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REVIEW OF DIELECTRIC PROPERTIES OF POLYMERIC MATERIALS USED IN ELECTRICAL APPLICATIONS

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Abstract: This review paper focuses on the dielectric properties of polymers used as electrical insulation and in capacitor films, for electrical and electronics applications. The high-power transmission is a fast emerging and high growth development area in our country, and it is expected to boost indigenous research and development of polymers required in this application and ancillary developments. The review discusses how improvements in fundamental dielectric properties helped to improve quality of the polymeric materials for electrical insulation and capacitors used in power industries and electronics applications. The basic polymer chemistry behind the development of suitable quality materials and structure-property relations that complement these developments are discussed. The review also draws attention to the less understood topic of features of polymers and their composites, like traps and interface, that influence dielectric properties. The requirements of environmental protection, conserving energy and resources during future developments are emphasized.

***Index Terms* -** dielectric properties, polymer, electrical insulation, capacitor

***Abbreviations* -** Biaxially oriented poly propylene (BOPP), Density Functional Theory (DFT), Polypropylene (PP), Low density poly ethylene (LDPE), High density poly ethylene (HDPE), crosslinked poly ethylene (XLPE), Polyethylene terephthalate (PET), Poly vinyl chloride (PVC), International Electrotechnical Commission (IEC), Poly vinylidene fluoride (PVDF), Poly tetra fluoro ethylene (PTFE), Poly phenylene sulfide (PPS), Polymers of benzene rings connected by ethylene bridges (Parylene)

I. INTRODUCTION

The dielectric properties of polymers reflect how they respond to an applied electric field and their capacity to store electrical energy within that field. Polymers have been used in electrical energy generation and transmission as insulation materials for past several decades due to advantages like lightweight, excellent electrical insulation properties and durability over a wide range of ambient conditions. Interestingly, many of the insulation materials like PP and PET can be used as part of the products developed for energy storage applications as capacitors and in power distribution setup. The polymers used only for insulation applications cover a wide range of products and sizable market of $22 billion [1]. The insulation polymers are used in variety of products such as motors of various sizes, electrical appliances, special applications in heavy duty transport, defense, space applications and high/medium voltage cable insulation. Within the country insulation products development will get a boost in coming months as Government of India recently declared that it would be spending Rs 53,000 Crore for nine 1100 kV high voltage AC cables and ten substations in the next 10 years [2]. The present global market for capacitor films is around $4 billion and is mainly for use in renewable energy storage and distribution, appliances and automotive sectors [3]. The capacitors are also finding use in new opportunities in smart phones and wearable electronics market segment.

Variety of polymers that belong to thermoplastics or thermosetting class (e.g., PP, XLPE, PET, PI, PPS, epoxy, polyurethanes, Silicone resins) are used as insulations. The polymers with high dielectric constant and excellent dielectric strength are used for capacitor films (e.g., PP, BOPP, PVDF, PI, PPS, crosslinked PVDF). [4,5] Further, to improve the dielectric properties and insulation performance of thermoplastic and thermosetting polymers, different approaches like addition of micro or nanosized fillers, fibers, additives, and fabrication of multilayer films (for capacitors) are commonly used. Even phase separated blends are also found useful for insulation and capacitors for better dielectric properties. Thus, various techniques in polymer technology can be used to fabricate insulation and capacitor materials, particularly for high temperature exposure [6].

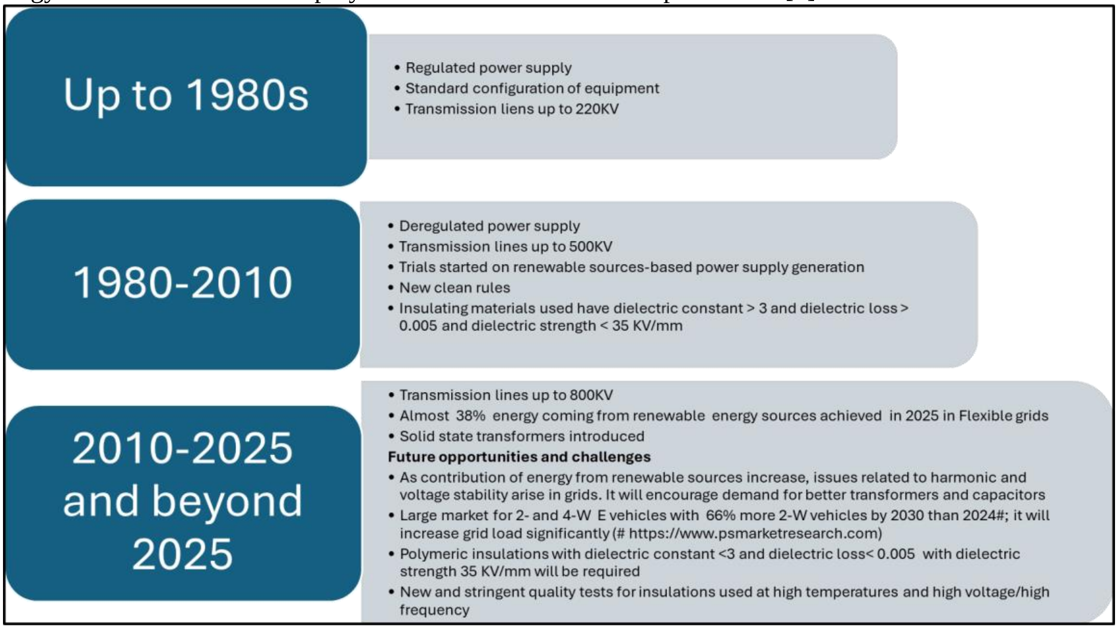
The recent developments in dielectric properties of polymers are closely associated with tough market demands and overcoming fundamental challenges arising from structure-property relations in polymers and polymer composites with variety of fillers [7,8]. Few examples are as follows:

(i) Qiao et al., observed in their review that while polar groups influence dielectric permittivity when used as pendant groups, the same groups present in monomers creating backbone polymer chain influences the thermal and mechanical properties. The optimum ratio of these two types of groups is required to balance the overall performance to meet requirements at low and high electric field. Mechanical properties like brittleness are also important when it comes to optimization of performance [6].

(ii) Almost all commercially produced polymers are bound by the inverse correlation between bandgap and glass transition temperature/ dielectric constant [9].

(iii) Thermal stability and electrical insulation in polymers are often inversely related [10].

(iv) Getting polymers with high dielectric strength and high dielectric constant is difficult but it can be achieved by carefully managing synergy between nanofiller and polymers to fabricate a nanocomposite film [8].



Scheme 1: Progress in polymeric materials market sector in domestic electrical applications

Scheme 1 gives idea of qualitative changes in three arbitrarily chosen periods (before 1980, 1980-2010 and 2010-2025 plus beyond 2025) for the polymers used for insulation and capacitors in the domestic market for power industries. As may be expected, many milestones were achieved between 1980-2010 and the same speed of development continues but with more demanding requirements. This in turn pushed developments in polymers for insulation and capacitors for better dielectric properties. In near future, we can expect significant changes in the dielectric properties of polymers as smarter phones, electric vehicles and ultra-high voltage transmission lines get tested to pave way for new developments. In addition, the use of more compact devices running at higher voltage as well as higher frequency will be commercialized, and those devices will require better quality polymers. For example, they will need better dielectric strength and lower dielectric loss at higher temperatures (above 100 ˚C), than what is used at present.

In this paper, focus is on dielectric properties related developments in polymer-based insulations and capacitors. We highlight the importance of improvements in dielectric properties by controlling the variables like structure of monomers, fillers, additives and characteristics like traps, interface and free volume that are relevant for dielectric performance. It is an endeavor to unravel the information about how various factors interact with each other and the polymer matrix and achieve the required performance in many cases. The discussion is restricted mostly to the reports of last five years. The framework of the paper is divided into five sections, and first part is about basic dielectric properties and fundamental factors that help insulation and capacitors perform better. The second section discussed developments in polymers for insulation and in the third part, developments in polymers for capacitors. The fourth section discussed nanocomposites developed for use as insulation and capacitors. Finally, we provide summary and scope for future developments.

1. Basic dielectric properties and factors that help performance of insulation and capacitors

Insulating materials in general cover solid and liquid resins that turn into solids, mineral oil liquids and gases like SF_6. In this paper, we are limiting the discussion to the insulation of solid polymeric materials (e.g., epoxy, PET). For capacitors also, we are restricting organic polymers and their composites, and ceramic or mica-based materials are excluded. The dielectrics derived from polymers for capacitors can be of four types: ferroelectric, relaxor ferroelectric, antiferroelectric, and linear dielectric materials, based on shape of graph of electrical displacement (D) - applied electric field (E) popularly described as D-E graph [8]. Most of the polymers discussed in this review are linear dielectric materials with linear D-E graph while PVDF and its copolymers are ferroelectric with loop type D-E graphs.

Before we go into the discussion on literature relevant to these materials, it is necessary to understand basic dielectric properties of these materials. We have summarized in Table 1 the important factors that influence performance of insulation materials and capacitors, and how they are tested. Many of the factors are common to insulators and capacitors. The energy density factor is more relevant to capacitors. The problem of thermal runaway is commonly observed in insulation and capacitors used at high frequency. Table 1 also gives typical values for PET and BOPP which are popular polymers used for insulation and for capacitors, and they indicate that PET is more effective in high temperature operations than BOPP. Table 2 gives a general idea of connection between various dielectric properties and applications.

Table 1: Important electrical properties of polymers used as insulation and capacitors

Property (units and Test method)	Significance of the property (Values for PET & BOPP are from reference [8])
Dielectric strength (Unit is KV/mm measured using IEC 60243-1:2013)	Maximum electric strength of the solid material before it breaks down and begins to conduct electricity. PET (570MV/M @150 ˚ C) and BOPP (496 MV/M@120 ˚C)
Dielectric constant (dimension less ratio, unitless, measured using IEC 60250 or IEC 60243 for solid materials)	Dielectric constant gives an idea of material’s ability to resist electric field and prevent electrical breakdown. High dielectric constant can lead to high breakdown voltage PET (~3 @25 ˚C) and BOPP (~2.25@20 ˚C)
Dielectric loss (Dimension less ratio, measured using IEC R. Cheng, IEC 60243-1and IEC 60034-27-3	Dielectric loss reduces efficiency of storage of electrical energy as some of the stored energy is lost as heat. This heat can initiate degradation of material and potentially premature failure of the insulation. PET (~0.0002 @25 ˚C) and BOPP (~0.0001@20 ˚C)
Electrical breakdown resistance for liquids and gases (Units used are V/cm or V/m or MV/m) measured using IEC 62271-200	This parameter determines the maximum voltage an insulating material (gas or liquid) can withstand, particularly for switchgear and control gear, before it fails and start conducting.
Partial discharge resistance (primary unit is picocoulomb (pC) but additional units like milli volts (mV) or micro volts (µv) are used to represent the voltage spike associated with partial discharge) measured using IEC 60664-1	Partial discharge (PD) refers to electric discharges appearing in high voltage insulation subjected to high voltage stress. Four main types of PD are known (corona discharge, surface discharge, internal discharge, and electric trees) and discussed by Haque et al [4]. PD can happen repetitively during the lifetime of insulation and directly impacts life of insulation.
Flashover voltage This voltage (unit kV) is tested by IEC method 60060-2	Flashover voltage is the minimum voltage at which an electrical discharge occurs across the surface of an insulating material, leading to a sudden and uncontrolled current flow. This phenomenon can result in equipment failure, fires etc. [11].
Space charge resistance (SC) Unit is Ω/cm^2 Measured using IEC 62758:2012 based on pulsed electro-acoustic (PEA) measurement	It is used to quantify the resistance caused by accumulation of electric charge in a material. SC has no single “safe value” as its accumulation is dynamic, and an acceptable range of values is decided by periodic measurements
Tracking resistance Unit is the number of drops of electrolyte required to extinguish the arc applied between two electrodes. Measured using IEC 60587	It is useful to detect single point of insulation failure that can cause irreversible damage and catastrophic consequences on the performance of electrical equipment
Thermal stability Usually expressed by temperature in Celsius or Kelvin unit Measured using IEC 60811/IEC60455	This information is useful to get an idea of reliability and longevity of electrical insulation
Energy density Usually expressed in J/cm^3 at specific temperature and frequency (Hz) for a capacitor film. Measured using IEC 60384-13:2020	Energy density of polymer capacitor film is expressed as energy stored per unit volume. It is customary to specify the temperature and frequency used for testing PET (0.93@150 ˚C and 10 Hz) and BOPP (1.28@120 ˚C and 10 Hz)
Thermal runaway in insulation and capacitors for high frequency electrical devices Unit is KV/mm at specified temperature.	This fault results because of sudden rise in temperature of the insulation after a critical voltage. It is relevant for devices that operate at high voltage and high frequencies, typically at 10 KHz or more [12]. There is no standard method yet for this parameter [13].

Few points to be noted before the discussion of polymers used for insulation and capacitors continue. The dielectric properties common to polymers used in insulation and capacitors are high dielectric strength and low dielectric loss. In addition, the insulation film in an electric motor is expected to be thermally and mechanically strong, to resist flow of electric current under thermal or mechanical stress. The polymer in a capacitor is expected to act as true dielectric that stores electric energy and hence dielectric constant and energy density needs to be high with as low value of dielectric loss as possible. It may be also noted that in addition to the good control over above-mentioned dielectric and thermo-mechanical properties, avoiding creation of voids during processing is very important for longer life of insulation and capacitor films. Also, we are not discussing in detail about Flashover voltage and space charge resistance, that are more critically considered properties for cable insulations. XLPE and Silicone resins are two well-known polymers for this application.

Table 2: Applications for polymeric materials with different dielectric property combinations

Combination of dielectric property	Application	Reference
High dielectric strength and low dielectric loss	High voltage Insulation in transformers, generators, cables	[14]
Low dielectric strength and high energy density	Thin film capacitors used in medical defibrillators, wearable electronics	[15]
High energy density and high dielectric constant	Capacitors for electric vehicles, invertors, pulsed power devices used in defense, 5G networks	[16]
High energy density and low dielectric constant	All solid Electrostatic capacitors used in camera flashes and power backup devices and pulse power lasers	[17]
high energy density and high dielectric loss	Applications requiring absorption and quick dissipation of electromagnetic energy such as in radars and surgery.	[18,19]

A few comments on the combinations of properties mentioned in Table 2 are as follows: The dielectric strength and dielectric constant are governed by different principles and hence they are not directly related. However, the high dielectric constant of polymer may favor damage causing activity in insulation, while for polymeric capacitors, high dielectric constant is certainly favorable property. Lower value of dielectric loss, on the other hand, is favorable for both insulations and capacitors. For insulations, low dielectric loss indicates less heat generation, and this indicates thermal stability of insulation is not affected. It also helps to retain high efficiency of electric devices containing insulation, particularly at high operating frequency. In the case of polymeric capacitors, lower dielectric loss ensures retention of higher amount of stored energy till it is discharged for target application and less energy loss as heat, to help thermal stability of capacitor film. The energy density is also directly dependent on dielectric constant and the square of the value of dielectric strength [7, 18, 19].

Polymers get their useful properties due to their configuration and chemical structure of monomers used. In addition to these properties, several features (e.g., free volume, crystallinity, crosslinking density in case of crosslinked polymers) are associated with polymers as materials. If these features and application related properties are complementary, it helps for the material to qualify for that application. In the context of this paper, the fundamentally important features that are closely associated with the dielectric properties of polymers and their composites are discussed below.

1) Phenomenon of Partial discharge (PD): PD is practically measured as partial discharge resistance and already mentioned in Table 1, as it is one of the important characteristics of insulation and capacitor films that influence performance throughout their useful life. PD has remained one of the longest studied topics in electrical insulation because of its complex and stochastic nature, and new studies continue to appear in literature. Two interesting recent reviews on various methods of PD measurement have discussed current progress on understanding of PD [20, 21]. PD is a repetitive fault and ultimately causes breakdown of the insulation. Hence, detecting PD in insulation under predefined conditions prior to breakdown can help to reduce the damage to the insulation. With this aim, Htet et al., performed measurements of temporal variations in the number and magnitude of PDs for a silica filled epoxy coated on copper rod. It was found that the number of PDs with larger magnitude is less before breakdown and that there is a decreased tendency of the number and magnitude of PDs with the elapsed time [22]. They also noted that differences in clear epoxy insulation, and silica filled insulation confirmed the beneficial role of the filler to delay electric tree formation. Another example of arresting electric tree growth following repeated PD events using small molecules as additive is reported by Li et al. They have mixed Anthracene and Anthrone with LDPE and peroxide catalyst to make XLPE film with good resistance to PD [23]. Combination of PP and aluminum metal film has been extensively used as capacitor in a wide range of voltage including high voltage applications. The presence of defects in aluminum and PP films in addition to exposure to high voltage and temperature rise during use, causes deterioration of the dielectric strength of the capacitor film. Use of extra protection using deposition of antistatic layer between the dielectric film layer and the metallization layer is proposed for extending the life of the capacitors [24].

2) Traps in dielectric materials: Trap is a useful concept to understand dipole formation and improvement in breakdown strength of the insulation polymer. The formation of the charge in localized states (associated with a certain potential energy level) in the material is named trap and various test methods to characterize traps are discussed by Hao et al [25]. Further, traps are of two types, shallow and deep traps. They differ in the potential energy level of each type of trap. The shallow traps are located near the valence or conduction band that makes it easy for the carriers to escape easily as compared to the deep traps [11]. Hence, understanding the type of traps and their distribution is important for improving life of insulation. In general, presence of deep traps in high voltage insulation materials can improve value of breakdown strength [25]. Recent reports show some interesting information: (i) High crystalline content is related to creating deep traps and hence improves the dielectric strength, while shallow traps are usually localized in amorphous regions in the polymers [26, 27]. As morphological factors, crystallinity and phase separated morphology (as in the case of epoxy- Polyether sulfone blends) are known to improve breakdown strength [28]. (ii) introducing in-built molecular charge traps or adding molecules favoring restricted movement of charges (e.g. Fluorine containing reactive molecules , or molecules containing carbonyl group) can help to improve breakdown strength [29, 30]. (iii) use of nano PVDF powder helps to create dual interface in the composite of epoxy-alumina-PVDF, first between epoxy and alumina and second between epoxy and PVDF. This is proposed to produce resistance for charge movement in addition to PVDF creating deep traps due to its high dipole moment. Consequently, this improves breakdown strength of the material [31, 32]. Li et al have developed an effective method for investigating the characteristics of traps at inaccessible interfaces which can help to improve understanding of the role of various nanofillers on dielectric properties of the nanocomposites in the future [33].

Ding et al have discussed recent literature on introducing deep traps in polymers films for capacitors. [34] Further, the approaches popularly employed include use of high bandwidth inorganic nanofiller and crosslinking or blending of polymers [34]. Wang et al have demonstrated that BOPP film or cycloolefin copolymer film can be irradiated with gamma rays to generate polar groups on the surface that act as deep traps. Further, the γ-irradiated BOPP film provides a high discharged energy density of 5.88 J/cm^3 with an efficiency of 90% at 770 MV/m at 125 ˚C [35]. Traps are helpful in improving performance of polymer films for capacitors operating under stressful conditions. Formation of deep traps in the PI capacitor film doped with 5% PVDF relaxor copolymer was detected using thermally stimulated depolarization current (TSDC) method [36]. Further, the doping helped to improve relative permittivity by ~20% to 3.81 and gave the product with energy density of 9.67 J/cm^3 with excellent charge-discharge cycle efficiency of 84.7% at 150 ˚C and field of 200MV/m. Such materials are expected to be useful in future for electric cars and aerospace-electronics.

3) Interface in Polymers and composites: The region between a polymer and other material like a filler, fiber, or another polymer in a composite is considered as the interface [14, 37]. It is a region within the material where physical and chemical interactions occur and influence the behavior of the composite under stress and load. The topic is very broad as it covers many properties and applications of polymer composites. The interface can help to improve insulation as well as energy storage properties, or it can act as a weak point to initiate deterioration of performance. A general view in literature is that good interfacial bonding enhances electrical insulation properties, and more work is of course necessary for better understanding. We have discussed below some recent interesting developments:

A recent review discussed the effects of interface on dielectric properties of composites by considering different actions of interfaces on the properties namely, the interface trap effect, interface barrier effect, and homogenization field strength effect, all of which can improve quality of electrical insulations [38]. Various techniques like FTIR, small angle X ray spectroscopy in addition to theoretical tools like density functional theory-based models can be used for understanding interface properties [39]. Luo et al [40] proposed that interface in polymer nanocomposites can influence dielectric properties in two ways: (a) it can enhance the exchange coupling effect via the dipole interface layer, which can increase polarization level, dielectric response, and breakdown strength (b) it can influence changes in molecular characteristics of polymers such as free volume, crystallinity, and polymer chain configuration, which can lead to changes in dielectric properties of the polymer [10]. Dong et al found that using a blend of PP with propylene-based elastomer produced a phase separated matrix that is reprocessable and generates interface between two phases. The interface in turn helps to create traps that hinder movement of charge carriers and improve insulation properties like breakdown strength and volume resistivity [41]. A recent modeling study shows that the interfaces between the different morphological regions in a polymer or interface between polymer and other molecules (e.g. transformer oil) generate two interfaces with charge traps particularly inside a region in the matrix that has relatively more structural imperfections and localized energy states at the boundaries. Further, these traps restrict the charge movement and consequently help to improve dielectric strength [42].

Capacitor size varies over a wide range depending upon whether the application is in small device like smart phone or bulk energy storage used in large air-conditioning setups. Multilayer films are popularly used in fabricating capacitor films to overcome space restriction, and it is not surprising that formation of many interfaces in such systems due to presence of folds at nano scale level; Wang et al., have reported one such film of PVDF with three layers to achieve high performance indicated by energy density value of 6.24 J/cm^3 and breakdown strength of 449 KV/mm [43]. These values are much higher than those of currently used films.

4) Free volume in polymers: In simple terms, free volume represents available space between polymeric chains, and it is an important thermodynamic property of polymers. Effects of free volume on polymer properties are not easy to understand. Correctly using available free volume can give better dielectric properties; for example, well dispersed nanofiller helps to improve Tg due to reduction in free volume by nanofiller using the available space but with significant agglomeration of nanofillers, the extent of benefit is usually reduced. Further, the free volume changes can influence dielectric properties depending on other variables like frequency. Many modern electrical applications require polymers that can work at high voltage and high frequency. Reduction in free volume to certain extent generally helps to increase Tg and therefore thermal stability of a polymer that can be used as insulation or capacitor. Recent reviews discussed different routes to control change in free volume in insulating polymeric materials [43-45]. In general, studying free volume and its control in any polymer for use in insulation or capacitor is important to improve performance. Some recent developments are discussed below: (i) An increase of free volume, particularly in epoxy systems, leads to an increase of dielectric constant and dielectric loss, especially when the glass transition temperature is lower than ambient temperature [45]. (ii) A very novel approach is proposed in a recent report to significantly reduce free volume in an insulating materials, and consequently very high breakdown strength value (550 MV/m) has been reported at 200 ˚C for the 1:1 blend of PI and PEI by making use of strong interaction between aromatic rings in the chains of these polymers that causes dense packing in the blend. Molecular dynamics simulation results support this improvement by predicting drastic reduction in void density and free volume for the 1:1 blend [46]. (iii) Li et. al., proposed that the use of controlled branching using trifunctional monomer in the synthesis of bismaleimide resin (BMI) can help provide more free volume in the network and better insulation properties with higher thermal conductivity than unfilled material was obtained at 10 % BN filler loading [47]. They also proposed that free volume helps in better dispersion of higher amount of nanofiller up to the certain amount of BN but at higher BN loading, the breakdown strength reduces due to agglomeration of BN particles (iv) Understanding the effect of free volume on dielectric properties at higher frequencies is important in modern high voltage capacitor applications. Yang et. al., used alumina nanofiller to introduce variation in free volume size in the PVDF matrix and studied changes in dielectric constant at different filler content. Firstly, free volume radius was found to increase as filler content was increased. Further, they recorded changes in dielectric constant (DC) of PVDF nanocomposites at different frequencies. Different trends were noticed for measurements made at 1 and 10 MHz frequencies. Thus, the experimentally measured DC was higher than the theoretical value at low frequency while much lower experimental value of DC was observed than the theoretical value at high frequency. Interestingly, the differences in theoretical and experimental values increase at higher filler content than at lower filler content. Thus, changes in free volume can contribute to frequency dependent changes in dielectric properties [48]. (v) Free volume can undergo simultaneous change with few other properties in polymer to give synergistic improvements for capacitor film properties. Liu et al reported study of PVDF film exposed to static horizontal magnetic field for 3 minutes and found several interesting changes in the film [49]. The free volume pore size shrinks to give the smallest size of 2.91 Å, change in the PVDF matrix morphology having the γ-phases content of 54.8% and energy density was very high, 12.68 J/cm^3. More work to understand these changes due to use of the magnetic field may be interesting.

5) Bandgap in polymers: It is reasonable to expect that high band gap in a dielectric material can give high dielectric strength, as charge carriers will require more energy to move into conduction band. The high band gap of about 9 eV is calculated for a bulk crystalline polyethylene, and this supports the established popularity of XLPE in high voltage cable insulation [50]. To get an unambiguous relation between intrinsic breakdown and bandgap in polymers is considered difficult because polymers do not have "perfect" structures as most of them are amorphous or semicrystalline [51]. However, DFT based calculation of bandgap can be calculated for a given configuration of atoms and this gives some idea for designing polymers with larger bandgap [51]. For the pressing needs of high-power devices that operate at high temperature and high voltage, the popularly used capacitor material BOPP cannot be used. Thermally stable polyimide (Kapton with bandgap 2.6 eV) and polyetherimide (Ultem with bandgap of 3.2 eV) are also not recommended. The vinyl fluoride family polymers with high bandgap (8-10 eV) like PTFE are highly thermally stable but

very difficult to process and make in high quality films easily. This has led to bandgap engineering efforts for new polymers of high bandgaps using different approaches. Chemical doping and mechanical stress have been used to simulate PE polymer structure with bandgap of 7.9 eV [52]. Wu et al have made use of flexible fluorine containing norbornene bicyclic fused ring monomer to make polymer with bandgap of about 5.7 eV and excellent stability at 160 ˚C [53]. Xiong et al. synthesized and compared two parylene polymers (Parylene C and Parylene N) and found that Parylene C shows energy density of 1.2 J/cm^3 at 150 ˚C and 200 MV/m field which is suitable for modern power electronics devices [54].

6) Use of mechanical forces to improve dielectric properties: Flexible polymers like elastomers are known for change in physical properties when subjected to mechanical force. The well-known polymers for cable accessories are crosslinked Silicone rubber, EPDM rubber and semicrystalline polymers like PVC and HDPE. BOPP is a well-known example of mechanically streched polymer film used commercially in capacitors. Usually, mechanical stretching can help to improve order and hence degree of crystallinity in polymers like PP and HDPE. Further, increase in value of degree of crystallinity can help to produce more traps in the polymer that in turn may help to improve breakdown strength. Low temperature uniaxial melt extrusion of PP to get about 20 microns thick films show change in crystal orientation and better thermal stability due to reduction in polymer chain movement on stretching [55]. (Wang, 2025) In addition, benefits of reduction in voids that benefit dielectric strength and mechanical properties were recorded. On the other hand, stretching of HDPE reduced band gap and breakdown strength for a melt extruded film of about 0.4 mm thickness [56]. More work is desired to understand relation between bandgap and crystalline based morphological changes in these results. Hu et al studied effect of mechanical stretching on the filled and unfilled Silicone rubber (SR) dielectric properties; they compared the parameter variations of SR samples with different filler contents and matrix compositions, the microscopic stretching behavior and performance change mechanisms under mechanical stretching. Further, the dielectric constant decreased but AC breakdown strength showed an increasing trend as stretching ratio increased. In addition, the increasing filler content suppressed the tensile effect while reducing filler content had the opposite effect [57]. Capacitors made using BOPP are in use for several years and a recent review updates the status [58].

7) Effects of polarization of polar groups in applied electric fields: The recent reviews discuss the concept of polarization of atoms or groups present in polymer chains in an applied electric field and its effect on dielectric properties that influence performance as insulation or capacitor [59, 60]. For capacitor application in particular, high-energy density and efficiency of its delivery repeatedly in thousands of cycles is possible with polymers containing polar groups. However, severe loss in polarization hysteresis causes reduction in charge-discharge efficiency that is an important issue for future developments . Polarization influences D-E graphs as mentioned earlier.

8) Tuning morphology to improve performance in capacitors: For this discussion, morphology of polymers refers to study of physical characteristics of polymers like presence of amorphous and crystalline regions, phases etc. Many commercially used polymers in capacitor applications have semi-crystalline structure. The morphology can be tuned to improve dielectric properties of the polymers. The control of morphology can help in many ways such as reduce defects, create changes that help withstand higher electric fields, and tune the interface to minimize energy loss in charge-discharge cycles. Morphological changes have been successfully used in capacitor films of PVDF and PP. In the case of PVDF, two approaches that gave excellent results are : (i) creating relaxor like nanostructure and then fabricating the film by Rill and Press method to form multi-layer structure that enhances polarization and relative dielectric strength [61]. (ii) adding comonomer during polymerization of vinylidene difluoride monomer to promote morphology dominated by gamma phase rather than alpha phase which gives high energy density of 20.8 J/cm^3 at 750 MV/m and dielectric strength of 716 MV/m[62] . In the case of PP, the dielectric constant can be improved using h-BN nanofiller as additive that provides nucleating sites and annealing at 120 ˚C/6 hr provided beneficent morphology with dielectric constant of 2.7 instead of 2.2 and dielectric strength of 671 MV/m at energy density of 11.35 J/cm^3 , much higher than the control sample [63].

2. Polymers and their composites for insulation

Polymer-based insulation materials can be broadly divided into three classes: (i) impregnating and casting resins (e.g., epoxy) used for making motors, transformers etc. (ii) insulators used in power transmission and (iii) overhead or underground or underwater cables used for transmission of medium and high voltage and their accessories. The general reviews give an idea of variety of polymers and their composites used for electrical insulation in low, medium and high voltage insulation applications [4,14,64,65]. The insulations are in general exposed to relatively higher temperatures and stress due to charge movement, as we move from low to medium to high voltage requirements. Table 3 provides some examples of insulating polymers used for different types of voltage ratings (low, medium and high) and capacitors, and their two important dielectric properties.

Table 3: Dielectric constant and Dielectric loss data for some polymers used in insulation and capacitors

Insulation/ capacitor	Voltage type (range)	Polymer	Dielectric constant [59]	Dielectric loss [59] (@ 1KHZ)	Typical application
Insulation	Low (< 1 KV)	PVC	3.4	0.018	Cable insulation
		BOPP*	2.2	0.0002	Cable insulation, *also in capacitors
	Medium (1-35 KV)	LDPE	2.3	0.0002-0.0007	Cable insulation
		PU	4.6	0.02	Cable insulation joints, outer jackets of E- Vehicles
		Silicone resin [66]	2.5-2.6	0.012 (@1MHz)	Impregnation of motor of Transformers
	High voltage (> 35 KV)	Epoxy	4.5	0.015	Impregnation of machines
		PEEK	4.0	0.009 (100 KHZ)	Cable, circuit board, electrical connectors
		PI*	3.5	0.04	Tapes for Motors, generators, *Also used in capacitors with better thermal stability
Capacitor		PET [62] (Fan, 2019)	3.3	<0.5	Energy storage
		PC [62]	2.8	<0.15	-do-
		PVDF [62]	12	<1.8	-do-
		Ultem [67]	3.1@25-200˚ C	0.2	-do-

Epoxy, unsaturated polyester, and Silicone resins are commonly used due to their excellent dielectric properties for protection of rotating machines used in generators and transformers [68-71]. Dry-type (solid state) transformers are popular in high voltage domain due to their compactness for power distribution, power electronic traction, pulse power supplies etc. These devices use epoxy casting compounds that contain fillers and additives suitable for excellent insulation at high frequencies, and additional requirements like thermal conductivity [72]. More stringent test to ascertain useful life of insulation in dry type transformers is proposed by Zhao et al., wherein applied test voltage is recommended to be 2.20 to 2.52 times their maximum operating voltages [73]. Silicone rubbers are popularly used in medium and high voltage insulators due to their weathering and moisture resistance [74]. Polymers like PTFE, fluorinated derivatives of polybezoxaole and polyarylene ethers, and porous poly arylene ether nitrile, polyimides have excellent thermal stability and low dielectric constant (< 2.5), which makes them suitable for components like antennas interlayer dielectrics and communication cables for high-speed communication networks [75]. Some results discussed below on new developments illustrate use of different approaches to improve insulation quality:

(i) Feng et al synthesized an epoxy resin wherein CH_3 groups in bisphenol A structure were replaced with two CF_3 groups to make fluorinated bisphenol epoxy resin (FEP). They proposed that compared to traditional bisphenol A Epoxy resin, a deeper trap level was introduced by the CF_3 group which helped the dielectric strength to improve after curing from 366.39 to 483.62 kV/mm, representing an increase of about 30%. They further stated that the significant improvement in the breakdown performance of FEP can be attributed to the trapping effect of these traps on charge migration [76].

(ii) Replacement of XLPE as cable insulating material is an active topic especially for higher power transmission lines. Despite crosslinking, XLPE cannot usually retain good insulation strength above 90 ˚C, its conventional maximum operating temperature. In the recent report of Zhang et al., a blend of PP with thermoplastic elastomer (SEBS) tested [77]. AC breakdown field strength of PP is 146.6 KV/mm, while that of XLPE is 88 KV/mm; the new blend reduces the AC breakdown strength of PP/SEBS to 137.3 kV/mm but is still much higher than XLPE and showed improved tensile strength as compared to PP, possibly because of phase separated morphology [77]. A ternary blend of iso tactic PP (iPP), ethylene-octene copolymer (EOC) and a poly propylene copolymer (PPC) containing ethylene propylene rubber (EPR) was tested in comparison with XLPE and found to possess better volume resistivity at ambient as well as at 110 ˚C, as compared to XLPE. Also, the dielectric strength of the blend was 182 KV/mm at 80 ˚ C, at which temperature XLPE is a poor insulation. Authors proposed that PP blend have the potential to replace existing XLPE as insulation materials for future HV power cables [78]. This needs to be substantiated by long-term ageing and performance testing.

(iii) Insulations inside the compact high-voltage power modules are facing hitherto unknown failure risks such as high temperature overheating, quicker breakdown or material cracking etc. Hence, Wang et al have proposed developing epoxy insulation with intrinsically high thermal conductivity and high Tg. Thus, a liquid crystalline epoxy resin based on biphenyl units was synthesized and cured with highly aromatic diamino diphenyl methane to give material with thermal conductivity of 0.53 W/(m. K) which is about 178% higher than conventional epoxy resin and dielectric strength of 57 KV/mm (16% higher than conventional epoxy resin) [79].

(iv) An enhanced performance of the phenyl silicone elastomer, as compared to conventional packaging materials for high power devices was confirmed by theoretical, experimental and simulation study. Thus, calculations of molecular orbital energy levels and electrostatic potential were conducted and corroborative evidence for theoretical results was collected using broadband dielectric spectroscopy. This confirmed that use of phenyl groups in polymer chain generated large number of deep electron traps.

Consequently, the breakdown strength and the inception voltage for electrical treeing for the newly developed phenyl silicone elastomer was found to increase by 24.5%, and 9.45%, respectively as compared to the control [80].
(v) Development of a stable insulation for high voltage direct current (HVDC) cable is a challenge, and lot of work is in progress to improve dielectric properties of XLPE. Ahmed et al proposed making a blend of LDPE with 2% polystyrene (PS) by injection molding followed by hot pressing the blend in the presence of peroxide to produce XLPE [81]. This alloy has some amount of linkages coming from styrene plus it also contains phase separated microgel PS particles. Further, the phase separation restricts easy movement of charges inside the matrix because of more interfaces and creation of additional trapping sites within XLPE. Consequently, breakdown strength improvements of 27.5% and 23.6% respectively, at 30 ˚C and 50 ˚C are achieved.
(vi) Zhang et al proposed that use of small amount of 5% of vinyl naphthalene monomer in a vinyl copolymer introduces trap energy levels. This controls movement of charges and effectively reduces leakage loss. Consequently, the probability of thermal and electrical breakdown is reduced and high discharge efficiency of 89% at 800 MV/m electric field was achieved [82]. Nazrin et al., have recently reviewed different approaches like use of different grafted groups for XLPE , additives like voltage stabilizer molecules or phenolic antioxidants and nanofillers. Further, different roles of the voltage stabilizer molecules for (a)improvement of breakdown voltage strength (b) reducing electrical tree growth (c) reducing space charge accumulation (d)reducing rate of thermal aging etc., were discussed in this review[83]. Use of voltage stabilizers as additives can be a good approach to improvise performance of presently used products.
(vii) Electron beam irradiation of epoxy surface can cause oxidation and introduce polar groups such as hydroxyl and ketone on the surface. Consequently, the surface deep trap density improves and therefore the DC flashover voltage improved from 35.26 to 38.9 KV [84].
(viii) Another interesting non-chemical method to improve dielectric properties of polymeric insulation is reported by Han et al. [85]. Thus, they prepared LDPE under the different applied AC-assisted electric fields of 0 to 2.0 kV/mm. Then, DC conductivity, space charge distribution, breakdown strength, surface potential decay, and morphology of these LDPE samples were characterized. The exposure to AC-assisted electric field not only reduces the DC conductivity and space charge accumulation but also increases the breakdown strength of LDPE [86]. The use of this new type of LDPE to make low voltage cable insulation or to make XLPE used in high voltage cables needs to be tested.
(ix) Silicone resins have been successfully used as insulation in 800 KV DC transmission lines. A review discussed various ageing tests conducted for this insulation and how to repair the ageing material [86].
(x) Carefully synthesized polyamide, epoxy and silicone hyperbranched polymers, mostly as additives in small amounts, have been useful to improve mechanical and electrical insulation properties [87, 88].
(xi) High voltage transmission cables and transformers are usually designed to have work-life of twenty years or more. Thermal ageing studies are helpful to understand which dielectric properties are sensitive to influence of exposure to higher temperature and what is the safe limit of temperature for ensuring longer life of insulations [89, 90].
Thus, as seen from above reports, modification of resin structure by chemical or irradiation induced changes, use of additives like voltage stabilizers or hyperbranched polymers and ageing studies are active areas in resins for insulation with better properties.

3. Developments in dielectric properties of polymeric film capacitors
Table 3 gives few examples of polymers used in capacitors; PP and PET are commonly used for general applications while PI and PPS are examples of polymers used for more specialized applications. A recent article on polymer containing capacitors gives useful information on many related points including classification of these capacitors in six types depending upon parameters like performance, electrode material, cost etc. [91]. The pressing demand for reducing size of equipment used in energy storage applications led the efforts to replace ceramic capacitors with much smaller and lightweight polymers and in more recent times with thin polymer film [7]. BOPP and PE are commonly used polymers for capacitor fabrication at moderate temperatures while poly ether imides are used for higher temperature exposure and high voltage capacitors. Specially designed polymeric film capacitors are useful for demanding applications in high-frequency and high-voltage devices. Efforts focused on making all-organic film capacitors as well as nanofiller containing polymer composites in the last few years have been reviewed [62]. In recent years, the polymer-based film capacitors are also finding use in electric vehicles [92]. Gnonhoue et al have reviewed the different technologies used for high voltage film capacitors [93]; they mentioned that for capacitors operating at high temperatures, PTFE, PET, PPS are used. Qiao et al have remarked that the polymeric capacitors need to have high thermal stability (high Tg), higher dielectric constant, high dielectric strength and broad bandgap to be useful in modern demanding applications [6]. The compact and non-toxic nature of polymers like PDMS (poly dimethyl siloxane) allows fabrication of highly sensitive capacitive sensors in wearable electronics that help to track physiological movements in patients by detecting minute changes in pressure by converting them into corresponding signals in capacitance change [94]. Using simulations and machine learning as screening tools, polyimides with high thermal stability and high energy density of about 4 J/cm^3 have been short-listed for detail study [95, 96]. Two important requirements of capacitors are ability to store a large amount of energy, often expressed as energy density and efficiency of charge-discharge process for several thousand cycles of operation at required temperature and frequency of applied voltage. Although IEC method 60384-13:2020 can give indirect idea of energy density of polymeric capacitors, there is no standard acceptable test method available for measuring energy density for dielectric capacitors at present[97]. A recent review combines reports related to laboratory experiments, artificial intelligence (AI) based sifting of data and possible molecular designs, and analysis of electrical properties of all organic dielectric polymers suitable for advanced capacitor applications [98]. Need for faster communication technology increases the demands for materials with extremely low dielectric constants to mitigate signal delay caused by the reduction in size of devices. Commercially available Polyethylene napthenate and poly phenylene sulfide are used for general applications while PTFE is used for aerospace and defense applications. Poly arylates derived from aromatic acyl chlorides are getting attention because of their low dielectric constant at very high frequencies with adequate thermal stability. Thus, capacitor films of polyarylates with dielectric constant values range from 1.21 to 2.07 at frequence of 10^7 Hz as well as the 10% weight loss temperatures (T_{d10}) in the range of 452°C and 469°C are reported by using mixtures of terephthaloyl chloride and *iso*-phthaloyl chloride [99].

Table 4: Reports on some very high Dielectric strength and energy density for polymers

Energy density J/cm^3	Dielectric strength	Polymer	Reference
24	> 1GV/m	Thermoplastic poly urethane (ArPTU)	[100]
37.7	748 MV/m	Ferroelectric polymer	[101]
8.2	865 KV/mm	PP copolymer with small amount of fluro methacrylate monomer	[102]
16.23	450MV/mm	Capacitor made with all-organic combination of acrylic and TPU polymers and no fillers	[103]

It appears from the recent literature that following approaches are useful to improve various dielectric properties of polymers for capacitor application : (i) new monomers and polymers therefrom (ii) use of polymer blends (iii) crosslinking using presence of suitable chemical groups or by UV irradiation (iv) surface modification (v) use of voltage stabilizer molecules as special additives to increase dielectric strength. Since the chemistries involved are different, dielectric properties over a wide range are available as seen from data in Table 4. More work can be expected in the future to make more structured efforts for scalable products. Since capacitors must survive several thousand cycles of charge-discharge of energy, particularly at higher temperatures in modern compact high-power equipment, thermal ageing study is very important for polymers used in these cases. Few more recent examples are discussed below:

(i) Based on theoretical evaluation of properties of a library of nearly 50,000 poly(sulfate) using a sophisticated computer program, Li et al narrowed the search to seven likely candidates having fluorene disulfate type structure. Further, they synthesized and characterized the monomers and their corresponding poly(sulfate) polymers to show that a 9,9-di(naphthalene)-fluorene repeat unit exhibits excellent thermal resilience and achieves ultrahigh discharged energy density with over 90% efficiency at 200 ˚C. Such highly efficient capacitor films at higher operating temperatures are necessary for future applications such as inverters in hybrid electric vehicles, underground oil and gas exploration and aircraft electrification [10].

(ii) Glassy PMMA polymer of molecular weight 257 kg/mol was used to make extremely thin film of 120 nm thickness. It showed energy density of 27.5 J/cm^3 at an electric field of 1438 V/ μm with efficiency above 80%, these values are much higher than those seen for any commercial capacitors [104]. Lot of work is desired to explore this interesting result.

(iii) Film capacitors required in modern high-power capacitors often operate at high temperatures (>120 ˚C). Extending use of BOPP for such demands requires additional cooling facility that is not feasible considering smaller size of devices. Wahner and Alba have reported an ethylene-propylene- norbornene copolymer film to replace BOPP for better thermal stability, high dielectric strength and lower dielectric loss but similar crystallization behavior and self-healing as in PP film capacitors, for high temperature use [105]. Other options like use of thermally stable polymers like polyamide or use of sandwich structure of high Tg polymer in between two ceramic fillers like alumina fail at higher operating temperatures. A new and very useful approach of using blend of thermally stable polymers is illustrated by two examples below: (a) A blend of poly ether imide (PEI) and polymer containing non bonded urea groups (poly arylene ether urea) that provide deep traps was tested by Ding et al [106]. The blend showed excellent high temperature performance: energy density of about 2.9 J/cm^3 and dielectric strength 400 MV/m at 150 ˚C, and ability to survive 20,000 charge-discharge cycles at 96% efficiency, which are very high values. (b) More recently, the blending approach was studied further by Yan et al [107]. They studied various blend compositions of PEI and poly urea and found that dielectric constant varies with blend composition and gave a high value of 5.8 at 50/50 ratio of composition. In addition, the dielectric strength increased simultaneously at this composition to reach 550 MV/m at 200 ˚C. Furthermore, 50/50 % blend gave very high energy density of 9 J/cm^3 at 150 ˚C, with a high charge-discharged energy efficiency of 93 %. The high dielectric constant was explained based on disruption of hydrogen bonds and increase in free volume. Further, the miscibility of polymers helped the strong electrostatic interactions between the molecular chains in the blended polymers which resulted in a tighter stacking of the polymer molecular chains. This gave significantly higher dielectric strength.

(iv) Hao et al have mentioned several examples where discharge efficiency of polymeric capacitors is around 70%. They proposed a novel approach of molecular design that requires synthesis of polymers comprising repeat units of rigid fused bicyclic structure and alkenes, separated by freely rotating single bonds [9]. Thus, a norbornene adduct monomer was derived from first reacting dicyclopentadiene and maleic anhydride and further reacting with amines having special pendant groups that have potential to work as deep traps for better insulation. The polymerization of this type of monomer gave polymeric insulations having wide bandgap (more than 4eV), high Tg in combination with high energy density and excellent charge-discharge efficiency (CDE). The best result was obtained for polymer made using amine of benzophenone core that showed CDE of 87% , energy densities of 6.38 J/cm^3 , breakdown strength of 660 MV/m, and high dielectric constant of 4 with Tg ~210 ˚C.

(v) The conventional all-aromatic polyimide, consisting of an alternating combination of aromatic dianhydride and diamine, offer high (>200 ˚C) but often suffer from small bandgaps that allows higher leakage current at higher temperatures and high electric fields due to highly conjugated molecular structure. This conjugation usually darkens the films due to formation of charge transfer complexes. The effect of conjugation can be hindered either by crosslinking or by introducing aliphatic rings that are spacers between aromatic rings. Thus, Wan et al., achieved CDE above 90% and energy density of 6.38 J/cm^3 and 3.04 J/cm^3 at 200 ˚C and 250 ˚C, respectively, for the crosslinked polyimide (CP) dielectric material [108]. The CP was made using diamine that has active benzyl structure in polymer made using 4,4′- (4,4′-isopropylidenediphenoxy) diphthalic anhydride. The benzyl group provided crosslinking active sites. Also, the dielectric strength of the CP was about 660 MV/m at 200 ˚C. Ding et al used saturated biphenyl spacer group with two anhydrides functional groups to avoid the detrimental effect of conjugation and recorded energy density of ~4.9 J/cm^3 with CDE > 95 % at 150 ˚ C with high Tg of 277 ˚C [109].

(vi) Crosslinking also helps to improve performance of PVDF at higher temperatures due to thermal stability introduced by crosslinking. UV irradiation is also reported for initiating crosslinking; it improves performance of PVDF capacitor film to provide energy density of 18.6 J/cm^3 and a CDE of 81% at 600 MV/m [110].

(vii) Ageing of capacitor films due to continuous exposure to high temperature needs to be understood accurately to ensure longer working life and such studies are important and necessary [111]. Thermal aging can also influence charge traps present in the polymers [112].

(viii) Liu et al have recorded breakdown strength of 499 MV/m at 150 ˚C in addition to high energy density of 6.29 J/cm^3 with 89% CDE at 150 ˚C for a capacitor film made with combination of three design factors. First, a series of thiourea- based polymers with tailored main-chain architectures are synthesized to optimize free volume and charge distribution in the polymer matrix. Second, Barium titanate nanofiller was added to modulate bandgap and achieve electrical rectification due to creation of deep traps in the interface region that effectively suppress electric field distortion. Thirdly, the mixture of polythiourea and poly ether imide with nanofiller in the middle, is believed to form a sandwich structure which homogenizes the electric field distribution and helps to improve dielectric breakdown strength. As a result, the polymer composites display markedly improved energy storage capabilities. [113].

4. Section on nanocomposites

a) Nanocomposites Insulation

Both micro and nano size fillers are used in polymer insulation composites. Specific fillers that do not affect insulation properties are required to make the composites. Common fillers used in electrical insulation include ceramic particles like aluminum hydroxide, boron nitride and silica. In addition, mineral-based fillers like glass fiber and mica are used; mica-based tapes are popularly used in fabrication of transformers and generators. In recent times, nanofillers have provided superior performance at lower concentrations like 5% or less as seen from some reports below.
(i) Ullah et al., have studied the aging mechanism of HTV silicone rubber loaded with mixture of nano or micro silica and alumina exposed to variety of stresses [114]. The composite containing 2% nano-silica showed the highest resistance in the multi-stress aging test.
(ii) Spacers provide mechanical support in Gas Insulated Switchgears (GIS), required in high voltage transmission and storage. Kim et al have developed a composite of epoxy containing a special nano filler derived from fusion of alumina and zinc oxide to replace commonly used epoxy spacers. Further, this composite showed good dielectric strength as well as stable tensile and flexural strength, even at high temperatures of 80 ˚C, making it a promising material for the application [115].
(iii) Li et al., discussed many options to improve breakdown strength of epoxy insulation such as use of micro and nanofillers, optimizing resin and hardener structure and modification in the curing process [116].
(iv) According to Rehman et. al., electrical insulation properties like resistance to PD for heat cured Silicone rubber improved in the presence of 5% nano TiO_2 filler by 24%, due to the interaction between doping levels and local charge diffusion dynamics which modifies the electric field distribution [117].
(v) Zhang et al tested different anhydride and diamine combinations to make polyimides(PI) from PMDA-ODA combination gave the highest dielectric strength. It was used to make nanocomposite with 3% silane treated mica. This nanocomposite gave dielectric strength of 442 KV/mm against the control PI with dielectric strength of 223 KV/mm [118].

b) Nanocomposites for capacitors

Apart from time consuming route of designing new molecules to improve dielectric properties for high temperature performance requirements, making composites by mixing nanofillers with specific advantages and commercially available polymers is an alternate popular route in recent years. Four types of fillers are commonly seen in the literature on polymer nanocomposites-based capacitors. These are (i) metallic fillers like aluminum, nickel (ii) ceramic fillers like barium titanate or modified titanium oxide (iii) carbon-based fillers like graphene and carbon black (iv) 2D fillers in sheet form like clays. One common problem with use of nanofillers is that use of more than certain amount of nanofiller leads to agglomeration and it can nullify the gain seen at lower concentrations [119]. Another disadvantage is that large contrast in dielectric constants between the nanoparticles and the polymers can enhance the local electric field, leading to a reduced breakdown strength for the nanocomposites [9]. More work is necessary to get solutions for these problems. Nevertheless, many interesting and useful results with use of nanofillers are seen, e.g., proper arrangement of nanofiller in the matrix improves dielectric properties and mixing nanofillers with high conductivity cerami fillers or using polymer coated nanofillers reduces disadvantages like agglomeration and dielectric loss etc. [120]. Some more recent reports are discussed below:
(i) The important requirements of good polymeric capacitors are high dielectric constant (DC) that ensures high energy density, high dielectric strength, and low dielectric loss. Two approaches to meet these requirements are as follows: (a) making use of high DC nanofillers: since polymers usually contribute to high dielectric strength but have relatively low DC than metal based nanofillers, efforts can be made to combine the two to get synergistic improvement. However, nanofillers are difficult to disperse and can lead to undesired effects due to agglomeration or formation of percolating conducting tracks. Using large amount of high DC nanofillers also has risk of local electric field distortion and high leakage current. Further, these effects can reduce dielectric strength significantly. To mitigate this problem, Li et have used mixture of high DC nanofiller Barium titanate (BT) and thermally conducting BN. They achieved high dielectric strength around 500 KV/mm (nearly 100% more) with two orders less leakage current than composite containing BT alone [121]. (b) use of machine learning platform to develop accurate simulation models considering the contribution of interface, for study of nanocomposites with better dielectric properties [122].
(ii) Interface in nanocomposites is recognized as a useful tool for modulation of better dielectric performance [123], but not much paid attention in theoretical modelling. An important reason for this is lack of accurate in-situ characterization of the interface under external physical stimuli, which makes it difficult to arrive at a direct relation between macroscopic properties and nanoscale interface characteristics [124]. In this report of Shen et al., interface has been considered as a variable in the simulation study. They used two characteristics of interface, namely, thickness and relative permittivity as variables for prediction of properties of nanocomposites. The properties of local electric field, effective permittivity and breakdown strength were targets of the outcome. The adjustments of variables showed a potential to get 83.6% increase in relative permittivity for PVDF-$BaTiO_3$ composite containing only 11 vol% nanofiller, and the energy density improved by 156%.
(iii) An interesting role of reduced graphene oxide nanofiller in promoting crystallization of β phase in PVDF that improves dielectric properties of the nanocomposites was reported [125]. This paper also discussed effects of nanofillers of different

dimensions on composite properties. Cheng et al have reviewed various nanocomposites using nanofillers of different types and dimensions for application as capacitors in demanding application [8].
(iv) Wu et al discussed several examples where nanofillers are used at low volume percentage get energy density values above 10 and corresponding dielectric strength > 400 V/micron) with low dielectric loss of less than 0.1 [126]. (iv) Dai et al have proposed a nanocomposite of commercially available polyimide and BNNS nanofiller at 0.1 volume% level to achieve excellent performance under working conditions of 200 MV/m and 150 ˚C, coupled with high energy density of 1.38 J/cm^3 and efficiency higher than 96% for 20000 cycles of operation for conditions used in running a hybrid electric vehicle. The use of nanofiller that was well dispersed in the matrix was found to help generate regions of high dielectric constant in interfaces that helped for this better performance. The use of nanofillers in general requires careful dispersion since agglomeration can lead to deterioration of properties [119].
(v) combination of epoxy, boron nitride thermally conducting filler and γ-glycidyl ether oxypropyl sesimoxane (G-POSS) provided thermally conducting composite. This material shows good thermal conductivity of about 0. 39 W/(K. m), low dielectric loss of about 0.01 and high thermal stability (thermal class index 190), due to synergy between additives and the resin [127].

5. Summary and future scope

We have discussed the recent developments in dielectric properties of polymers and their composites for electrical insulation and capacitor applications. The topic can be visualized as a composite of two different layers. The top layer represents dielectric properties like dielectric strength, energy density suitable for given range of operational variables like voltage, frequency, temperature and climate conditions, and mechanical properties. The bottom layer is the mixture of several aspects like (i) structure-dielectric property relations between polymer, fillers and additives (ii) effect of features like interface and traps (iii) various interactions between raw materials like fillers and features of polymers like band gap, between two polymer chains in a blend; all these are often linked in subtle manner. Blending carefully selected polymers improves dielectric properties significantly, as shown in this paper. Size reduction coupled with use of higher voltage at higher frequencies will be the norm for electrical devices in near future. Very interesting results [9,10] discussed above have potential to address these needs. The reports in the last few years, mentioned in this paper, have shown the possibility of using "green" techniques like UV or electron beam irradiation, use of external magnetic or electric field to improve dielectric properties of commercially available polymers.
The development of new materials offers scope to improve understanding of subtle relations between polymer architecture and dielectric properties. Use of new approaches like machine learning using large data base and combination of outcomes of such results with simulation are showing their value in new developments and more such examples can be expected in near future. Use of copolymers instead of BOPP to use in high temperature capacitors or blends of PP to match insulation performance of XLPE are important developments because unlike XLPE, PP and BOPP are reprocessable polymers. Further, they can have potential for recycling and reducing generation of polymeric waste that is threatening environment. Development of new thermoplastic blends, use of biobased monomers to make epoxy and other thermosetting polymers and use of special additive molecules like voltage stabilizers are other examples of research opportunities that need more attention.

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