillers shows promising results as discussed above but it requires control of agglomeration and interface issues in nanocomposites, and data related effect of ageing on performance is required. Use of fluorine containing monomers and synthetic aromatic diamines give encouraging results for very high frequency insulations but regulations on such chemicals for environmental concerns may demand different approaches. Finding solutions for these problems will help development of advanced materials for next-generation applications.

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