Innovative: International Multi-disciplinary
Journal of Applied Technology
(ISSN 2995-486X) VOLUME 03 ISSUE 9, 2025

A REVIEW OF THE ELECTRICAL PROPERTIES OF POLYMER MATERIALS

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Abstract:

In recent decades, the application of polymers and polymer-based materials has expanded significantly, encompassing numerous industrial and technological fields. Among these, electrical applications represent a particularly important domain. Polymers are utilized not only as insulators, protective coatings, and elastic substrate, but also as electrically conductive components in devices such as batteries, capacitors, sensors, and photovoltaic systems. They are appreciated for their low weight, cost efficiency, ease of fabrication, and the ability to tailor their properties to meet specific performance requirements. Nevertheless, a notable drawback—especially for petroleum-derived plastics—is their adverse environmental impact, primarily due to the complexity and expense of recycling processes. One potential solution is to replace conventional plastics with biodegradable alternatives, either obtained from natural sources (e.g., proteins, polysaccharides) or synthesized from bio-based monomers (e.g., poly (lactic acid)), as well as biodegradable polyesters derived from petroleum feedstocks (e.g., poly (butylene adipate-co-terephthalate)). This paper examines the essential electrical characteristics of polymeric materials, the mechanisms leading to electrical breakdown, preventive approaches, and the selection of polymers suitable for high-voltage applications.

Keywords: Electrical Properties, Electrical Breakdown, Thermoplastic, Thermoset, Elastomer, High-Voltage Applications

Introduction

In recent years, the swift progress of electrical engineering technologies has significantly broadened the integration of electronic devices into numerous aspects of everyday life [1]. This expansion, however, has been accompanied by a marked rise in electronic waste, raising serious environmental toxicity issues [2]. In response, the past few decades have seen the emergence of polymer electronics as a promising alternative to conventional device materials, employing conductive and semiconductive polymers that are lighter in weight, more cost-effective, and easier to fabricate [3]. Although such polymers are generally considered non-toxic, their degradation in natural environments is exceedingly slow, motivating ongoing research toward the creation of sustainable electronic devices from biodegradable polymeric materials [2,4]. This sustainability-oriented approach is also increasingly reflected in the development of energy storage systems [5,6]. For use in electrotechnical applications, materials must not only withstand electrical stress, temperature variations, and diverse mechanical loads, but also comply with environmental sustainability requirements [7,8].

Polymeric materials are mainly categorised as electrical insulators. Typical examples of such insulating polymers include PVC, PP, PE, PMMA, PS, and PC. When an insulating polymer is subjected to an external electric field, the enduring and/or induced dipole moments within the material tend to align, producing a net dipole moment per unit volume, a phenomenon referred to as polarization. As a result, the magnitude of the external field is reduced by a factor known as the relative permittivity (dielectric constant), defined by ε_r=ε⁄ε_(o) where ε is the dielectric permittivity of the material, and ε_o=8,85.10-12 F/m F/m represents the permittivity of free space.

Polymer chemistry

A polymer is a large macromolecule consisting of hundreds to thousands of atoms. The term derives from Greek, where poly- signifies “many” and -mer denotes “part” or “segment.” Owing to their low electrical conductivity, minimal dielectric loss, high breakdown strength, and other advantageous electrical properties, polymers play a vital role in modern electronic and electrical technologies. The study of dielectric behavior in materials subjected to an electric field has become a prominent area of research in physics, chemistry, biology, and materials science [9]. Polymeric substances may possess either low or high dielectric constants, which are directly determined by their permittivity. This constant is expressed as the relation between the dielectric’s permittivity and the permittivity of a vacuum. Generally, a higher dielectric constant indicates a greater degree of polarization in the field [9] and polyvinyl fluoride have been adopted as di-electric resources in capacitors. The inclusion of higher polarizes collections—such as aromatic-rings, bromine, or iodine cans substantially intensification a material’s dielectric constant. At present, both higher di-electric (Table 1) and lower di-electric (Table 2) polymers are applied in capacitor technologies.

Table 1. High dielectric materials for capacitors [10].

Materials	Dielectric permittivity
$La_{1.8}Sr_{0.2}NiO_4$	100000
$CaCu_3Ti_4O_{12}$	60000
α-LaAlO3	30
Y_2O_3	15
La_2O_3	30
$HfSiO_4$	11
HfO_2	25
ZrO_2	25
$SrTiO_3$	2000
TiO_2	80
Ta_2O_5	22
Al_2O_3	9
SiO_2	3.9
PLZT (7/60/40)	2590
$PbNb_2O_6$	225
PMN-PT (65/35)	3640
$BaTiO_3$	1700

Table 2. Low di-electric resources for capacitor [10].

Materials	Dielectric permittivity
Poly (ether ketone ketone)	3.5
Poly(vinylidene fluoride-co-hexafluoropropylene)	12
Perfluorocyclobutane polyether	2.4
Silsesquioxane	2.8–3.0
Poly(phenyl quinoxaline)	2.8
Polyquinoline	2.8
Poly(norborene)	2.4
Polystyrene	2.6
Poly(tetrafluoroethylene)	1.9
Polynaphthalene	2.2
Fluorinated polyimide	2.6–2.8

Metallic materials, including iron and copper, as well as nonmetallic in-organic compounds such as $CaCO3$ and $MgSO4$, are extensively existing but are generally characterized by high density, which can limit their practicality in certain applications. By contrast, polymeric materials are primarily collected of light essentials such as carbon, hydrogen, oxygen, and nitrogen, resulting in a significantly lower overall mass. This inherent lightness is a key factor behind the extensive use of polymers in everyday life. Additionally, polymers are available in a broad spectrum of types sourced from various origins and could be synthetic at relatively low cost, makes its highly attractive for integration into diverse industrial processes [11].

Electrical Properties

Electrical properties of polymeric materials can be categorized into two main groups. The first group, typically assessed under low electric field conditions, includes the di-electric constant, dissipation factor, static electrification, and electrical conductivity. The second group comprises properties that are significant under very high electric field strengths, such as electrical discharge, dielectric breakdown, and arc resistance, representing the ultimate electrical characteristics of polymers, while the properties of the first primarily dictated by the chemical structure of the polymer, those in the second substantially influenced by further factors associated with the measurement techniques. Notably, the dielectric constant is the only property within these groups that can be reasonably estimated using additive quantities [12].

Di-electric Polarization

Di-electric constant (permittivity, electric inductive capacity)

The relative dielectric constant (ε) of an insulating material is defined as the ratio between the capacitance of a parallel-plate capacitor containing the dielectric and the capacitance of the same capacitor in the absence of the dielectric. This difference is attributed to the polarization of the material and is expressed as a dimensionless quantity.

$$\varepsilon = n^2 \qquad 1$$

In this context, ε denotes the di-electric constant at the frequency corresponding to the refractive index n. For a precise comparison, both parameters should ideally be measured at the same frequency. In practice, however, ε is usually determined at relatively low frequencies (10-2-10-9 Hz), whereas n is measured in the visible light range (approximately $5–7\times10^{14}$ Hz, typically at the sodium D line). Nonetheless, a direct comparison between ε and nD can yield valuable information. A considerable discrepancy between these values may suggest semiconductive properties, although it is more often caused by the presence of permanent dipoles within the dielectric [12].

Relationship between dielectric constant and polarization

When a volume element composed of molecules lacking permanent dipole moments is subjected to an electric field, the distribution of charges within the molecules is altered. This leads to the creation of induced dipoles, the magnitude of which is directly proportional to the strength of the applied electric field at the molecular scale.

$$P = N_O \alpha E_L \qquad 2$$

where P = polarization (C/m^^{2}); N_O = total of molecules per unit volume (m^$^{-3}$); α = molecular polarisability (J^$^{-1}$ C^^{2} m^^{2}); E_L= local electric field (V/m = J/C/m). The relationship between the polarization and the applied electric field is

$$P = \varepsilon_O E(\varepsilon - 1) \quad \text{or} \quad \varepsilon = \frac{\varepsilon_O E + P}{\varepsilon_O E} = 1 + \frac{P}{\varepsilon_O E} \qquad 3$$

where ε_O is the permittivity of vacuum = 8.854188 (10$^{\wedge -12}$J^$^{-1}$ C$^{\wedge 2}$/m). The local field $E_L$is

$$E_L = E + \frac{P}{3\varepsilon_O} = \frac{1}{3}(\varepsilon + 2)E \qquad 4$$

Upon substitution Eqs. (1.2) and (1.3) in Eq. (1.1) we finally find

$$\frac{\varepsilon - 1}{\varepsilon + 2} = \frac{N_O \alpha}{3\varepsilon_O} \qquad 5$$

The relationship linking the dielectric constant to molecular polarization is expressed through the Clausius–Mossotti equation.

Molar polarization

The molar polarization of a dielectric, measured in cubic meters per mole (m^3/mol), is defined as follows:

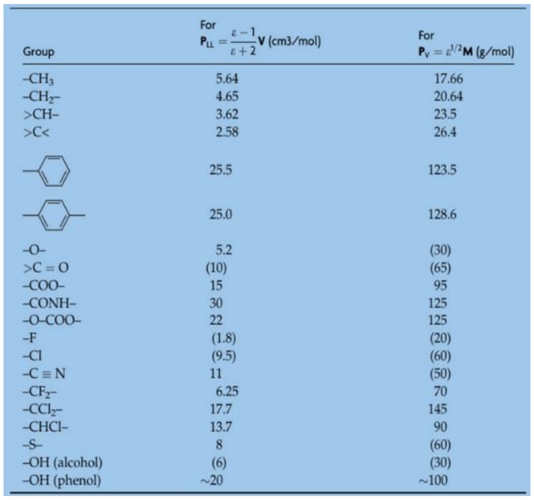
$$P_{LL} = \frac{\varepsilon - 1}{\varepsilon + 2} V \qquad 6$$

Or

$$P_V = \varepsilon^{1/2} M \qquad 7$$

The molar polarization contributions of various molecular groups in isotropic polymers are presented in Table 3. Using Eqs. (6) and (7), the corresponding dielectric properties can be determined.

Table 3. Contributions of molecular groups to the molar dielectric polarization (P) in isotropic polymers (cm³/mol).



Group	For $P_{LL} = \frac{\varepsilon - 1}{\varepsilon + 2} V$ (cm3/mol)	For $P_V = \varepsilon^{1/2} M$ (g/mol)
$-CH_3$	5.64	17.66
$-CH_2-$	4.65	20.64
>CH–	3.62	23.5
>C<	2.58	26.4
–⬡	25.5	123.5
–⬡–	25.0	128.6
–O–	5.2	(30)
>C = O	(10)	(65)
–COO–	15	95
–CONH–	30	125
–O–COO–	22	125
–F	(1.8)	(20)
–Cl	(9.5)	(60)
–C ≡ N	11	(50)
$-CF_2-$	6.25	70
$-CCl_2-$	17.7	145
–CHCl–	13.7	90
–S–	8	(60)
–OH (alcohol)	(6)	(30)
–OH (phenol)	~20	~100

Constant ε if the structur al unit is known.

The Dielectric Constant and the Refractive Index

In nonpolar material, the molar Clausius–Mossotti relation defines the connection between the molar polarization (P_LL), the dielectric constant (ε), and the molecular polarizability (α), and can be expressed as follows:

$$P_{LL} = \frac{\varepsilon-1}{\varepsilon+2}\frac{M}{\rho} = \frac{N_A\alpha}{3\varepsilon_o} \qquad 8$$

Here, μ= denotes the permanent dipole moment of the molecule, expressed either in coulomb-meters Cm or, more commonly, in debye units (D), where D.(1 D=3.33564 ×10^{-30}C m).

Dielectric relaxation or Debye relaxation

As discussed above, the relationship between polarization, the applied electric field, and the dielectric constant can be expressed as follows:

$$P = \varepsilon_o E(\varepsilon - 1) \quad \text{or} \quad \varepsilon = 1 + P/(\varepsilon_o E) \qquad 10$$

Polarization, similar to molecular polarizability, originates from two mechanisms: deformational polarization P_d and orientation polarization P_s . Consequently, the total polarization is expressed as P =P_d+P_s. Due to the inertia of atomic groups within the dielectric, a delay exists between changes in the applied electric field and the resulting polarization. Deformational polarization, however, occurs almost instantaneously, on a timescale of about10^{-14}, upon using of the electric field. Two controlling values of the dielectric constant are defined: ε: ε_∞ at short times or high frequencies, and ε_s at long times or low frequencies. For deformational polarization, this leads to the following expression:

$$P_d = \varepsilon_o(\varepsilon_\infty - 1)\mathrm{E} \qquad 11$$

While for the orientation deformation after application of the constant electric field E

$$\frac{dP_S}{dt} = \frac{\varepsilon_o(\varepsilon_S-\varepsilon_\infty)\mathrm{E}-P_S}{\tau} \qquad 12$$

so that the time dependent dielectric constant reads

$$\varepsilon(t) = \varepsilon_\infty + (\varepsilon_s - \varepsilon_\infty)(1 - e^{-t/\tau}) \qquad 13$$

Thermally Stimulated Discharge (TSD)

Polymeric materials display a notable relaxation phenomenon when exposed to combined temperature and electric field treatments. As previously discussed, the polarization of a polymer increases from the initial, instantaneous polarization to a relaxed polarization upon application of an electric field. When the electric field is detached, the polarization gradually diminishes over time. On the other hand, when the polarization occurs at a temperature above the glass transition temperatureTg, and the material is subsequently cooled well below Tg, depolarization becomes inhibited due to immobilization of the polymer chains. This process can result in the formation of an electret, which is the dielectric analogue of a permanent electromagnet. An electret is a dielectric material that maintains quasi-permanent electric charge or dipole polarization, with opposite charges on its surfaces, generating both internal and external electric fields. The term "electret" was coined by Heaviside in 1885, combining "electric" and "magnet." Materials with electret properties have been studied since the early eighteenth century, beginning with the invention of the electrophorus by Wilcke in 1764, later refined by Volta in 1775. Electrets can produce strong electric fields, approximately 3000 kV/m, and have been applied in various technologies. Their commercial and technical applications include microphones, photocopy machines, electrostatic dust collection, and ionization chambers for detecting radiation or radon [12].

Relations Between Dielectric Constant and Optical Quantities

The complex dielectric constant is intrinsically linked to the optical properties of a material, specifically the refractive index (n) and the extinction coefficient (k). These relationships can be expressed mathematically as follows:

$$\varepsilon^* = (n^*)^2$$

$$\varepsilon^* = \varepsilon' - i\varepsilon'' \ : \ n^* = n' - in'' = n - ik$$

$$\varepsilon' = n^2 - k^2$$

$$\varepsilon'' = 2nk$$

$$\frac{\varepsilon''}{\varepsilon'} = \tan\delta = \frac{2kn}{n^2 - k^2}$$

Correlation between dielectric constant and solubility parameter

Given that cohesive energy is largely governed by electrostatic forces associated with molecular polarizability and dipole moment, a theoretical relationship between the dielectric constant and the solubility parameter is anticipated. Empirical studies have demonstrated that, in the case of polymers, this correlation manifests in an unexpectedly simple form, viz. [12]:

$$\delta \approx 7.0\varepsilon$$

Conductivity

Electric conductivity, σ(in S/cm or in $\Omega^{-1}\ cm^{-1}$), of materials in general extends over a wide range, from 10^{-20} to 10^{6} S/cm (see Fig.1). This range is subdivided into conductors (σ =10^4–10^6), semi-conductors (σ =10^{-4}–10^2) and insulators (σ =10^{-20}–10^{-6}).

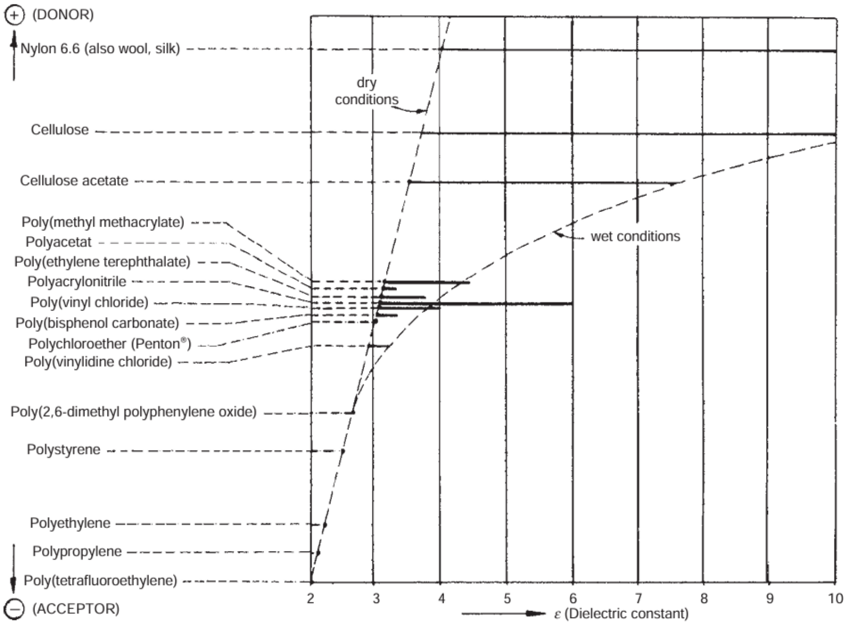


Figure 1. Triboelectric series of polymers.

Table 4. Work function,ϕ,of polymers^{s}.

Polymer	**ϕ polymer^{b}(ev)**
Poly(vinylacetate)	4.38
Poly(ethyleneoxide)	3.95
Nylon6.6	4.30
2-vinylpyridine/styrenecopolymer	4.27
Poly(vinylbutyral)	4.30
Poly(methylmethacrylate)	4.68
Ethylene/vinylacetate copolymer	4.79
Polycarbonate (=Lexan^®)	4.80
Polyethylene	4.90
Polystyrene	4.90
Epoxy resin (Hydrin^®)	4.95
PVC	5.13
Chlorinated-polypropylene(CPP)	5.14
Poly(trifluorochloroethylene)	5.3
Poly(tetrafluoroethylene)(=Teflon^® rod)	5.75

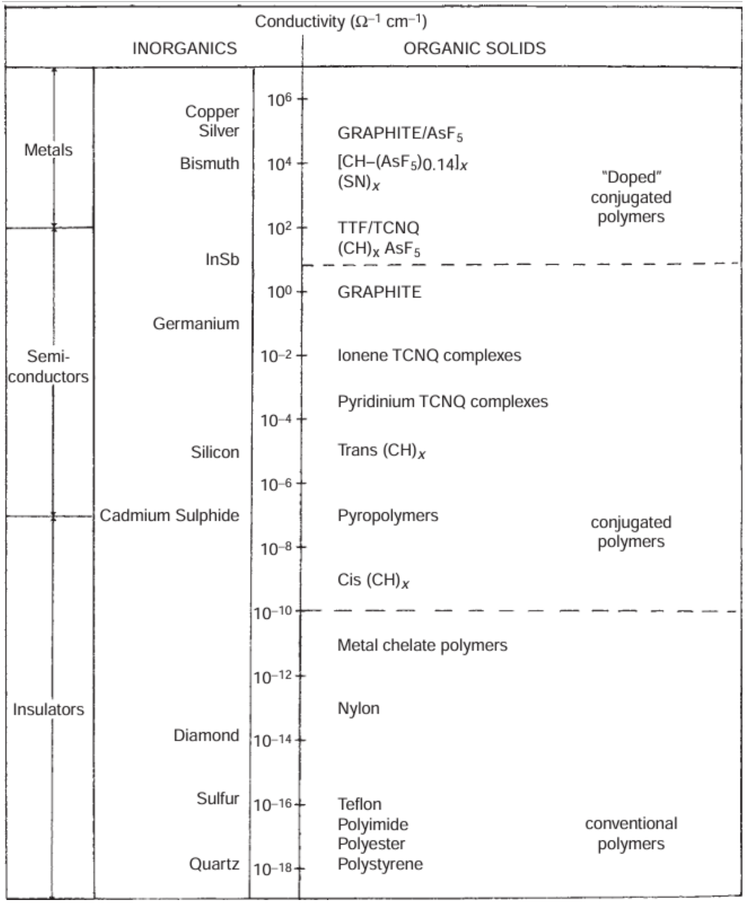


Figure 2. Electrical conductivity of materials.

Ultimate Electrical Properties

Dielectric strength

As soon as an increasing voltage is applied across an insulating material, a critical point is eventually reached where the dielectric undergoes physical failure, leading to a sharp decline in its resistance. This critical threshold is defined as the dielectric strength. By plotting time-to-failure against applied voltage, two distinct modes of failure are typically observed. The first, short-term failure arises from the inability of conduction electrons to dissipate the energy absorbed from the electric field efficiently. The second, long-term failure is predominantly associated with degradation mechanisms such as corona discharge.

Dielectric strength is significantly influenced by the physical form or morphology of the material, sometimes to a greater extent than variations in its molecular configuration. For pure polymers, the average dielectric strength is around 200 kV/cm. In contrast, chlorinated polymers can exhibit values as high as 500 kV/cm, while those containing aromatic rings often demonstrate lower strengths, approximately 160 kV/cm.

There exists a strong parallel between mechanical and dielectric strength, as both are linked through mechanisms of physical degradation. Electrical breakdown, like mechanical failure, involves structural damage, and both properties show marked decreases within similar temperature ranges, reflecting a shared sensitivity to thermal effects.

Arc resistance

Exposure to electrical discharges can result in surface carbonization of certain polymers, which may subsequently become conductive. This behavior is evaluated through the property known as arc resistance, which is particularly significant in applications requiring reliable electrical insulation, such as in ignition systems of internal combustion engines. Arc resistance is expressed in seconds and varies notably across different polymer types—ranging for approximately 400 seconds for poly(chlorotrifluoroethylene) to roughly 50 seconds for poly(vinylidene fluoride). Despite extensive analysis, no consistent or straight relation between arc resistance values and the polymers' chemical structures has been clearly established. [12].

How electrical breakdown happens in polymeric materials

The electrical breakdown of polymer-based insulating materials is typically attributed to various factors, including electrical stress, thermal effects, chemical degradation, mechanical forces, and moisture exposure. These influences contribute to the aging of the insulation, ultimately compromising its integrity and leading to electrical failure.

A. Non-uniform electric field degree

Typically, solid dielectrics that are uniform and densely structured exhibit breakdown strengths in the range of 1 to 10 MV/cm. This characteristic is predominantly determined by the intrinsic structural properties of the material, with limited influence from external factors. In contrast, for dielectric materials exhibiting inhomogeneity, an increase in insulation thickness generally leads to a decrease in breakdown strength. However, when the insulation layer becomes extremely thin—around 3 micrometers—the breakdown voltage tends to increase once again. Furthermore, localized intensification of the electric field may result in partial discharges, which, if sustained over time, can initiate chemical degradation processes and ultimately lead to dielectric failure.

B. Function time and types of voltage

Solid dielectric breakdown can occur in three primary forms: electrical breakdown, thermal breakdown, and electrochemical breakdown. All of these modes are influenced by the time-dependent behavior of the applied voltage. In the presence of an electric field, the breakdown voltage under a lightning impulse is generally higher than that under power frequency conditions. As the frequency of the alternating current increases, both partial discharge activity and dielectric losses tend to intensify, thereby elevating the risk of thermal and chemical degradation within the insulating material.

C. Temperature

At relatively low temperatures and within the range of electrical breakdown, the breakdown strength of insulating materials is generally independent of temperature. However, when the temperature rises significantly, thermal breakdown may occur due to the accumulation of heat and insufficient heat dissipation. Under such high-temperature conditions, the breakdown strength decreases considerably.

D. Dielectric performance and structure

Solid dielectric materials are often characterized by heterogeneity and high density; however, the presence of air voids within these materials can cause localized distortions in the electric field, which may lead to structural damage. Additionally, an increase in material thickness tends to produce non-uniform electric field distributions and hampers effective heat dissipation, thereby decreasing the dielectric breakdown strength. Thanks to their inherent thermal conductivity, solid dielectrics typically experience minimal dielectric losses, which contributes to an improved dielectric strength.

E. Mechanical load

The presence of cracks within a material subjected to mechanical stress leads to a reduction in its breakdown voltage.

F. Humidity

The breakdown voltage of solid dielectric insulations decreases when they are exposed to moisture.

How to avoid Electrical breakdown

Considering the factors that influence electrical breakdown in solid dielectric materials, several preventative measures can be adopted to reduce its occurrence [13,14]:

a. Achieving a more uniform electric field: Non-uniformities in the electric field often lead to partial discharges, which are a primary cause of electrical breakdown.

b. Lowering the frequency of alternating current: Reducing the AC frequency in polymeric insulations can effectively decrease the probability of breakdown.

c. Controlling temperature levels: At low temperatures, the effect of temperature on breakdown strength is minimal; however, elevated temperatures can significantly increase the risk of dielectric failure.

d. Avoiding excessive mechanical stress: Ensuring that mechanical loads remain within safe limits is important, as excessive stress can diminish the breakdown voltage of the material.

e. Minimizing exposure to moisture: High humidity environments should be avoided because moisture absorption by the insulation material can lead to a reduction in breakdown voltage.

Polymers used in high-voltage applications

Polymeric materials could be classified into natural and synthetic categories, depending on their origin and method of production. Natural polymers include substances such cellulose, and rubber. In contrast, synthetic polymers are typically produced through controlled chemical reactions in laboratories; a notable example is phenol-formaldehyde resin, normally well-known as Bakelite. In various electrical engineering applications, basic polymers combined with specific additives are widely utilized in components such as power cables, transformers, insulators, and rotating electrical machines, [15 & 16]. Generally, polymers employed in high-voltage applications can be categorized into three main groups based on their properties, including thermal performance, physical and chemical structure, as well as mechanical and electrical behavior, (see Table 5) [17 & 18].

Table 5. Types of polymeric insulation.

Type	Material	Application
Thermoplastics	Polyethylene (PE) Polyvinylchloride (PVC), polypropylene (PP), polyamide (PA)	Cables Transformers
Thermosets	Epoxy impregnant: Epoxy resins Silicon-resin Phenol-resin Polyester-resin	Rotating machines

Elastomers	Ethylene propylene diene monomer (EPDM)	
	Ethylene propylene rubber (EPR)	Shed materials
	Silicone	Polymer insulators

1. Thermoplastic polymers: These materials are characterized as plastics that soften and become flexible upon heating and subsequently harden again upon cooling, [14]. These materials can undergo repeated heating and cooling cycles within specific temperature ranges without any significant alteration to their properties and without requiring prior chemical treatment, [19]. Among synthetic thermoplastic polymers, polyethylene (PE), polyvinyl chloride (PVC), polypropylene (PP), and polyamide (PA) are predominantly employed as insulation materials in electrical machinery and equipment. These polymers can also be categorized into two main groups—amorphous and crystalline—based on their transition temperature behaviors, [20].

Polyethylene is one of the most prevalent commodity polymers widely utilized in applications such as household products, packaging, electrical insulation, medical devices, automotive components, and containers. The polymerization of ethylene monomers yields either linear or branched polyethylene, which predominantly exhibits thermoplastic behavior. Conservative PE can be chemically or physically cross-linked to produce cross-linked polyethylene (XLPE or XPE), a thermosetting polymer with enhanced properties. XLPE consists of polyethylene chains linked into a three-dimensional network, leading to increased density, greater chemical resistance, and decreased polymer flow.

Cross-linking is commonly performed via chemical agents like peroxides or silanes, or through radiation methods such as electron beam irradiation. The radiation technique offers the advantage of modifying the polymer without the addition of extra chemicals, preserving the original polymer composition, [21].

2. Thermoset polymers: These materials undergo curing through heat or chemical reactions, resulting in a network structure that renders them infusible and insoluble. This transformation process is commonly referred to as the polymer setting, [22].

A key feature of these materials is their permanent and irreversible polymerization, which arises from their cross-linked molecular architecture. Their formation involves two distinct polymerization stages: initially, linear polymer chains are synthesized, followed by the development of a final cross-linked network structure, [19-21]. The thermal, mechanical, and electrical properties of thermosetting polymers can vary widely depending on their specific applications. Once cross-linking is complete, these materials do not soften when reheated; rather, they demonstrate superior thermal stability compared to thermoplastics. Common examples of cross-linked polymer resins include polyester resin, phenolic resin, silicone resin, and epoxy resin, which are extensively utilized in the insulation of rotating electrical machines, [14].

3. Elastomer polymers: Elastomers are elastic materials characterized by possessing a low Young's modulus and a high failure strain. Key elastomers frequently utilizing in electrical insulation include silicone, ethylene propylene rubber (EPR), and ethylene propylene diene monomer (EPDM). These materials form essential components of polymer insulators. Moreover, thermoplastic, thermoset, and elastomeric polymers all undergo various aging mechanisms when utilized as insulation in electrical systems subjected to electrical fields, [15-18].

Conclusion

In conclusion, polymers play a crucial role in various electrical applications, providing essential characteristics such as insulation, dielectric strength, and electrical conductivity. These materials are invaluable in devices such as batteries, capacitors, sensors, and photovoltaic systems due to their low cost, light weight, and adaptability to different performance requirements. Despite their advantages, the environmental impact of petroleum-based polymers, particularly in terms of slow degradation, remains a significant challenge. Efforts to replace conventional plastics with biodegradable alternatives, derived from natural sources or bio-based monomers, are critical for the sustainable development of polymer-based electrical technologies. The study highlights the importance of understanding the electrical properties of polymers, such as their dielectric constant, breakdown strength, and arc resistance, which influence their suitability for high-voltage applications. Further research and innovations in polymer chemistry and material engineering are necessary to develop sustainable, efficient, and environmentally friendly materials for the future of electrical technologies.

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