Research Progress on Electrical Treeing in Environmentally Friendly Polypropylene Insulation for DC Cable Materials: Postprint

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Abstract

Polypropylene has attracted considerable attention due to its excellent electrical and thermal properties, which align with the development requirements for environmentally friendly and recyclable cable insulation materials. During operation, high-voltage direct current (HVDC) cables are subjected to not only DC rated voltage but also pulse voltage, causing rapid voltage fluctuations along the line and aggravating electric field distortion. Temperature variations in cables affect the conductivity of insulation materials and space charge accumulation, leading to electric field distortion within the insulation material and resulting in the initiation and growth of electrical trees. This paper compares the electrical tree growth characteristics of polypropylene and cross-linked polyethylene under identical conditions, analyzes the influence patterns of DC-pulse composite fields, temperature, and other factors on the electrical tree growth characteristics of polypropylene, and explores the mechanisms of different methods for suppressing electrical trees.

Full Text

Preamble

Research Status on Electrical Treeing in Environmentally Friendly Polypropylene Insulation for HVDC Cables

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Abstract

Polypropylene (PP) has attracted widespread attention as an environmentally friendly and recyclable cable insulation material due to its excellent electrical and thermal properties. During operation, HVDC cables are subjected not only to DC rated voltage but also to impulse voltages, causing rapid voltage fluctuations that intensify electric field distortion. Temperature variations affect the conductivity and space charge accumulation in insulating materials, leading to internal electric field distortion and the initiation and growth of electrical trees. This paper compares the electrical tree growth characteristics of polypropylene and cross-linked polyethylene under identical conditions, analyzes the influence of DC-pulse combined electric fields and temperature on PP electrical tree growth, and discusses the mechanisms of different methods for suppressing electrical trees.

Keywords: HVDC cable, polypropylene, electrical tree, DC-pulse combined voltages, temperature

Author Biographies

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1. Introduction

Electrical treeing is a phenomenon where localized field concentration caused by defects such as impurities and voids in insulating materials leads to partial breakdown, forming micrometer-scale discharge channels that resemble tree branches [?]. Once initiated, electrical trees propagate at extremely high speeds, and when they grow through the entire insulation layer, electrical failure occurs, compromising cable operational safety [?]. In 1972, Japanese scholars reported at the Conference on Electrical Insulation and Dielectric Phenomena that electrical tree aging represents cumulative damage in solid dielectric insulation, prompting extensive research worldwide [?].

Early research primarily focused on electrical trees under AC voltage. Scholars generally agree that direct impact damage from injected or generated charge carriers on polymer chains, along with energy released from charge carrier recombination, constitutes a major cause of electrical tree initiation in polymers [?]. Under DC voltage, however, the single polarity and long-term stable waveform make it difficult for injected charge carriers to acquire sufficient energy to impact molecular chains, hindering tree initiation. Nevertheless, HVDC cables experience not only DC rated voltage but also impulse voltages during operation, which may include lightning impulses from overhead lines or switching impulses from line faults and twelve-pulse converters [?]. When these impulses combine with DC voltage in HVDC cables, they create a complex DC-pulse combined field that causes rapid voltage fluctuations and intensifies electric field distortion [?].

High-voltage DC cables operate at elevated temperatures due to high voltage levels and large currents that generate significant heat in the conductor [?]. Under DC electric fields, the electric field strength in cable insulation depends on resistivity, which is highly temperature-dependent. Temperature also affects charge injection and mobility in cable insulation. As temperature increases, more charges are injected and carrier mobility increases [?], influencing space charge accumulation [?]. Space charge accumulation accelerates electric field distortion, initiating insulation aging and electrical tree growth, while carrier movement is intimately related to tree propagation. Thus, temperature variations have a complex and close relationship with electrical tree growth characteristics.

Plastic-insulated cables have been widely adopted due to their excellent electrical, mechanical, and thermal properties, with cross-linked polyethylene (XLPE) HVDC cables being the most prominent and widely applied [?]. However, XLPE cables have a maximum operating temperature of only 70°C, and the crosslinking agents and byproducts introduced during manufacturing can exacerbate space charge accumulation under DC electric fields, accelerating insulation aging. The crosslinking process transforms polyethylene from a thermoplastic to a thermosetting material, making direct recycling impossible at end-of-life and creating significant environmental waste problems [?].

Polypropylene (PP) insulation materials offer higher melting points to meet cable operation requirements at elevated temperatures. PP exhibits higher breakdown strength and volume resistivity, which is significant for increasing cable voltage ratings and line current capacity. Additionally, without requiring crosslinking, PP can be recycled at end-of-life, making it an environmentally friendly DC cable insulation material [?]. Since research on PP materials is relatively recent, understanding of their aging and breakdown characteristics remains insufficient, necessitating systematic investigation of PP aging and breakdown properties under various conditions to provide theoretical foundations for cable structural design and life prediction.

2. Comparison of Electrical Tree Growth Characteristics in PP and XLPE

To compare the electrical tree resistance of PP and XLPE, Tianjin University conducted electrical tree growth experiments on both materials under identical impulse voltages [?]. The research revealed that electrical trees in PP exhibit sparser morphology with thinner channels compared to XLPE. At an applied voltage time of 10 minutes, PP showed lower electrical tree initiation probability, indicating that trees are more difficult to initiate in PP, as shown in [Figure 1: see original paper]. Within the same time period, electrical trees grew more slowly in PP with smaller fractal dimensions, as illustrated in [Figure 2: see original paper].

Holto et al. investigated electrical tree morphology in PP and XLPE, finding that two types of trees grew in PP before breakdown: single-branch trees that caused breakdown upon reaching the ground electrode, and multi-branch trees requiring multiple branches to reach the ground electrode before breakdown occurred. In contrast, XLPE more readily formed bush-type trees before breakdown, as shown in [Figure 3: see original paper]. It was also speculated that the electrical tree regions formed in PP have lower conductivity than those in XLPE [**?**].

3.1 Influence of DC-Pulse Combined Voltage on Electrical Tree Growth Characteristics

HVDC cables in operation are affected by lightning overvoltages and switching impulses from twelve-pulse converters. In actual cable circuit operation, the amplitude and frequency of generated impulse voltages vary widely [**?**]. When these impulses combine with the rated DC voltage in HVDC cables, they create a complex DC-pulse combined field that causes rapid line voltage fluctuations, intensifies electric field distortion, and leads to electrical tree initiation.

Tianjin University investigated electrical tree initiation and growth characteristics in polypropylene under combined DC and impulse voltages of different amplitudes [**?**]. The study found that when DC voltage increased from -5 kV to -15 kV, the electrical tree growth rate increased, as shown in [Figure 4: see original paper]. [Figure 5: see original paper]a illustrates the charge transport process under -5 kV and -15 kV DC combined with +25 kV impulse voltage. When DC voltage was applied to the needle tip, electrons were injected and accumulated around the tip. After applying the positive impulse voltage, some electrons were extracted from the tip. As the combined voltage polarity changed from negative to positive, positive charges were injected. Negative and positive charges recombined, releasing energy that accelerated electrical tree growth [**?**]. As DC voltage amplitude increased from -5 kV to -15 kV, more homocharges were injected at the needle tip due to Schottky emission. When the voltage polarity changed from negative to positive, electrons transformed from homocharges to heterocharges, causing electric field distortion and partial discharges that led to molecular chain breakage [**?**].

However, as shown in [Figure 4: see original paper], when DC voltage increased from -15 kV to -25 kV, the growth rate decreased. [Figure 5: see original paper]b shows the charge transport process under +25 kV impulse combined with -25 kV DC voltage. After impulse voltage application, electrons were extracted because the needle tip potential decreased [**?**]. This charge movement caused molecular chain breakage, leading to tree growth. Due to the lack of polarity change process and the reduced average value of the combined voltage, the electrical tree growth rate under +25 kV impulse combined with -25 kV DC was lower than that under +25 kV impulse combined with -5 kV or -15 kV DC.

[Figure 6: see original paper] shows the simulated electric field distribution from needle tip to ground electrode at time t0 (when the combined voltage first reached maximum amplitude) [?]. When combined with +25 kV impulse voltage, the -15 kV DC condition produced a larger electric field peak, indicating stronger polarity change effects. However, the -25 kV DC condition showed reduced growth rate due to the absence of polarity change and lower average combined voltage.

Research shows that impulse amplitude significantly affects electrical tree structure, as illustrated in [Figure 7: see original paper]. With increasing voltage, deeper charge injection creates charge fronts farther from the needle tip or tree tips. Electrical trees are more likely to branch ahead of the charge front [?]. Therefore, as impulse amplitude increases, more side branches grow from main branches. Impulse amplitude has a significant effect on tree growth, with increasing amplitude leading to higher growth rates and cumulative damage. Due to higher combined voltage electric field strength, impulse voltages with the same polarity as DC voltage cause breakdown more easily than those with opposite polarity [?].

Studies have found that under electric field polarity reversal, space charges cause severe electric field distortion [?]. Tanaka discovered that after polarization at 80 kV/mm for 30 minutes, negative charge accumulation at the cathode reduced the cathode field to approximately 50 kV/mm while increasing the anode field to about 120 kV/mm. When voltage polarity reversed, space charges could not change instantaneously, so the space charge field combined with the applied field increased the cathode field to approximately 130 kV/mm [?]. Research shows that polarity reversal reduces breakdown strength. After DC voltage application, the positive impulse breakdown field strength of tested samples was lower under negative DC prestress compared to positive DC prestress [?].

Xi’ an Jiaotong University studied electrical tree initiation voltage in XLPE under impulse voltage after DC prestressing, finding that tree length was primarily determined by impulse voltage amplitude, with DC prestress having minimal effect [?]. Saito et al. investigated electrical tree initiation characteristics in polyethylene (PE) under impulse voltage after DC prestressing, discovering that different dwell times after DC prestressing affected charge characteristics and thus altered tree initiation properties [?]. Although these studies revealed space charge effects on tree growth characteristics to some extent, they did not achieve true DC and impulse voltage superposition, only DC prestressing.

3.2 Influence of Other Combined Voltages on Electrical Tree Growth Characteristics

DC voltage output from rectifiers and other power electronic devices in HVDC transmission systems contains significant harmonics, with harmonic coefficients reaching over 10%. When DC cable systems contain harmonic components, both the magnitude and frequency of harmonics affect electrical tree growth characteristics. Iddrissu et al. studied the effects of DC-AC combined voltage on electrical tree growth in epoxy, finding that tree growth characteristics differed under positive and negative DC bias voltages [?]. Additionally, AC voltage amplitude significantly affected electrical tree growth under DC-AC combined voltage [?]. These studies provide a foundation for understanding tree growth mechanisms under DC-AC combined fields, but tree growth characteristics vary across different materials, and research on electrical trees in polypropylene under combined fields remains to be conducted.

4. Research Status on Temperature Effects on Electrical Trees

Tianjin University investigated polypropylene electrical tree growth characteristics across temperatures ranging from -196°C to 130°C [?, ?]. The study found that as temperature varied from -196°C to -30°C, electrical tree morphology changed from branch-type to bush-type and back to branch-type, as shown in the table below.

Table: Typical Electrical Tree Structures at Different Temperatures and Frequencies [?]

Temperature variations affect material mechanical properties. As temperature decreases, PP' s elastic modulus increases, meaning PP becomes more brittle at -90°C than at -30°C and is more prone to cracking. During thermal electron impact on molecular chains creating electrical tree channels, mechanical cracks also form as defects, and avalanche discharges occur in these cracks, creating denser tree structures. Oxygen plays an important role in PP degradation. When free radicals react with oxygen, autoxidation reactions occur, decomposing the polymer. However, at -196°C, oxygen liquefies and autoxidation reactions are inhibited. Therefore, at -196°C, PP molecular chains are extremely difficult to break, forming sparse branch-type trees.

When temperature increased from 50°C to 130°C, tree structure remained branch-type, but branches became thicker with rising temperature. Tree growth speed increased from 50°C to 110°C, but growth at 130°C was slower than at 110°C, as shown in [Figure 8: see original paper] [?].

After impulse voltage application to the needle tip, charges are injected when applied voltage exceeds the injection barrier. During charge trapping, excess energy transfers to electrons, making them hot electrons that impact molecular chains, degrading polymers into free radicals. Oxygen participation accelerates this process, and after repeated cycles, low-density regions form where collision ionization occurs, eventually initiating electrical trees. As temperature increased from 50°C to 110°C, thermal energy caused single-bond rotation on main chains and excited molecular chain movement. With rising temperature, molecular chain thermal motion gradually increased, causing partial relaxation of polymer segments and weakening the region around the needle tip, increasing tree initiation probability. Simultaneously, at high temperatures and high field strengths, deeply adsorbed oxygen in the polymer matrix was released to participate in oxidation reactions, accelerating growth. Additionally, as temperature increased, large crystals in crystalline regions slowly melted, increasing amorphous regions and free volume. Electrons accelerated in free volume, acquiring greater energy. However, DSC curves show that at 130°C, crystals melted extensively, approaching the melting point temperature. At this point, the elastic modulus suddenly decreased, making dense tree regions easier to form. As dense regions formed, some injected charges were captured and distributed uniformly, creating a space charge layer that formed an electric field shield, reducing electric field intensity at the needle tip at 130°C. Consequently, growth speed at 130°C was slower than at 110°C.

To further investigate microstructural differences between original samples and breakdown channels, Tianjin University studied them using scanning electron microscopy (SEM) and infrared spectroscopy [?]. The breakdown channels contained more oxygen elements than original samples, as shown in [Figure 9: see original paper]. The composition of breakdown channels included more C=O and C-O groups than original samples. Kosaki et al. found that temperature affects DC electrical tree initiation voltage, with initiation voltages at 20°C and -196°C being 35 kV and over 50 kV, respectively [?]. Ieda et al. observed DC electrical tree lengths at different temperatures, finding that tree length increased with temperature under positive DC voltage [?]. Studies on DC grounded electrical trees at different temperatures found that tree length increased with rising temperature. As temperature increased, carrier mobility increased, making charges in deep traps easier to detrap, thus increasing tree length [?]. Temperature also affects tree morphology, with segmental relaxation at higher temperatures making it easier to form longer single-branch trees [?].

5. Methods for Suppressing Electrical Tree Initiation and Growth

Nanocomposites are novel materials formed by uniformly adding small amounts (typically below 10%) of nanoparticles to polymers. Most scholars believe that the interface regions formed between polymer matrices and nanoparticles in nanocomposites introduce numerous traps that alter trap energy levels in the composite, significantly affecting electrical tree growth [?]. Tianjin University studied the addition of polyoxyethylene (POE) to PP to improve toughness, but experiments found that PP/POE blends exhibited increased space charge accumulation. Adding nano-ZnO particles to PP/POE improved tensile strength while maintaining good mechanical toughness. Nano-ZnO particles increased trap energy level density in PP/POE, reducing charge injection and suppressing space charge accumulation. Compared with PP/POE blends, PP/POE/ZnO nanocomposites showed lower dielectric constants, along with improved breakdown strength and volume resistivity [?].

Montanari et al. studied charge trapping behavior in isotactic PP and syndiotactic PP nanocomposites with synthetic montmorillonite (MMT) nanoparticles. Compared with pure PP, nanocomposites showed significantly enhanced charge trapping capability, and reduced space charge accumulation under DC polarization fields indicated overall improved insulation performance [?]. MMT has a one-dimensional nanolayered structure. Harbin University of Science and Technology found that adding appropriate amounts of MMT to PE and PP could suppress electrical tree growth [?]. Analysis suggests that MMT suppresses electrical trees in PE and PP through similar mechanisms. On one hand, MMT primarily suppresses tree growth along the electric field direction; when trees grow to MMT layers, they cannot penetrate but must grow along the surface before bypassing the layers. On the other hand, MMT improves electrical tree resistance by altering crystalline size. Additionally, MMT addition transforms PP' s large crystals into lamellar structures, affecting the interface energy between crystalline and amorphous regions, increasing resistance to tree growth. The introduction of layered nanofillers explains tree growth suppression through both physical blocking and crystalline morphology changes, though distinctions between layered and spherical nanoparticles require further demonstration.

Current research shows that adding voltage stabilizers that can capture high-energy electrons in materials under strong electric fields can improve electrical tree resistance [?]. The mechanism of aromatic compound voltage stabilizers is illustrated in [Figure 10: see original paper] [?]. Since most aromatic compounds have high electron affinity, they are impacted and excited or ionized by electrons under strong electric fields, preventing polymer molecular chain damage and improving insulation performance. Excited aromatic compound molecules release energy harmlessly through luminescence or vibration and return to their original state, while positively charged free radicals formed by ionization are reduced by electron interaction. As most aromatic compounds have ionization energies lower than polymer chain bond energies, they can combine with high-energy electrons under high electric fields, significantly reducing injected electron energy in polymers and improving dielectric performance. Additionally, aromatic compounds can interact with already-ionized aromatic compounds and be reduced to their original state. Mechanistically, these voltage stabilizers are non-consumable and can function continuously, offering high research value. However, most existing research focuses on AC voltage conditions, and their effectiveness under DC voltage, particularly for polypropylene materials, requires further investigation.

S.S. Bamji et al. believe that trace amounts of oxygen in PE amorphous phases play an important role during electrical tree initiation and growth. Oxygen undergoes oxidation chain reactions with polymers, accelerating molecular chain breakage [?]. Antioxidant addition can inhibit these oxidation chain reactions in polymers, thereby suppressing tree growth. Y. Sekii et al. studied the effects of phenolic and sulfur-based antioxidants on DC grounded electrical tree initiation characteristics in XLPE, finding that phenolic antioxidants had no significant effect on initiation voltage, while sulfur-based antioxidants increased initiation voltage [?]. During grounding, antioxidants functioned similarly to traps by capturing charges, thus suppressing trees. Currently, research on electrical tree characteristics in antioxidant-added polypropylene composite insulation materials is limited, and whether antioxidants can suppress tree growth in polypropylene requires further study.

6. Conclusions

Comparison with XLPE reveals that electrical trees are more difficult to initiate and propagate in PP. When polarity change processes exist in DC-pulse combined voltages, electric field distortion caused by space charges intensifies tree growth. Within a certain range, temperature increases accelerate tree growth, but when approaching PP' s melting temperature, tree growth slows. Additionally, many issues regarding electrical trees in environmentally friendly HVDC cable polypropylene insulation require further investigation. Due to complex DC cable operating conditions, electrical tree growth characteristics and mechanisms under multi-physical field coupling require further study. Meanwhile, the effects and failure mechanisms of voltage stabilizers and antioxidants remain unclear, particularly their effectiveness under DC voltage, which requires further research.

References

[10] Du B X, Li Z L, Li J. Effects of direct fluorination on space charge accumulation in HTV silicone rubber[J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2016, 23(4): 2353-2360.

[13] Chen G, Hao M, Xu Z, et al. Review of high voltage direct current cables[J]. Csee Journal of Power & Energy Systems, 2015, 1(2): 9-21.

[14] Stancu C, Notingher P V, Notingher P, et al. Space charge and electric field in thermally aged multilayer joints model[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2016, 23(2): 633-644.

[15] Kosaki M, Nagao M, Shimizu N, et al. Solid insulation and its deterioration[J]. Cryogenics, 1998, 38(11): 1095-1104.

[16] Shimizu N, Shibata Y, Ito K, et al. Electrical tree at high temperature in XLPE and effect of oxygen[C]. IEEE Report Conference on Electrical Insulation and Dielectric Phenomena, 2000: 329-332.

[17] Danikas M G, Tanaka T. Nanocomposites-a review of electrical treeing and breakdown[J]. IEEE Electrical Insulation Magazine, 2009, 25(4): 19-25.

[18] Ieda M, Nawata M. A consideration of treeing breakdown in polymers[C]. IEEE Annal Report Conference Electric Insulation and Dielectric Phenomenon, Tokyo, Japan, 1972: 143-150.

[19] Du B X, Zhu L W, Han T. Effect of low temperature on electrical treeing of polypropylene with repetitive pulse voltage[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2016, 23(4): 1915-1923.

[20] Holto J, Ildstad E. Electrical treeing in extruded polypropylene high voltage cable insulation[C]. IEEE International Conference on High Voltage Engineering and Application, 2010: 373-376.

[21] Holto J, Ildstad E, Lunde I. Characteristics of electrical treeing in extruded polypropylene and cross-linked polyethylene cable insulation[C]. IEEE International Conference on High Voltage Engineering and Application, 2012: 63-67.

[22] Hagiwara M, Akagi H. Control and experiment of pulsewidth-modulated modular multilevel converters[J]. IEEE Transactions on Power Electronics, 2009, 24(7): 1737-1746.

[23] Murata Y, Katakai S, Kanaoka M. Impulse breakdown superposed on ac voltage in XLPE cable insulation[J]. IEEE Transactions on Dielectrics & Electrical Insulation, 1996, 3(3): 361-365.

[24] Liu Y, Cao X L. Electrical tree initiation in XLPE cable insulation by application of DC and impulse voltage[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2013, 20(5): 1691-1698.

[25] Nota F, Yoshimura N, Oota T. Tree initiation in polyethylene by application of DC and impulse voltage[C]. IEEE International Conference on Electrical Insulation, 1976: 205-208.

[26] Iddrissu I, Rowland S M. The impact of DC bias on electrical tree growth characteristics in epoxy resin samples[C]. IEEE Conference on Electrical Insulation and Dielectric Phenomena, Piscataway, NJ, USA, 2015: 876-879.

[27] Liu M, Liu Y, Li Y, et al. Growth and partial discharge characteristics of electrical tree in XLPE under AC-DC composite voltage[J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2017, 24(4): 2282-2290.

[28] Du B X, Zhu L W, Han T. Effect of ambient temperature on electrical treeing and breakdown phenomenon of polypropylene with repetitive pulse voltage[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2017, 24(4): 2216-2224.

[29] Kosaki M, Nagao M, Shimizu N, et al. Solid insulation and its deterioration[J]. Cryogenics, 1998, 38(11): 1095-1104.

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[30] Ieda M, Nawata M. DC treeing breakdown associated with space charge formation in polyethylene[J]. IEEE Transactions on Electrical Insulation, 1977, EI-12(1): 19-25.

[31] Kaneko K. Effect of space charge on the breakdown strength under polarity reversal[J]. Electrical Engineering in Japan, 1986, 106(3): 565-572.

[32] Liang H, Du B, Li J, et al. Numerical simulation on the surface charge accumulation process of epoxy insulator under needle-plane corona discharge in air[J]. Iet Science Measurement & Technology, 2018, 12(1): 9-16.

[33] Tanaka T. Space charge injected via interfaces and tree initiation in polymers[J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2001, 8(5): 733-741.

[34] Tanaka Y, Kodera R, Kato T, et al. Observation of space charge accumulation behavior in cross-linked polyethylene at voltage polarity reversal[C]. IEEE Conference on Electrical Insulation and Dielectric Phenomena, Ann Arbor, USA, 2015: 23-26.

[35] Wang Y, Li G, Wu J, et al. Effect of temperature on space charge detrapping and periodic grounded DC tree in cross-linked polyethylene[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2017, 23(6): 3704-3711.

[36] Zhang Y, Zhang L, Zhou Y, et al. Temperature dependence of DC electrical tree initiation in silicone rubber considering defect type and polarity[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 2017, 24(5): 2694-2702.

[37] Luo Yang, Wu Guangning, Peng Jia, et al. Research progress on interface properties of polymer nanocomposite dielectrics[J]. High Voltage Engineering, 2012, 38(9): 2455-2464.

[38] Du B X, Xu H, Li J, et al. Space charge behaviors of PP/POE/ZnO nanocomposites for HVDC cables[J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2016, 23(5): 3165-3174.

[39] Montanari G C, Teyssedre G, Laurent C, et al. Charge trapping behavior of nanostructured polypropylene matrix[C]. IEEE International Conference on Solid Dielectrics, 2004, 2: 836-839.

[40] Zhang Huazhong, Li Jian, Liang Yong, et al. Growth properties of the electrical trees in LDPE-MMT nano-composites[J]. Proceedings of the CSEE, 2010, 30(31): 137-142.

[41] Chi Xiaohong. Study on structure morphology and electrical tree growth mechanism of montmorillonite/polyolefin composites[D]. Harbin: Harbin University of Science and Technology, 2015.

[42] Heidt L J. Solid dielectric polyolefin compositions containing various voltage stabilizers: U. S. , Patent 3, 522, 183[P]. 1970.

[43] Hunt G H. Cross-linked polyolefin compositions: U. S. , Patent 3, 632, 680[P]. 1972.

[44] Kisin S, Doelder J D, Eaton R F, et al. Quantum mechanical criteria for choosing appropriate voltage stabilization additives for polyethylene[J]. Polymer Degradation & Stability, 2009, 94(2): 171-175.

[45] Jarvid M, Johansson A, Bjuggren J M, et al. Tailored side-chain architecture of benzil voltage stabilizers for enhanced dielectric strength of cross-linked polyethylene[J]. Journal of Polymer Science Part B Polymer Physics, 2014, 52(16): 1047-1054.

[46] Ashcraft A C, Eichhorn R M, Shaw R G. Laboratory studies of treeing in solid dielectrics and voltage stabilization of polyethylene[C]. IEEE International Conference on Electrical Insulation, Montreal, 1976: 134-138.

[47] Bamji S S, Bulinski A T, Densley R J. Evidence of near-ultraviolet emission during electrical-tree initiation in polyethylene[J]. Journal of Applied Physics, 1987, 61(2): 694-699.

[48] Bamji S S, Bulinski A T, Densley R J, et al. The role of antioxidants on polymeric dielectrics[C]. IEEE International Symposium on Electrical Insulation, 1990: 37-41.

[49] Sekii Y, Kawanami H, Saito M, et al. DC tree and grounded DC tree in XLPE[C]. IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Nashville, America, 2005: 523-526.

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