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Chapter 2

A Review of Polypropylene and Polypropylene/Inorganic Nanocomposites for HVDC Cable Insulation

Boxue Du, Zhaohao Hou and Jin Li

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Abstract

Due to its excellent electrical and thermal performance, as well as satisfying the needs for developing the environmentally friendly and recyclable cable insulation material, polypropylene has caused widespread concern. Nanodoping can effectively improve the electrical, thermal and mechanical properties of polypropylene nanocomposites, which provides a new method to solve the problems in its application in HVDC cable insulation. This chapter introduces research achievements on polypropylene and polypropylene/inorganic nanocomposites, which states the effects of nanodoping on the electrical properties, such as space charge behaviors, electrical tree aging, breakdown strength, etc. thermal conductivity and mechanical properties of the polypropylene and its multi-blends. The aging mechanism under different conditions is also discussed. The analysis shows that the surface treatment of nanoparticles can reduce the aggregation of nanoparticles and strengthen the interface effect, thus improving the comprehensive properties of polypropylene nanocomposites. This chapter also summarized the feasibility and future development of the polypropylene and its nanocomposites application in the insulation of HVDC cables.

Keywords: polypropylene, nanocomposites, HVDC, cable insulation

1. Introduction

With the constant construction and commissioning of HVDC transmission projects worldwide, the problems exposed by the production and operation of high-voltage DC cables using XLPE as insulating materials are also increasing. Crosslinking agents used in the production of XLPE cables and by-products from the cross-linking process may be introduced into the insulation layer, making the space charge accumulation under the DC electric field more serious, thereby accelerating the insulation aging. In addition, the cross-linking process used in

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the manufacture of XLPE cables is inherently inefficient and inefficient. Moreover, after the XLPE cable has reached the end of its useful life, it is very difficult to recycle and reuse the insulating waste. Incineration processing not only pollutes the environment, but also wastes resources [1].

The research of domestic and foreign researchers on the large-capacity environment-friendly DC cable insulation material mainly focuses on polyethylene (PE) and polypropylene (PP)-based materials. Compared with PE, PP has a relatively high melting point, which can meet the demand of cables operating at higher temperatures, and has higher breakdown strength and volume resistivity, which is of great significance for increasing the operating voltage level of the cable and the line ampacity. However, polypropylene materials have strong brittleness and rigidity, poor resistance to low temperature impact, and low thermal conductivity. The operating conditions of high-voltage DC cables are complex, and the insulation medium is affected by the strong electric field with constant polarity, the temperature field generated by conductor heating, and the mechanical stress generated externally or internally in the medium. Therefore, the research on polypropylene-based environment-friendly insulating materials needs to be conducted to meet electrical, thermal and mechanical performance requirements [2].

In recent years, it has been found that nanoparticles have excellent performance in improving the properties of polymer materials because of their quantum size effect and large specific surface area [3]. Since 1994, when Lewis proposed the concept of nanodielectrics [4], scholars from various countries have extensively studied the improvement of the properties of polymer insulating materials after adding nanoparticles and their improvement mechanisms. The thermal performance, as well as the mechanical properties such as tensile strength and elongation at break, are not exactly the same. Most scholars believe that the nanoscale transition region between the polymer and the nanofiller, i.e. the interface, is a key factor affecting the performance of the nanocomposite [5–7]. The characteristics of the polymer matrix and the characteristics of the nanofiller determine the interface structure and properties of the composite material. Although many scholars have proposed different models to explain this, there is still no conclusion.

This chapter summarizes the research results at home and abroad, introduces the feasibility of polypropylene and its application in high-voltage DC cables, and discusses the role and mechanism of nanofillers in improving the electrical, thermal and mechanical properties of polypropylene monomers and multi-component blends. The effect of aging conditions on the properties of polypropylene nanocomposites was summarized, and the research on polypropylene-based nanocomposites for high voltage DC cables was summarized and forecasted.

2. Polypropylene and its feasibility study for insulation materials of high-voltage DC cables

2.1. Physical and chemical properties of polypropylene materials

Polypropylene is a thermoplastic resin obtained by polymerization of propylene as a monomer, which has a regular structure, high crystallinity, good corrosion resistance, and excellent

heat resistance. Polypropylene can be divided into isotactic polypropylene (iPP), syndiotactic polypropylene (sPP) and atactic polypropylene (aPP) according to its methyl group position. The molecular structure of the three polypropylenes is shown in **Figure 1**.

The melting point of polypropylene can reach more than 150°C (different melting point of different brands), about 40–50% higher than that of polyethylene, and the long-term working temperature can reach 90°C. Polypropylene is a non-polar material with high breakdown strength (mostly around 300 kV/mm), high bulk resistivity (mostly around 10^{16} Ω m) and insignificant change with temperature, can be in the same insulation. Polypropylene has less space charge accumulation and the charge injection has a higher threshold electric field. Polypropylene hardly absorbs water, so its insulation properties are less affected by the ambient humidity.

In addition, polypropylene materials have high mechanical strength without cross-linking treatment, and are typical thermoplastic materials that can be recycled and used in line with the development needs of environmentally friendly cable insulation. However, the polypropylene material itself also has some disadvantages, such as large low-temperature brittleness, poor aging resistance, low thermal conductivity, etc., which have certain limitations on the application of DC cable insulation.

2.2. Feasibility of polypropylene applied to insulation material for high-voltage DC cable

Polypropylene has excellent dielectric and heat resistance properties. As early as 2002, some scholars have studied the feasibility of applying it to the main insulation material of power cables. Among them, the Japanese researcher Kurahashi found that sPP-based insulation, adding PE and antioxidant blends made of 0.6 and 22 kV cable, at different temperatures in the cable line AC breakdown strength and dielectric loss can meet the requirements of practical applications [8]. Yoshino et al. found that the electrical, thermal, and mechanical properties of sPP were superior to those of iPP, aPP, and PE materials [9]. The 22 kV cable prepared by the authors using sPP and elastomer blends has excellent electrical properties and shown a high

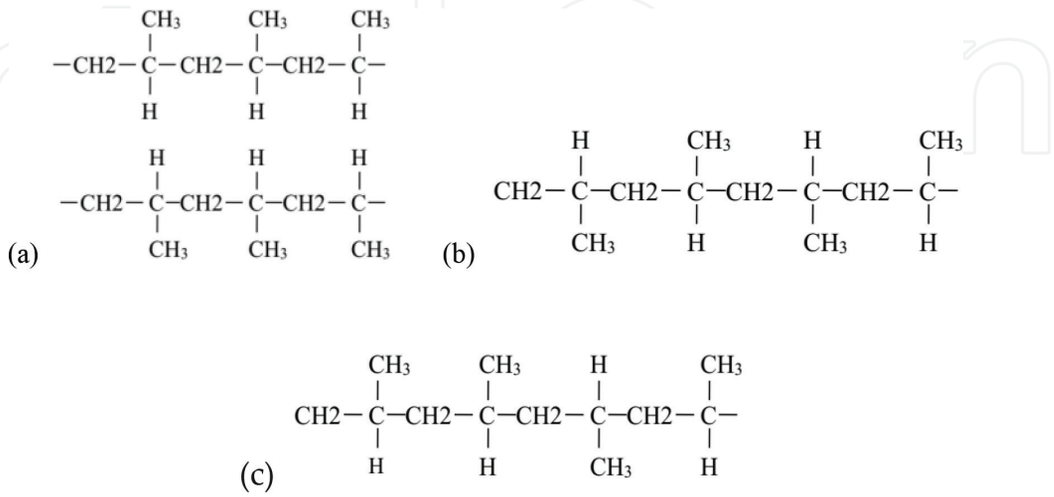


Figure 1. Molecular structure of the three kinds of polypropylene: (a) iPP, (b) sPP and (c) aPP. (a) (b) (c).

impulse breakdown strength than XLPE at 25, 90, 110°C, as shown in **Figure 2**. Hosier et al. found that insulating materials obtained by blending iPP with ethylene-propylene copolymers exhibit good mechanical toughness and electrical properties [10]. As shown in **Figure 3**, the PP (as labeled with H) shows a lower temperature dependence- conductive current than that of PE (as labeled with 1,2,3,4,5) [11].

At present, the commercial application of polypropylene-based materials as the main insulating material for high-voltage DC cables is still in the research and development stage. In 2010, Belli et al. of Prysmian, Italy disclosed high-performance thermoplastic elastomer insulation material HPTE (High Performance Thermoplastic Elastomer) [12] developed based on polypropylene material. The study found that P-Laser cable developed based on HPTE material is more traditional than traditional. XLPE cables have better electrical properties and have better mechanical properties than polypropylene.

Polypropylene materials have excellent comprehensive performance, and the research in the field of main insulation of high-voltage DC cables also shows great potential, but there is still a certain distance from practical application. Polypropylene materials have insufficient flexibility and poor low temperature toughness at room temperature and cannot be directly used for main insulation of cables. Moreover, most researchers are concerned about the improvement of the mechanical properties of polypropylene. The study of the dielectric properties of polypropylene based materials is not comprehensive enough, and space charge, electrical branch, etc. are not considered.

In the operation of high-voltage DC cables, there are problems such as aging and breakdown of electrical branches due to the space charge accumulation and internal electric field distortion problems [13]; the electric field reversal that may be caused by the influence of heat

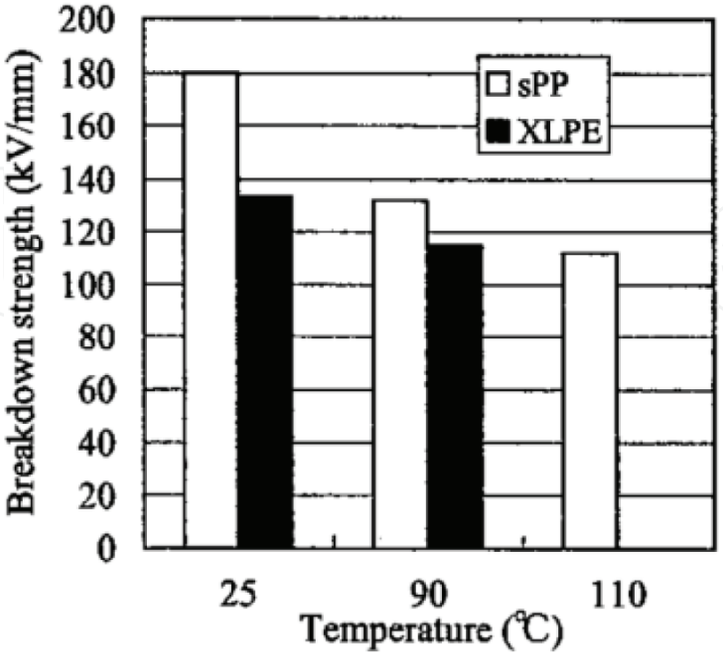


Figure 2. Impulse breakdown strength of 22 kV class sPP and XLPE cable.

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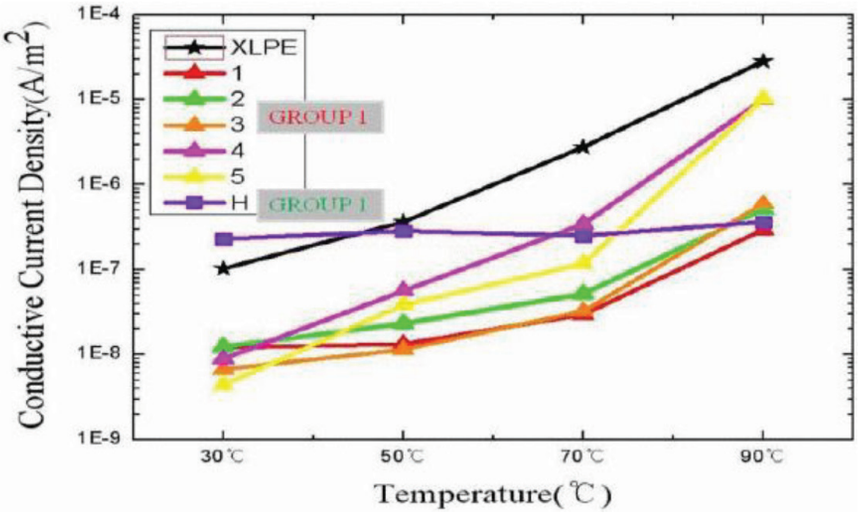


Figure 3. Temperature dependence of conductive current.

dissipation and temperature gradient of the insulation layer, Problems such as the degradation of electrical performance and service life; and the problems of internal defects caused by mechanical stress, etc. If polypropylene is used as insulation material for high-voltage DC cables, it must be modified to improve the above-mentioned deficiencies in dielectric, thermal and mechanical properties. Nanoparticles modification can significantly improve the electrical, thermal and mechanical properties of solid dielectrics. Many scholars have conducted useful explorations on the performance of polypropylene-based nanocomposites.

3. Research status of polypropylene-based nanocomposites for HVDC cable insulation materials

3.1. Study on dielectric properties of polypropylene nanocomposites

3.1.1. Space charge

The space charge effect is a key issue in the development of high performance DC insulation materials [14]. When the high-voltage DC cable runs normally, the electric field with the same polarity and high strength acts on the insulating medium for a long time, resulting in the accumulation of the space charge of the insulating layer and the distortion of the internal electric field. The distorted electric field can cause partial discharge in the medium, accelerate the aging of the polymer material and the growth of the electric branch, and eventually lead to insulation breakdown failure, which seriously affects the performance and service life of the cable. Since the mid-1990s, scholars such as Suzuoki and others have found that the pre-applied voltage causes the distortion of the internal electric field due to the space charge accumulation in polypropylene and reduces the dielectric breakdown strength [15]. Therefore, how to improve the space charge characteristics of polypropylene insulation materials is an important issue for the development of polypropylene-based insulation materials for high-voltage DC cables.

Most scholars believe that the interface region formed between the polymer matrix and the nanoparticle in the nanocomposite material introduces a large number of traps, changes the trap energy level of the composite material, and has an important influence on the space charge injection, migration and dissipation behavior. However, due to the complexity of the interface behavior (affecting polymer crystallization, changing the internal stress of the medium, etc.), and the ability to directly observe the microstructure and mechanism of action in the interface region, many scholars have proposed different models for this, such as proposed by Lewis et al. The nanodielectric "dielectric double layer" structure [5] (as shown in **Figure 4**), the multi-core model proposed by Tanaka [6] (as shown in **Figure 5**), Kindersberger et al. The volumetric model [7], to a certain extent, helps to speculate and explain the superior performance of nanocomposite dielectric materials, but it has not yet reached a conclusion.

Montanari et al. studied the charge trapping behavior of nanocomposites of iPP and sPP with synthetic Montmorillonite (MMT) nanoparticles. Compared with pure PP, the charge trapping ability of nanocomposites significantly increased. The reduction of the space charge accumulation under the electric field shows that the insulation performance of nanocomposites has been improved overall [16].

Due to the large surface energy of nanoparticles, nanoagglomeration is likely to occur during the preparation of nanocomposites, which not only reduces its dispersivity and interaction with the polymer matrix, but also aggravates the composite materials. Accumulation of space charge. Fuse et al. found that the introduction of ionic groups during the dispersion of nanoclay particles into polypropylene-based materials aggravated the space charge accumulation of the composite [17].

In order to solve the problem of nanoagglomeration, researchers have done a lot of research work and achieved certain results. It has been found that by adjusting the conditions for preparing the nanoparticle and the polymer matrix, such as temperature, the dispersion effect of the nanoparticle can be improved. Li et al. obtained different nanodoped iPP/MgO nanocomposites through mechanical blending at six different temperatures. It was found that when the temperature was 200° C., the nanoparticle dispersion was good, and MgO nanoparticles were in the composite. Nucleation occurs while suppressing the accumulation of space charge [18].

The use of coupling agents, surfactants, grafting, in-situ polymerization and other means of surface treatment of nanoparticles can reduce nanoaggregation and promote the dispersion of nanoparticles in the polymer and its interaction with the matrix. Abou-Dakka and others filled with synthetic nano-mica particles and natural montmorillonite nanoparticles modified

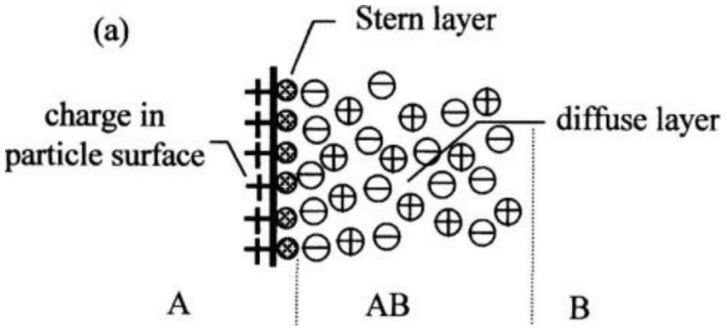


Figure 4. The diffuse electrical double layer produced by a charged particle A in a matrix B containing mobile ions.

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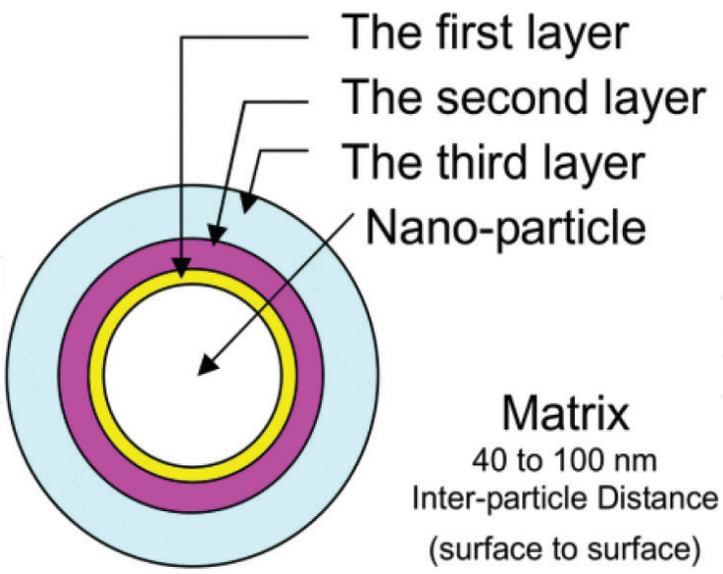


Figure 5. Multi-core model for nanoparticle - polymer interfaces.

with silane coupling agent make the trap-belt of polypropylene-based composite materials move to the shallow and the charge dissipation rate is much faster than that without filling. The charge in shallow traps at the unipolar level can be effectively suppressed in reverse polarity, and the charge in deep traps is also significantly constrained [19]. Zhou et al. found that a large number of shallow traps introduced into polypropylene composites by surface-modified TiO_2 nanoparticles replaced the original deep traps in PP, which in turn enhanced carrier migration and improved space charge accumulation [20].

3.1.2. Aging of electrical trees

During the production and operation of high-voltage plastic DC cables, defects such as impurities, voids, and molecular bond bonds may be generated in the insulating medium. When the polymer insulating material is placed under a high-intensity electric field for a long period of time, electric field concentration and partial discharge caused by defects or the like easily cause dendritic partial damage in the insulation, and the dendritic microchannels grow along the direction of the electric field to form electric branches. It can penetrate the entire insulation and cause breakdown accidents [21].

Du et al. found that dendritic electrical branches can be grown when PP is subjected to a pulse voltage of 12 kV and a frequency of 400 Hz at different temperatures. Compared to XLPE, the electrical branches in polypropylene are more difficult to produce and the growth speed and size are smaller [22], as shown in **Figure 6**, which is of great significance for improving the reliability of cable operation. Holto et al. observed that there were single and multiple branches growing before sPP breakdown [23]. Therefore, research on insulating materials suitable for high-voltage DC cables requires the suppression of their electrical branches.

In nanocomposites, when the dendrites grow to nanometer positions, it is generally difficult to pass through the nanoparticles, and the branch channels bypass the nanoparticles or stop growth, especially when the nanoparticles are lamellar structures. In addition, the added nanoparticles have a large specific surface area, and the tiny holes generated around

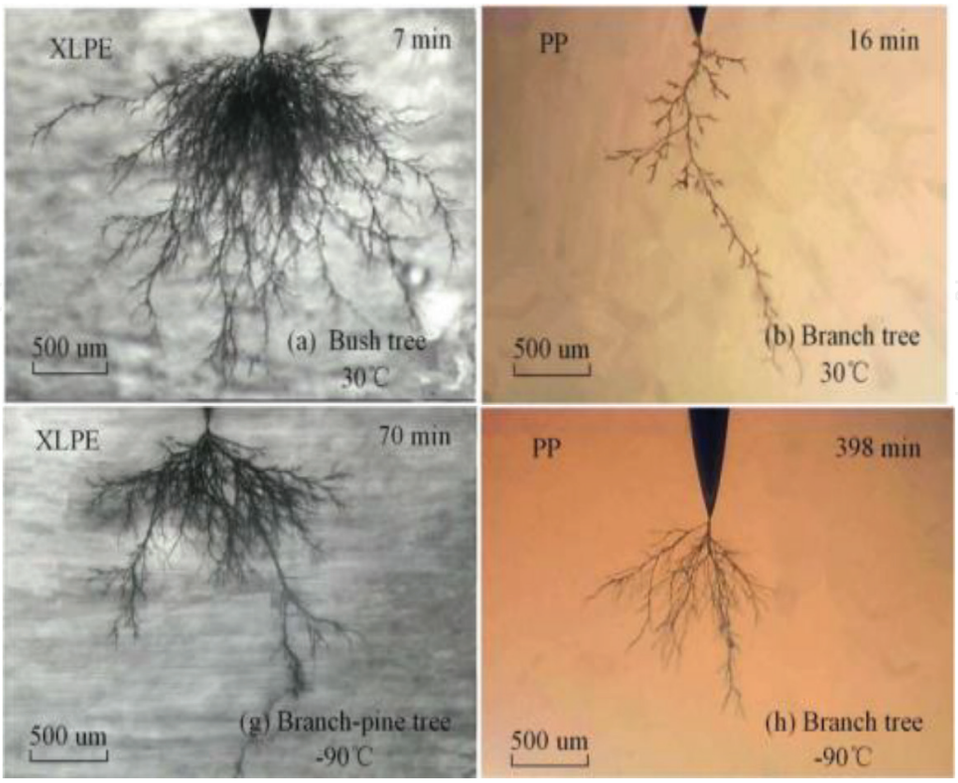


Figure 6. Electrical trees in XLPE and the PP.

the particles increase the number of branches of the electric tree, consume the energy of the development of the electric tree, and increase the probability of appearance of the jungle-like electric tree structure, delaying the electric branch. Growth rate and breakdown time.

3.1.3. Breakdown strength

The compressive strength of insulating materials is an important indicator for evaluating the electrical performance of cables. Nanodoping can increase the breakdown strength of polymers. It is of great significance for the development of polypropylene-based cable materials. According to the "dielectric double layer" structure model, filling a certain amount of nanoparticles can increase the trap energy level and trap density of the composite material, so that the same polarity charge accumulates on the surface of the material, the injection amount of carriers is reduced, and the material is weakened. Distortion of the electric field caused by the accumulation of charge in the space increases the field strength required for the composite to reach breakdown. At the same time, the nanoparticles can fill the spherulite gap formed during the crystallization of the polymer, blocking the transport and injection of charge.

At present, many literatures have studied the breakdown characteristics of polypropylene nanocomposites. Takala et al. found that POSS nanoparticles can be filled with polypropylene spherulite gaps to block the transport of charge and greatly increase the breakdown strength of nanocomposites [24]. Takala et al. also found that compared with pure PP, the AC/DC breakdown field strength of PP/SiO2 nanocomposites was significantly improved, and the DC breakdown strength increased by 52.3% [25].

When studying the breakdown properties of composites, the analysis of microstructures is also worthy of attention. Virtanen et al. found that the dispersion levels of nano-$CaCO_3$ particles with different doping levels were almost the same in the polypropylene matrix, while the density of particles caused by nanoagglomeration increased exponentially with the increase of nanodoping concentration. The dc breakdown strength of the composites is the largest at a mass fraction of 1.8%, and the density of the particles increases as the concentration of nanoparticles increases and decreases [26].

To improve the breakdown strength of polypropylene, SiO_2, Al_2O_3, $CaCO_3$, POSS and other nanomaterials are used, so that the amount of the composite material to achieve the best breakdown characteristics is also different. The use of nanosurface treatment to improve the agglomeration and its combination with the matrix The study of improving the breakdown strength of composites can be further explored.

3.2. Thermal conductivity of polypropylene nanocomposites

When the high-voltage DC cable runs normally, the heat of the cable conductor causes the temperature distribution of the insulating medium to decrease from the inner to the outer gradient, which has a great influence on the insulation layer charge transport, electric field distribution, and service life [27]. The electric field intensity distribution of the cable insulation layer under direct voltage is proportional to the resistivity, while the electric resistance of the polymer insulation material decreases with increasing temperature, so that the electric field strength outside the cable insulation layer is higher than the inside. At the same time, the effect of the temperature gradient aggravates the injection and migration of the cable conductor into the dielectric, further enhancing the electric field strength outside the insulating layer. When the accumulation of heteropolar space charge in the medium is serious, it can cause the reversal of the electric field, and even insulation breakdown. Moreover, the elevated operating temperature of the cable accelerates the aging of the polymer insulation and shortens the service life of the cable. Therefore, it is of great significance to improve the thermal conductivity of polypropylene insulation materials, to extend the service life of cables, and to increase the operating voltage and operating temperature of cables.

Filling metal or inorganic fillers with high thermal conductivity is an important method to improve the thermal conductivity of polymers. The thermal conductivity of composite materials is not only related to the intrinsic thermal conductivity of fillers and polymers, but also affected by the size, shape, and dispersion state of the filler. Generally, the smaller the size of the thermal conductive filler, the larger the interface area between the filler and the matrix, the more severe the phonon scattering, the higher the thermal resistance at the interface, and the worse the thermal conductivity. In terms of shape, the sheet-like or whisker-like heat-conductive filler has a large specific surface area, and it is easier to form a heat-conducting channel in the polymer matrix and improve the heat-transfer efficiency of the composite material.

For fillers with higher intrinsic thermal conductivity, such as nanosized boron nitride (BN), the thermal conductivity of the composite can be maintained at a high level even if the filler size is reduced to the nanoscale. Couderc et al. found that when the mass fraction of hexagonal boron nitride (hBN) particles is 50–80%, the thermal conductivity of composites is

significantly higher than that of pure PP, and is almost unaffected by the concentration of boron nitride. At the same time, the introduction of nano-hBN particles can promote the dispersion of hBN micro-particles in the polypropylene micro-nano composite materials, thereby forming a more compact structure and weakening the thermal aging rate of the sample [28].

The introduction of nanosized thermally conductive fillers not only improves the thermal conductivity of the polypropylene material, but also improves the electrical properties of the composite material by the interfacial effect between the nanoparticles and the matrix. Du et al. found that the addition of nano-BN in polypropylene can significantly increase the thermal conductivity of composites. The direct-current body breakdown strength of PP/BN nanocomposites is not only higher than that of pure PP and PP/BN micron composites. As the content of nanomaterials increases, it increases accordingly [29].

Fukuyam et al. found that the thermal conductivity of grafted PP/SiO2 nanocomposites was higher than that of untreated composites [30]. The authors found that the thermal conductivity of the PP/SiO_2 nanocomposites treated with grafts was analyzed by using the three-phase model and considering the interface layer. The interface layer is the main channel for thermal conduction of the iPP-grafted molecular chains. **Figure 7** shows TEM images of nano-SiO_2 particles doped with grafted and ungrafted.

3.3. Study on mechanical properties of polypropylene nanocomposites

When the high-voltage DC plastic cable is working under load, the temperature distribution in the insulating layer is not uniform due to the conductor heating, and the thermo-mechanical

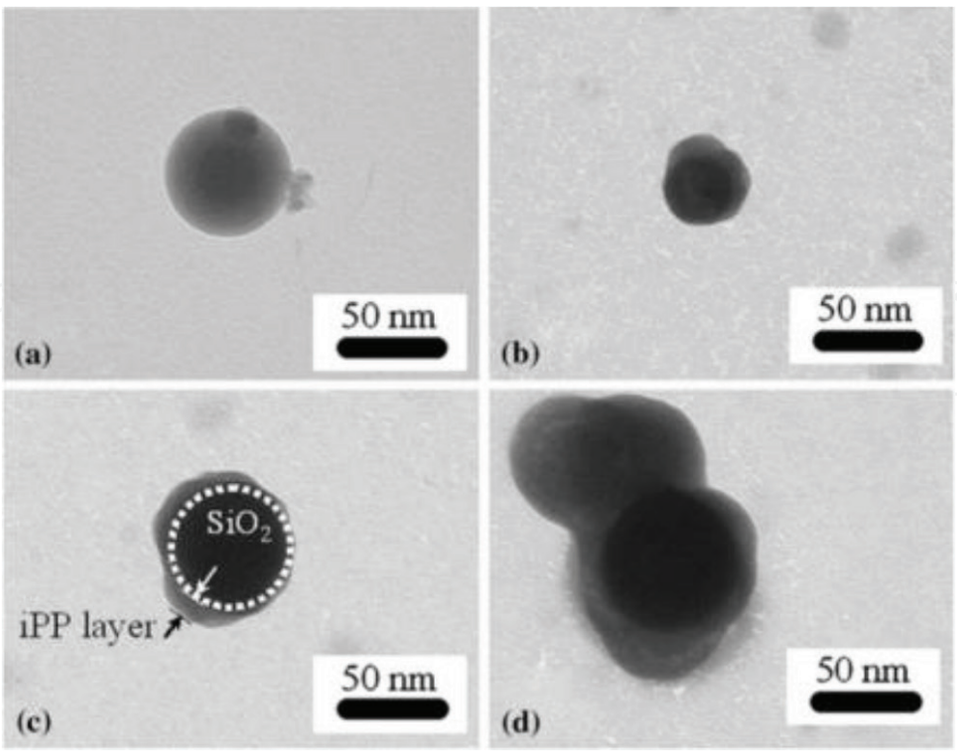


Figure 7. TEM images of n-SiO_2 (a) and g-SiO_2 (b–d) particles with various molecular weight of iPP.

performance changes due to thermal expansion and thermal stress can occur in the dielectric; the cable manufacturing and laying process may also cause Concentration of stress in insulating media. The role of mechanical stress can produce air gaps or micro cracks in the medium to form defects. The defects are easily discharged under the action of an electric field, causing serious breakdown of the material and threatening the operational safety of the cable. Polypropylene has high crystallinity, regularity, and excellent resistance to bending fatigue, but its high brittleness and low impact strength, especially in low temperature environments, need to be toughened and modified before it can be applied to the insulation of high-voltage DC cables.

Nano-doping can significantly increase the mechanical strength and fracture toughness of polypropylene materials, and reduce the generation of micro cracks and internal air gaps. The surface treatment or grafting process causes a physical adsorption or chemical reaction between the nanoparticles and the polymer matrix or the surface modifier, improving the mechanical properties of the polymer material. The grafted nanoparticles can promote the crystallization of the composite material, strengthen the link between the matrix and the nanoparticles, and improve the mechanical properties of the composite material. Umemori et al. found that the grafted PP-g-SiO2 nanoparticles have improved dispersibility in polypropylene and nucleation of PP crystals; the end of the grafted chain directly connects the PP matrix and SiO2 nanoparticles. By bridging together, the Young's modulus and tensile strength of composites can be greatly improved when the nano-mass fraction is 2.3% [31].

The introduction of nanoparticles can avoid the problem of reduced fluidity of the system caused by simple elastomer toughening, and can also promote the dispersion of elastomers, resulting in a synergistic toughening effect. Lee et al. found that the dispersion of nano-SiO2 particles treated with maleic anhydride in the matrix was more uniform; while the introduction of nano-SiO2 particles increased the shear force during the mixing process, and the particle size of the elastomer POE was further decomposed. Small, more uniform dispersion; synergistic toughening effect of nanoparticles and elastomers, so that the bending strength and Young's modulus of the composite material significantly improved [32].

3.4. Effect of nanofillers on properties of polypropylene composites

The brittleness of polypropylene is a key factor limiting its use as a high voltage DC cable insulation. Many studies have shown that the blending of polypropylene with elastomers is an effective means to improve the mechanical toughness. However, it was also found that the elastomer introduced more interfaces and traps in the blends, leading to more space charge accumulation, lower breakdown strength, and other insulation problems in the blends. Considering that nanoparticles have excellent performance in improving the insulation properties of polypropylene monomer, many scholars have studied the effect of nanoparticles on polypropylene multicomponent composites.

Du et al. found that POE can significantly improve the toughness of PP, but the space charge accumulation of PP/POE blends increases, and the breakdown field strength also decreases significantly; nano-ZnO particles maintain good mechanical toughness after PP/POE introduction. It also increased the tensile strength of PP/POE; filled nano-ZnO particles increased the trap level density of PP/POE, reduced the charge injection, and thus suppressed the space

charge accumulation [33], as shown in **Figure 8**. Compared with PP/POE blends, PP/POE/ZnO nanocomposites have lower dielectric constants and higher breakdown and volume resistivity.

Zhou et al. mixed surface-modified nano-MgO particles into PP/POE. The study found that the DC breakdown strength and space charge suppression ability of PP/POE/MgO nanocomposites were enhanced, and the synergies between nanoparticles and POE were also increased. Tenacity results in a significant increase in the tensile strength and elongation at break of the composite [34]. Dang et al. found that the introduction of nano-ZnO reduced the number of deep traps in the PP/PER/ZnO nanocomposites, promoted the dissipation of heteropolar charges in the composites, and effectively inhibited the formation of space charge [35].

3.5. Effect of nanofillers on the properties of polypropylene composites under aging conditions

When polypropylene is applied to the insulation material of high-voltage DC cables, the problem of material aging is an important index for evaluating its insulation performance and service life. The combined action of the electric field and heat during normal operation of the cable accelerates the aging of polymer insulation performance. The entrapment and extinction of the electric charge in the insulating medium of the cable is accompanied by the release and transfer of energy. The ultraviolet radiation generated at this time can lead to polymer degradation. The conductor heat directly acts on the dielectric insulating layer, and the weak link of the covalent bond of the polymer molecular chain first initiates free radicals and undergoes chain reaction, resulting in chain scission and destroying the structure of the polymer. A large number of tertiary carbon atoms are distributed on the molecular chains of polypropylene polymerized from propylene. Under aerobic conditions, tertiary carbon atoms are extremely unstable and easily convert to very active tertiary carbon radicals, resulting in PP chain growth, chain degradation. In the process of developing polypropylene-based high-voltage DC cable insulation materials, the effect of nanofillers on their performance under electrical and thermal aging has attracted the attention of relevant scholars.

The nanometer lamellar structure has mechanical protection and physical barrier effect on the polymer, and the interface interaction between the nanoparticle and the polypropylene restricts the movement of the amorphous phase molecules. These enhance the commonness of

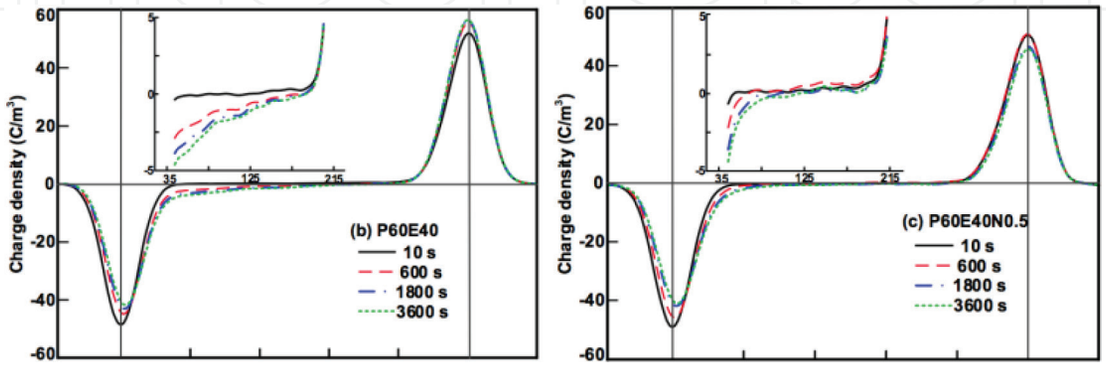


Figure 8. Space charge distribution of PP/POE(left) and PP/POE/Nano-ZnO(right).

the polypropylene nanocomposite in the electric field and temperature field. Under the effect of thermal aging resistance and insulation performance. Moreover, lamellae-structured nanoparticles have a higher surface energy, so that carriers are trapped by interface traps between the nanoparticle and the polymer matrix during the transition, limiting the migration of electrons and holes. In the composite material, when the nanometer doping amount is large, the overlap of the "media bilayer" structure between the nanoparticles can be enhanced, the space charge transfer is promoted, and the electrical conductivity of the nanocomposite material becomes large. Guastavino et al. found that the nanometer MMT mass fraction of polypropylene nanocomposites with the mass fraction of 10% was the highest in the mid-term (about 277 h) electrical aging test [36]. Bulinski et al. added polypropylene tetra-mica nanoparticles containing synthetic tetrasilicic fluormica nanoparticles to a DC −40 kV/mm electric field intensity at room temperature and 90°C, respectively, and accumulated aging for 500 h. The tensile strength is still about 12% higher than that of pure polypropylene, and there is no significant change in the dielectric loss factor, and the DC conductivity is only slightly increased [37].

4. Conclusions

The development of high-voltage direct current (HVDC) transmission technology places higher demands on the cable's current-carrying capacity, voltage operating level, and operating temperature. Polypropylene has good heat resistance, high melting point and long-term working temperature, excellent electrical properties such as breakdown strength, volume resistivity, space charge, etc. No cross-linking is required to simplify the production process, thermos plasticity can be recycled, and it is in line with large-capacity and environmental protection Technical requirements for DC cables. However, polypropylene has the disadvantages of poor low-temperature impact performance and low thermal conductivity, as well as the problem of space charge accumulation and aging of the polymer in the DC field. Therefore, polypropylene needs to be modified in order to meet the electrical, thermal, and mechanical properties of the cable insulation material under the complex working conditions of high-voltage DC. Nanodoping can effectively improve the overall performance of polypropylene monomer and multicomponent blended composites, such as suppression of space charge accumulation, resistance to aging of electrical branches, improvement of dielectric strength such as breakdown strength, and improvement of thermal conductivity, tensile strength, and elasticity. Modulus and other thermal, mechanical properties, and nanofiller on the electric and thermal aging properties of the polypropylene composite material improvement effect is also very obvious.

At present, the research on the application of polypropylene and its nanocomposites in the insulation of high-voltage DC cables is still in its infancy, and there are still many issues that need further study:

1. A large number of experimental results show that nanodoping can improve the dielectric, thermal and mechanical properties of polypropylene, but scholars have not reached a consensus on the explanation of the improvement mechanism. A systematic and comprehensive analysis of the impact of factors such as the selection of single or multiple nanometers, the optimal ratio of additives, interface compatibility, nanosurface treatment, and dispersion

methods on the performance improvement of polypropylene is needed for the theoretical foundation research.

2. During normal operation, the insulation medium of high-voltage DC cables may also be affected by the coupling field consisting of stress strain field, electric field, magnetic field and temperature field. There is no corresponding experimental research on the dielectric, thermal and mechanical properties of polypropylene and its nanocomposites under coupled field.
3. Polypropylene materials are easily affected by electricity, heat, or light, aging, cable preparation methods, process flow and other effects on the performance of polypropylene nanocomposite insulation materials, the future still need to carry out corresponding research work.

Author details

Boxue Du, Zhaohao Hou and Jin Li*

*Address all correspondence to: lijin@tju.edu.cn

Key Laboratory of Smart Grid of Education Ministry, School of Electrical and Information Engineering, Tianjin University, Tianjin, China

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