

Reliable and environmentally friendly material HVDC cable insulation based on electrical tree: a progress and challenges

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ABSTRACT

This research collects, summarizes, and explores over two hundred significant publications regarding various causes, triggers, and advances in monitoring extruded power cables, especially improvements in insulation materials under DC voltage due to electrical treeing (ET). Four research facets are the main topics of this review due to ET under DC voltage: influencing factors, various available and development techniques for improved insulation materials, physical lifetime models when ET occurs, and material recycling challenges. Several reviews and analyses have already been conducted on extruded power cables regarding ET. However, most reviews focus on the factors causing ET; some also discuss techniques for observing ET under AC voltage and developing insulation materials only, while others do not provide a comprehensive review. In contrast to previously published reviews, this paper highlights several key factors, including the causes of preconditions. It triggers for ET, leading to improvements in insulation materials, physical lifetime models that accommodate ET under DC voltage, and the potential for recyclable insulation materials. This review also provides the latest position and developments in the causes of ET, material improvement, insulation lifetime, and material recycling. This might serve as a reference for researchers looking to learn more about the real impact of these topics in the field.

Keywords: *Environmentally Friendly material, DC cable insulation, Electrical treeing, Green energy, Physical lifetime model*

1. INTRODUCTION

Air pollution and global warming are world problems that are of serious concern now and in the future. To overcome this problem, various countries are targeting NZE energy in 2050 [1], [2], [3], [4], [5], [6], [7]. Apart from that, the need to increase power transmission capacity and distance [8], cheaper for longer transmission and low losses [9], [10], [11][12], solve interconnection problems [13], all of these problems can be overcome with HVDC technology. This is proven by the significant increase in Patent HVDC transmission technology compared to HVAC transmission technology [14], and it is concluded that the best route for the energy transition is through HVDC transmission systems. [11]. However, due to the limited number of HVDC connections, the understanding of the cable aging process under HVDC insulation is more limited compared to HVAC.

In several surveys of electrical systems in various countries, cable insulation often has the highest failure rate [15], [16], [17], [18]. With the earliest articles reportedly appearing in 1912, electrical treeing (ET) is one of the most crucial physical lifetime indicators of internal damage to cable insulation by high electrical stress [19]. Apart from that, ET has become a critical issue in achieving the best properties of XLPE cables [20] and needs to be a primary concern and key to reliable insulation materials [21][22]. However, ET in HVDC is not well understood, unlike ET in HVAC, which is

well-documented [23]. Amid these limitations, it does not mean that reliability can be ignored, but it is a challenge to realize environmentally friendly energy transmission under DC voltage.

This problem must be handled comprehensively, starting before and after ET occurrence. Handling before ET occurs can be done when making materials or observing preconditions and triggers for ET. Handling after ET occurs can be done by studying the lifetime model of DC cable insulation, which is in line with the concept of reliability during the Industrial Revolution 4.0, which is very dependent on the age of the equipment [24], [25], [26], [27], [28], [29]. There are two models of DC cable insulation lifetime: physical and phenomenological. Physical lifetime models offer accuracy in calculations but have complexity due to careful consideration of physicochemical processes in insulating materials. Meanwhile, the phenomenological lifetime model simplifies calculations, but the results are less accurate because it includes a black box model between isolation stress and age. Due to its accuracy, direct impact on the insulation material, and ability to accommodate ET phenomena, this review will focus on physical life models [30][31]. However, in the end, insulation failure cannot be avoided, so this research will also discuss the challenges of recycling insulation materials.

This comprehensive treatment is not yet available in the literature; therefore, this research will investigate this gap. Previous research on this problem has been carried out separately. Still, a comprehensive study has not been conducted, especially investigating the causes of ET, material improvement, physical lifetime due to ET, and recycling polymer insulation materials under DC voltage. Recently, such partial studies have been proposed and improved. In this regard, a thorough discussion and connection are required. Numerous evaluations have been written and made available in the literature, covering particular themes and facets of the causes of ET [32], [33], [34], material improvements due to ET [34], [35], [36], [37], physical lifetime models [4], [18], [30], [38], [39], [40], [41], and recycling [42], [43], [44], [45]. This final study includes a comprehensive review of the causes of ET, material improvement, physical lifetime models, and recycling of HVDC extruded power cable materials.

The motivation of this paper is to review recent developments and trends toward a comprehensive evaluation of ET-causing polymer extrusion power cables, material improvements, the physical lifetime model under DC voltage, and the recycling of insulation materials. The causes of the precondition and trigger phenomena for ET are highlighted in this review, which focuses on works from the recent few decades, various insulation material improvement techniques, physical lifetime models for insulation, as well as the challenges of environmentally friendly materials in the form of recycling. In addition, a taxonomy of some of the approaches used in the literature is presented in this review, highlighting pertinent gaps and providing a basis for further investigation.

2. ET IN DC CABLE INSULATION

The reliability of DC cable insulation depends heavily on when the material was made, which is expected to have a lifetime design of 40 years. In general, the comprehensive lifetime cycles of DC cable insulation can be seen in Figure 1 below.

In Figure 1, the lifetime of DC cable insulation after production, namely aging, degradation, and breakdown until recycling, is influenced by the Thermal, Electrical, Environment/ Ambient, Mechanical stress [46], [47], [48], [49], [50], [51], [52] and space charge accumulation [53], [54], [55], [56] (TEAMS). Where t_p is during the production process, t_0 was the new cable/insulation sample material that has been made, then small voids appear at t_1 and void growth at t_2 . As for PD appearing in t_3 , t_4 is the ET phenomenon occurrence, breakdown occurs in t_5 , and t_r is the recycling process carried out.

As time goes by, these factors will decrease the dielectric insulation strength; then, voids appear until partial discharge (PD) occurs [57]. Following its appearance, PD will cause degradation phenomena until failure occurs. When designing cables, ET is a significant worry for high-voltage insulation and an intriguing degradation event. The remaining useful lifetime (RUL) of the insulation in DC cables will be accelerated by these degrading phenomena. The preconditions factor (TEAMS) and triggers of ET occurrence will be discussed below.

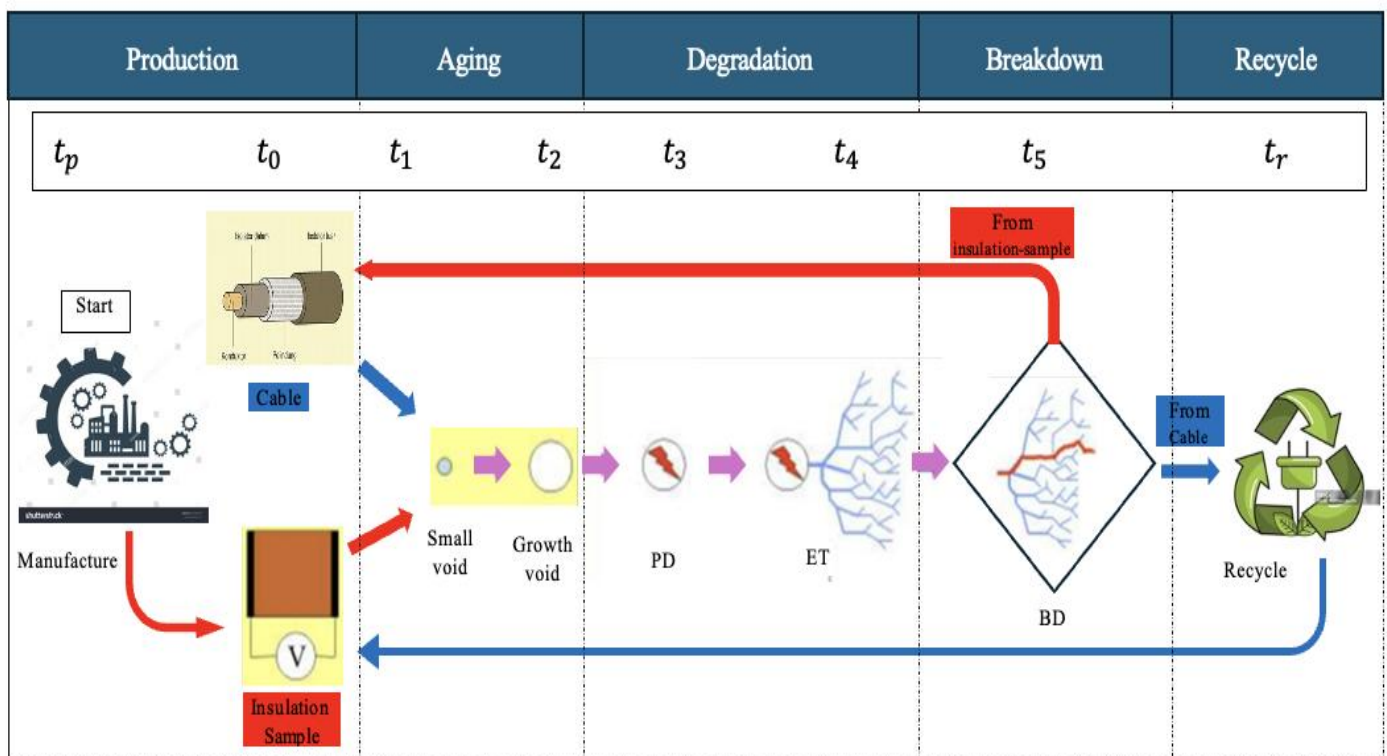


Figure 1. Comprehensive lifetime cycles of power cable [33], [35], [41]

2.1. Precondition Factors of ET Occurrence

In Figure 1, TEAMS affects the lifetime of DC cable insulation. Between the material production and ET occurrence, several stages are identified, including nanovoid, micro void, PD, and finally ET. This subchapter discusses the influence of each TEAMS on the preconditions of ET occurrence. Various studies related to the impact of thermal increase will weaken the strength of insulation such as tensile strength, dielectric strength, and volume resistivity decrease [58]; volume resistivity decrease and $\tan \delta$ increase [59]; crystallinity decrease, and carbonyl index increase [60]; the trapped charge associated with the appearance of oxidized species, crystallinity rate variations, and cross-linking byproducts [61]; decrease in mechanic strength [62]; defect insulation (crystallinity) impact to leakage current, and trapped charge affected by thermos-oxidation degradation (carbonyl groups) [63]; the characteristics of the material and promote the accumulation of space charges and the increase in trap energy density. [64] This process causes samples to re-crystallize and re-degas, thereby enhancing the behavior of space charges and the charge carrier trapping phenomenon. Consequently, DC conductivity increases, and DC breakdown decreases [65]. Notably, the parameters of XLPE remain relatively stable before reaching the aging lifetime [66]. The electric field increase effect causes lifetime acceleration [67].

Then extreme ambient/environmental variations will also cause a rise in surface conductivity, flashover voltage decreasing, and the surface is no significant changes [68]; volume and surface resistivity, breakdown strength, elongation, and tensile strength at break are decreasing behaviours. In contrast, degradation in an arid desert climate occurred more quickly than in a coastal environment [69]; mechanical strength declines and this decline is more noticeable than the rise in temperature aging [62]; humidity increase will accelerated DC flashover voltage (surface charge) and shot time occurs [70]; While the shallow water and super deep water sea trials are scheduled for 2023, the deep water sea trial has already been successful [71]. Then, increasing the mechanic parameter effect causes lifetime acceleration [67]. Space charge (SC) has the potential to directly or indirectly impact

accelerated degradation and failure of insulation. In addition, it affects the design, functionality, and dependability of insulating systems [72]; it seems to be an ageing condition sensitive and evolving uniformly under all ageing situations, although at varying kinetics [73].

Apart from that, there are also multi-stress effects, namely space charge and temperature gradient increase effect to accelerates the injection and migration of homocharge near inner semi conductive and electric field increase, and electric field decrease affected by polarity reversal affected by electron injection and carrier recombination [74]; thermal gradient in jointing cable causes change occurs to SC distribution, charge trap, charge mobility, charge transport [75]. Thermal and electrical increases may lead to increased capacitance, which may be related to the formation of carbonyl groups. $\tan \delta$ increases, SC variations over time appear to be sensitive to aging conditions, volume resistivity does not show significant evolution [73]. Electric and thermal causes of SC sensitivity accelerate the lifetime of coaxial cables [76]. Mechanical and thermal increases cause accelerated aging of insulation, which is affected by microstructure and ultimately damaged [77].

2.2. Triggers Causes of ET Occurrence

TEAMS generally only causes normal aging of the insulation. At the same time, ET occurs due to triggering factors such as AC/DC voltage, voltage level (VL), resistance grounded (RG), grounded, periodic grounded (PG), temperature gradient (TG), harmonic, High temperature superconducting (HTS), combination and increase of TEAMS stresses, space charge (SC), lightning impulse (LI), switching surges (SS), polarity, short circuit (SHC). Before and when ET occurs, it will be accompanied by various phenomena in aging and insulation degradation, such as breakdown voltage strength (BDV) decrease, Self-Healing (SH), partial discharge (PD), electroluminescence (EL), SC, polarity, PD, chemical degradation (crystalline, carbonyl, oxidation), and others. Generally, there are three stages to the ET growth process under DC and AC voltages: initiation, propagation, and runaway [33]. Table 1 summarizes various trigger factors, accompanying dielectric properties, and growth of ET in DC cable insulations.

Table 1 Trigger factors, accompanying dielectric properties, and growth of ET in DC cable insulation

Trigger	Material	Effect on dielectric properties	Effect on ET growth			Ref
			Int	Prp	Rnw	
AC/DC, VL	LDPE	PD, SC, polarity, conducting, and non-conducting of ET	✓	✓	✓	[23]
VL, RG	XLPE	Discharge characteristic	✓	-	-	[78]
TG, RG, temperature	XLPE	SC, BDV	✓	-	-	[79]
TG, Harmonic	EPDM	Polarity, conductivity, electric field distribution	✓	✓	-	[80]
PG, Temperature	XLPE	SC, SH	✓	-	-	[81]
Harmonic, HTS	XLPE	Polarity, +DC bias	✓	✓	-	[82]
TG, harmonic, radical scavengers	XLPE	Polarity, SC	✓	✓	✓	[83]
Harmonic	XLPE	PD	✓	✓	-	[84]
Electric, thermal	PVC	Multi-scale analysis: micro meso, macro	✓	✓	-	[32]
Polarity, grounding	XLPE	SC, energy dissipation, stored energy	✓	-	-	[85]
SHC, VL	XLPE	Stored energy, electromechanical stresses	✓	-	-	[86]
Disturbed DC waveforms	XLPE	Microscopic observation, PD	✓	✓	-	[87]
AC and DC divergent field	Epoxy resin	EL, electrical degradation: intensity, UV, PD	✓	-	-	[88]

Trigger	Material	Effect on dielectric properties	Effect on ET growth			Ref
			Int	Prp	Rnw	
SC detrapping, PG, temperature	XLPE	Tree mechanism: initiation rate, length, width	✓	✓	-	[89]
SC, PG, Temperature	XLPE	Polarity, charge mobility	✓	✓	-	[90]
TEMS	Polymer	Review: EL, PD, ET formulation, ET model	✓	✓	✓	[91]
TEM	Polymer	PD, RUL insulation	✓	✓	✓	[92]
TEMS, grounded, LI, SS, AC/DC	Polymer	Review: chemical degradation, ET chemical process, PD	✓	✓	✓	[34]
TG, harmonic, $\pm$ DC	XLPE	SC, PD, polarity	✓	✓	✓	[93]
LI, VL, grounded	XLPE	PD, SC	✓	✓	✓	[94]
AC/DC, $\pm$ DC, VL	XLPE	PD, SC	✓	✓	-	[95]
VL, Thermal	XLPE	Charge injection and trapping	✓	✓	-	[96]
AC, DC	XLPE, SIR	PD-AC vs PD-DC, ET-AC vs ET-DC	✓	✓	-	[97]
$\pm$ DC, VL	XLPE	PD, SH in -DC, polarity	✓	✓	✓	[98]
AC, DC	Epoxy resin	EL, ET-DC vs ET-AC, PD, degradation insulation	✓	✓	-	[99]
AC, DC stepped	XLPE	SC, chemical degradation	✓	✓	-	[100]
TG,	EPDM	SC, conductivity and electric field distribution	✓	✓	-	[101]
Thermal	XLPE	PD	✓	✓	-	[102]
SC, DC superimposed pulsed electric	XLPE	microstructure damage, polarity	✓	-	-	[53]
VL, electrode shape, short cable	XLPE	PD	✓	✓	-	[103]
VL, DC-integrated current, SC	XLPE	Water tree	✓	-	-	[104]
Electric, thermal, ambient	XLPE	chemical reaction and degradation, ET and WT	✓	-	-	[105]
Thermal	XLPE	Aging, DC BD strength	✓	-	-	[106]
TEAM	XLPE	Aging and degradation in detail	✓	✓	✓	[33]

*Int: Initiation, Prp: propagation, Rnw: Runaway

Table 1 summarizes research in recent years regarding triggers that impact the dielectric properties and growth of ET in various DC cable insulation materials. When ET occurs, failure will generally take a short time. The diagnosis of ET inception remains a mystery to this day, prompting the use of various methods and the emergence of several theories, including Maxwell's electro-mechanical stress theory, charge injection extraction theory, charge trapping theory, and EL theory [34]. The causes of preconditions and triggers of ET have been discussed in this chapter, and improvements to insulation materials due to ET will be addressed.

3. IMPROVEMENT MATERIAL DC CABLE INSULATION

ET is a phenomenon that accelerates cable lifetime; when it appears, it will immediately cause insulation breakdown. Of course, to prevent this phenomenon, the emergence of ET

requires serious attention or prompt handling when it occurs. In the literature [21], [22], [37], [107], [108], [109], several techniques for improving insulation materials are presented, including manufacturing methods, grafting, self-healing, and voltage stabilizers, as illustrated in Figure 2. Each of these techniques will be discussed as follows.

3.1. Manufacturer of Materials

ET, as the primary phenomenon causing insulation failure, needs to be handled seriously. The best approach is to conduct treatment as early as possible during the manufacturing process of insulation materials, explicitly focusing on fillers, blends, purity/degassing, and annealing. The following is a recap of the manufacture of insulation materials and their effects on the occurrence of ET, as well as the decrease in dielectric properties, which serves as a sign of the inception of ET, presented in Table 2.

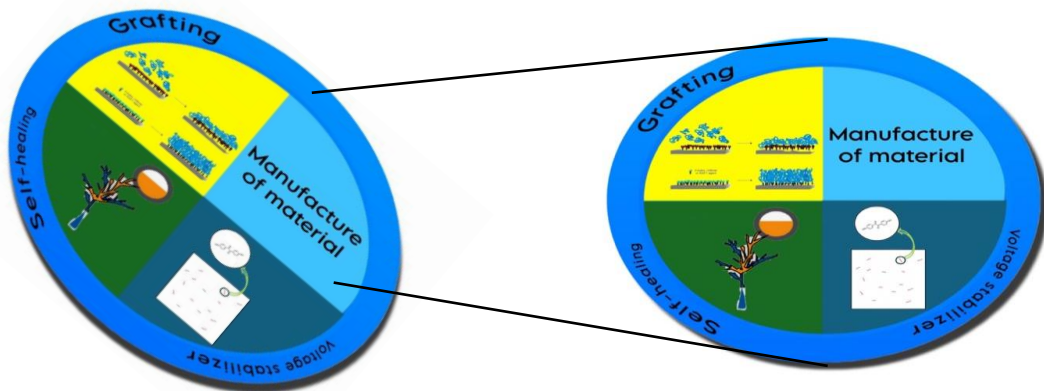


Figure 2. Various strategies for improving insulation materials due to ET [110], [111], [112], [113]

Table 2 Manufacture of materials effect to dielectric properties and ET in DC cable insulation

Enginnering improvement	Material	Effect on dielectric properties	Effect on ET	Ref.
Filler (ZnO)	XLPE	DC breakdown strength, polarity reversal	-	[114]
Filler (MgAl2O4, CaCO3, CaCO3T)	PP	DC breakdown, Thermally aging	-	[115]
Filler (glycidyl methacrylate acrylic acid)	LDPE	DC conductivity, activation energy, dielectric response, and losses, trap energy distributions	-	[116]
Filler (miscellaneous)	XLPE	Comprehensive of ET and chemical degradation	√	[34]
Filler (MgO)	Polymer	Morphology & structure insulation, trap characteristic, conductivity, SC, BD	-	[117]
Filler (2D platelet variation)	silicate XLPE	SC, permittivity, quasi-DC process & relaxation of charges trapped	-	[118]
Filler (miscellaneous)	Polymer	Physical & chemical insulation, cold plasma treatment, PD, BD strength	√	[119]
Filler (miscellaneous)	Polymer	Under high thermal conductivity: aging, TG, structure design insulation	-	[120]
Filler (OVPOSS)	EPDM	Chemical reaction process, Inception probability of ET, Trap distribution and carrier mobility behaviours, 3D electrostatic potential and density of behaviours	√	[121]
Filler (miscellaneous)	PE, PVC	DC & Impulse breakdown strength, Permittivity, Conductivity, and Dielectric Loss, PD	√	[107]
Filler	Polymer	Insulation filler & geometry, BD probability	√	[22]
Filler (miscellaneous)	Polymer	Making process, electrical conductivity, permittivity and loss Factor, PD, SC, electrical breakdown, WT	√	[37]
Filler (MgO)	XLPE	Grounded, SC	√	[122]
Filler (miscellaneous)	PE, PP	Hard/soft interface, trap-modulated carrier energy and electrical breakdown, DC breakdown and corona-resistance	-	[123]
Blends (POE)	PP	BD and Mechanical strength	√	[124]
Blends (iPP, sPP, aPP)	PP	Crystallinity, dielectric constant and losses, DC breakdown characteristics, Trap level characteristics	-	[125]
Blends (HDPE)	LDPE, XLPE	Crystalline, nanostructure correlates in DC conductivity	-	[126]
Blends (HDPE)	LDPE	Trap energy levels & Crystalline morphology, BD probability	√	[21]
Blends (HDPE, LDPE)	LDPE, PP	Crystalline, charge injection, trapping, transport, BD, lifetime	√	[127]
Degassing	XLPE	Crosslinking byproducts effect, crystallinity and degree of crosslinking, DC conductivity	-	[128]
Degassing	XLPE	Under EHVDC: heat flow, crystallinity, byproduct, weight loss, oxidation, tensile, current density, SC, BD	-	[129]
Degassing	XLPE	Under EHVDC: tensile strength, Heat flow and crystallinity, SC, current density, DC BD strength	-	[112]
Annealing process	PP	Crystal, heat flow, SC, DC conductivity, DC BD strength	-	[130]
Annealing process	XLPE	Aging, SC and conductivity decrease	-	[131]
Annealing process	PP	Crystalline, SC, low-temperature brittleness	-	[132]

In Table 2, several methods are presented to enhance material reliability in terms of both dielectric properties and ET. When the dielectric properties weaken, the insulation will also weaken and trigger ET to occur. There are numerous possibilities for enhancing this material, including filler materials, material composition, and improvement techniques. Consequently, this improvement process requires considerable time, cost, and energy. Therefore, in carrying out experiments and testing the number and treatment of samples taken to be efficient, the Taguchi method can be used [133], [134], [135], [136], [137].

3.2. Grafting

The gradual substitution of synthetic or modified natural materials for natural ones is one of the trends in modern civilization. Modern polymers require their properties to be altered to meet custom requirements created for the intended use. Covalent bonding, or the modification of monomers to polymer chains, is known as grafting. Contrastingly, polymerizing a mixture of oligomers creates a layer physically bonded to the substrate during the curing process. [138].In [139], grafting applied to the semiconductive layer and XLPE insulation is discussed. Then, tests are carried out to reduce the effect of space

charge, which can trigger treeing and significantly affect the DC XLPE power cable's reliability. The experimental treatment samples have three forms, namely, no graphene, graphene on the semiconductive layer, and graphene on the XLPE and semiconductive layer. The results obtained showed a reduced effect of SC as measured using the PEA technique. However, a drawback of this study is that the graphene layer can be easily removed from the Semiconductive surface, which can have a negative impact on SC accumulation. Therefore, further research is needed to prevent this problem and improve coating efficiency. So, in another report, it is not surprising to find that XLPE material has better performance on mechanical, electrical, SC, and water tree properties when doped with a small amount of graphene [140].

In addition, grafting was also carried out on PP with methyl methacrylate (MMA) material. The research was carried out by treating variations in temperature settings and MMA composition. The findings suggest that elevated temperatures can facilitate the ET process, and the properties of the traps reveal the introduction of more deep traps in the grafted materials, which can constrain electron transportation and, in turn, the commencement and ET growth. The results of this study will be used as a guide when creating power cable grafted PP insulation. [141].

Antioxidant grafting on PP material is also carried out with the monomers di benzylidene acetone, 2'-hydroxychalcone, and 2-(2-hydroxy -3-tert-butyl-5-methylbenzyl) -4-methyl-6-tert-butylphenyl acrylate (A03052). Test temperature settings are carried out at varying temperatures. The results obtained show that DC conductivity decreases, SC accumulation decreases, DC breakdown increases (after heteropolar pre-stressing), and trap level distribution increases. Thus, antioxidant grafting, which is anticipated to be used on PP-insulated cables, can significantly improve PP's SC and breakdown characteristics. [142]. Finally, graphene oxide quantum wells research was carried out on the surface of XLPE material by chemically grafting the polycyclic aromatic compounds. The results obtained were lower DC conductivity, less SC accumulation, and increased strength of DC breakdown compared to pure XLPE [143]. Additionally, paying attention to the effect of polarity reversal on the above characteristics yielded satisfactory results [144].

3.3. Self-healing

Self-healing (SH) dielectrics can replace degraded characteristics and cure internal damage, prolonging the material's service life by emulating biological systems that can self-heal wounds to improve survival. SH research on polymers has recently gained significant attention in various fields, including high voltage insulation, particularly in the context of ET in HV insulating polymers. There are many SH methods currently, namely conventional, new strategies, and potential future mechanisms. Generally, SH for insulation currently employs a new strategy involving four schemes: defect-targeted superparamagnetic heating for remolding multiscale damage, in situ EL for autonomous SH of ET, anionic polymerization for SH dielectric polymers, and SH at polymer thin-film electrical breakdown [145].

The research involved autonomously triggering in situ electroluminescence in SH dielectrics via UV-shielding shell microcapsules (polyurea-formaldehyde), which can be generated by ET. This process allows the ET trajectory to be attracted by microcapsules with a high dielectric constant, facilitating the repeated repair of ET damage. The healing agent material consists of TiO₂, trimethylolhexane triacrylate, 1,6-hexanediol diacrylate, tripropylene glycol diacrylate, 1-Hydroxycyclohexyl phenyl ketone via one-step pickering emulsion polymerization. The results obtained by the insulation material were successful healing after treeing, and the probability of insulation failure was better than when treeing or insulation occurred at the start of production [146]. Other research highlights SH and the problem of recyclability in insulation materials by developing polymers from an intrinsic structure with the design and synthesis of recyclable and self-healing polyimide (RSPI) film materials using an amino-terminated polyimide prepolymer. The results obtained by the RSPI film have a similar pattern to the original FT-IR RSPI; the probability of breakdown strength of RSPI after electrical damage only slightly decreases, and the SH after mechanical and electrical damage of the RSPI film only experiences a slight decrease [147].

Finally, SH research was carried out on PE material with ethylene-anisylpropylene as a copolymer. Tests were carried out on thermal properties, mechanical properties, and material characteristics of the electric field (volume and resistivities, high voltage: surface discharge, breakdown voltage). The results obtained for the thermal properties demonstrate the tested material's steady thermal characteristics in its pristine state. Furthermore, the mechanical SH efficiency obtained for the pristine material and the 1st – 3rd break is all above 30%. As for electricity, the materials tested showed comparable surface and volume resistivity to other insulating materials. High voltage testing is consistently demanding on whatever material and ultimately causes structural damage (electrical damage). Further research is needed to enhance the material and high-voltage test techniques. Though this hasn't been demonstrated with many specimens, the SH material studied nevertheless showed that it partially regained its insulating properties. [148].

3.4. Voltage Stabilizer

Adding some organic aromatic compounds, sometimes called voltage stabilizers, is another method of enhancing dielectric characteristics. Due to their low ionization potential and strong electron affinity, voltage stabilizers can disperse the energy of energetic electrons. On the other hand, low-weight molecular stress stabilizers often suffer from the issue of migrating to the polymer surface, which is detrimental for long-term use at high temperatures. To keep the polyolefin at a high DC breakdown strength level for an extended period, the reactive stress stabilizer 4-acyloxy acetophenone (AAP) was employed. This was accomplished by grafting AAP onto the LLDPE backbone using a straightforward technique. After heat-treating samples for varying durations at 60 °C, the DC breakdown strength of the grafted samples was found to be significantly greater. High DC breakdown strength was also seen in the pure grafted samples, indicating that the grafting approach may sustain AAP. Rheological data, meanwhile, demonstrated the grafted materials' robust processability [149]. The other research discusses fullerenes (voltage stabilizers) in XLPE materials using Buckminsterfullerene (C₆₀) and phenyl-C₆₁-butyric acid methyl ester (PCBM). The results obtained indicated that PCBM was the best voltage stabilizer material in terms of reducing the chance of failure due to treeing compared to neat XLPE and C₆₀ [150]. Jarvid., et al. investigated graft tension stabilizers with alkyl side chains to increase their solubility with polymers, which showed excellent results [151]. However, this technique does not effectively stop the voltage stabilizer from migrating. Connecting them with nanoparticles is one possible strategy to stop voltage stabilizer migration. [152].

Then, research was carried out on voltage stabilizers, which were divided into three groups based on distinct methods that prevent the start of the electric tree: PD inhibition, high-energy electron capture, and macromolecular degradation inhibition. Much recent research on voltage stabilizers has focused on pertinent topics such as alkylated voltage stabilizers, quantum chemical calculations, and the combined use of voltage stabilizers and nanoparticles. [110]. The effectiveness of voltage stabilizers in enhancing

DC breakdown strength and DC power tree resistance is noteworthy, as they inhibit space charge accumulation of polymer insulation, including PE and PP. Further research is necessary to understand how voltage stabilizers affect charge transport behavior in polymer insulation and how to employ them to control charge transport [36]. To determine the voltage stabilizers' effect on SC, research was carried out by Du et. al. in the next year [153]. In its paper, a voltage stabilizer that has excellent compatibility with XLPE is used to suppress SC (which is the most serious problem in HVDC cables) in XLPE insulation. Three different tension stabilizers, 4,4'-Difluoro benzophenone, 4,4'-Dihydroxybenzophenone, and 4,4'-Bis (dimethyl amino) benzyl, respectively, were included in the XLPE material at a 0.5% additive content. Various dielectric properties tests were carried out, and the results obtained showed a good ability to suppress SC in XLPE insulation, namely, less SC accumulation and faster dissipation of SC than pure XLPE.

Finally, discussed voltage stabilizers combined with nanofillers in insulation materials. The first examines the interfacial effect of inorganic nano-SiO₂ and the voltage stabilizer m-aminobenzoic acid (m-ABA-SiO₂) into cycloaliphatic epoxy (CE) Resin to capture high-energy electrons through collisions. The results obtained by the damage field strength of m-ABA-SiO₂/CE reached 53 kV/mm (40.8% higher than pure CE). Likewise, the volume resistivity and tensile strength of glass transition temperature increase significantly. This work shows the great application potential of m-ABA-SiO₂ as a nanocomposite and voltage stabilizer in high-voltage insulated electrical equipment [154]. Second, experiments reveal that material stress stabilizers with certain treatments show great promise for use in HVDC cable applications to minimize ET. Polycyclic compounds to PP can effectively inhibit the degradation of power trees, which

have excellent potential for application in recycling HVDC cables [155]. Finally, research was carried out on PP insulation accompanied by SiO₂ and a voltage stabilizer. The results obtained show a significant increase in breakdown strength of 46%. Apart from that, surface potential decay, crystallinity, and super molecular nanocomposite with improved electrical properties were also obtained. These results show the potential for developing environmentally friendly HVDC cable insulation using voltage stabilizers and nanocomposites [156].

4. PHYSICAL LIFETIME MODELS DUE TO ET

The phenomenological lifetime model development is much more developed than the physical lifetime model due to its simplicity. This appears not only to be used as a standard reference, but also, several contemporary issues can be resolved using this model, such as overstress, AC/DC hybrid systems, and degradation due to PD [41]. In fact, in recent years, phenomenological lifetime models have been combined with artificial intelligence (AI) [157][158][159][40]. However, in terms of accuracy and direct impact on the development of insulation materials, this can only be done with a physical lifetime model.

Lifetime models of physical or microscopic phenomena rely on the hypothesis that accelerated localized degradation due to microdefects is the primary cause of aging. They aim to describe local degradation as accurately as possible through physical-chemical mechanisms [41]. This modelling mechanism process causes the slow development of the physical lifetime model. Table 3 lists the variables used in the lifetime model, and there are several models included in this group presented in Table 4.

Table 3 Variables of lifetime models used in extruded power cables

Symbol	Information	Symbol	Information
T	Cable insulation temperature rate	N_{CH}	CH-bonds affected by the aging process
E	Electric field strength	R_{dis}	Damage growth rate in polymer
B	The quotient between the activation energy of the main thermal aging reaction (ΔW) and the Boltzmann constant (k_B)	w, k_1, k_2	Parameter of model
ΔG	Gibbs (free) activation energy of the main thermal degradation reaction	A^*	Critical fraction of degraded moieties A
C_E	Constant related to material characteristics	b_q	Parameter of SC storage characteristic
ε	Dielectric permittivity	d_c	Critical size of damage zone
ΔH	Activation enthalpy	t_{dis}	Time to disruption of a slab of thickness D_{dis}
Δ	The free energy difference between the degradation state and the reactants	R_{el}	Number of electrons hitting void–polymer interface
L	Lifetime	F_{hot}	Hot fraction of electrons
h_p	Planck constant	F_{eff}	Effective fraction of electrons
N_V	Insulation size	δ	elemental strain
b_{ET}	Parameter ruling the synergism between thermal and electric stress	V_{elm}	Elemental volume
C'	A constant that depends on the properties of the material	σ_s	mechanical or electromechanical stress
$A_{eq}(E)$	The equilibrium value between the backward and forward reactions A	l	Tree length
ΔS	Entropy per moiety	t	t_0 : new insulation, t_1 : small void, t_2 : void growth, t_3 : PD, t_{4-a} : tree initiation, t_{4-b} : tree stagnation, t_{4-c} : tree transition, t_5 : BD

Table 4 Physical lifetime model for DC cable insulation

Model	Stress	Formulation	Time to failure								Ref
			t_0	t_1	t_2	t_3	t_4	t_5			
Thermodynamic model (Endicott's)	TE	$L(E, T) = C_E T^{-w} e^{-\frac{\Delta G}{k_B T}} e^{-\frac{k_1 + k_2 E}{T}}$	-	✓	✓	✓	t_{4-a}	t_{4-b}	t_{4-c}	-	[30]
Thermodynamic model (Crine's)	TE	$L(E, T) = \frac{h_p}{2k_B T} e^{\frac{\Delta G}{k_B T}} \left(\frac{1}{2} \frac{\varepsilon \Delta V E^2}{k_B T} \right)$	-	✓	✓	✓	✓	-	-	-	[30]
Space charge-based models (DMM)	TES	$L(E, T) = \frac{h_p}{2k_B T} e^{\frac{\frac{\Delta H}{k_B} - \frac{C' E^{2bq}}{2}}{\tau} - \frac{\Delta S}{k_B}} \times \ln \left(\frac{A_{eq}}{A_{eq} - A^*} \right) \left(\frac{\frac{\Delta}{k_B} - C' E^{2bq}}{2T} \right),$	-	✓	✓	✓	✓	-	-	-	[160], [161]
Models based on PD-induced damage growth from micro voids	TES, void	$L = \frac{d_c}{R_{dis}},$ with $R_{dis} = \frac{D_{dis}}{t_{dis}}$ and $t_{dis} = \frac{N_{CH}}{2 R_{el} F_{eff} F_{hot}}$	-	✓	✓	✓	✓	-	-	-	[162], [163]
Electrical life model based electromechanical energy	TEM	$L = \frac{h}{2k_B T} \frac{e^{\frac{\Delta G - B \frac{1}{2} \alpha E^2 \delta V_{elm}}{k_B T}}}{\cosh \left(\frac{\Delta - B \frac{1}{2} \alpha E^2 \delta V_{elm}}{2k_B T} \right)} \ln \left(\frac{A_{eq}(\sigma_s)}{A_{eq}(\sigma_s) - A^*} \right),$	-	✓	✓	✓	✓	-	-	-	[67]
Mathematical model for Electric conductive ET growth	Electric	$\left\{ \frac{dl}{dt} = al^2 - bl + c. \quad l _{t=t_0} = 0, (a, b, c > 0) \right.$	-	-	-	-	✓	✓	✓	-	[164], [165]

Table 4 shows that the available physical lifetime models do not accommodate all TEAMS stresses. However, each of these models has a history dating back almost a century and a half, starting with Arrhenius in 1889, namely the influence of temperature on the rate of inversion of sucrose [166]. Research and research related to insulation continued [167], [168], [169], [170], [171], [172], [173], [174] to obtain a thermodynamic model. Likewise, the process of forming space charge-based models (DMM) [30], [46], [72], [160], [161], [175], [176], [177], models based on PD-induced damage growth from micro voids [30], [162], [163], [178], [179], [180], [181], [182], [183], [184], [185], and electrical life model based on electromechanical energy [67], [173], [186]. This is due to complexity, and care must be taken to pay attention to the physic-chemical reactions of the insulation in modelling. Apart from that, the lifetime model generally accommodates a time period for insulation that ranges from small void t_1 to several micrometers, which is assumed to be the initiation of treeing t_{4-a} . As for when t_{4-a} occurs, that time is also assumed to be the end of the cable's lifetime insulation. This is a result of the ET model's complexity, and when treeing is initiated, cable failure usually occurs shortly thereafter.

In 2022 [164][165], ET growth modelling was carried out, which was correlated with cable life from t_{4-a} to t_{4-c} . The conductive ET growth research, as degradation phenomena in the dielectric (related to PD) and mathematical modelling, were proposed in this regard. With the four assumptions [187], [188], [189]. The results of these assumptions are equivalent to the mathematical model formulation for conductive ET growth in the last row of Table 3. The solution of this model yields three types of solutions related to quadratic equation solutions, correlating to three cases for ET growth in dielectrics, i.e., the initiation case t_{4-a} , the propagation case t_{4-b} , and the runaway case t_{4-c} , which is then accompanied by verification/validation. Various current developments in insulation technology, including lifetime modelling, causative factors, and life cycles, as well as very rapid developments in insulation material engineering, make it possible to carry out improvement strategies, which are presented in Figure 3 below.

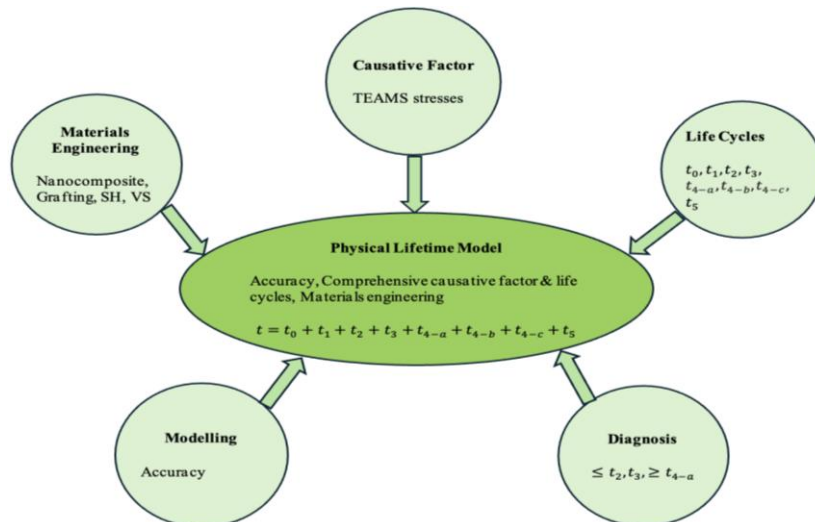


Figure 3. Development strategies for a comprehensive physical lifetime model

Figure 3 presents various strategies for technology development in the physical lifetime model of DC cable insulation. Causative factors consisting of TEAMS stresses are expected to be fully accommodated as input in the lifetime model. The lifecycle is designed to accommodate all lifecycle time components that need to be modeled. The modelling aims to enhance the accuracy of a formulation that represents the lifetime insulation phenomenon according to the lifecycle. Material engineering, both during the manufacture of the material, grafting, SH and VS, will impact the insulation's dielectric strength. This engineering needs to compare the insulation strength and lifetime of the model before and after material engineering. Diagnosis is required to determine the insulation condition according to the life cycle in real-time, where the PD signal is generally used as a benchmark ($\geq t_3$). Overall, this is expected to impact a physical lifetime model that is accurate, comprehensive, and accommodating of causative factors and life cycles, accompanied by improvements in materials engineering.

5. RESEARCH CHALLENGES

Research on extruded DC cable insulation is crucial for addressing the growing need for reliable and environmentally friendly energy distribution solutions, both now and in the future. This challenge has been discussed in various aspects [39]. Research that focuses on the lifetime of DC cable insulation has also been discussed [41]. Various efforts have been made, such as discussing the qualities of the best insulating materials for HVDC extruded cables, how the distribution of trap levels affects these qualities, and material development [36]. Other research discusses the need for XLPE nanocomposite materials that are resistant to PD, ET, and WT, as well as various materials as fillers and ways for recyclability [190]. This section will discuss the challenges of the latest research on DC cable insulation due to ET, self-healing, and lifetime. Ultimately, insulation failure cannot be avoided, so recycling of insulation materials will also be discussed.

5.1. ET on DC Cable

Research on ET on DC cable is still minimal compared to AC cable. The relationship between PD and ET is very close, so the PD diagnosis pattern can be used as an entry point to diagnose various degradation phenomena, especially ET efficiently. However, standards for observing PD under DC voltage are not yet available, let alone standards for observing ET under DC voltage. So, it is necessary to address the root of the problem above. Apart from that, ET observation technology is also a challenge in itself [102][191].

DC-Tree is more challenging to initiate and grow than AC-Tree. Until now, no standard has been available for experimental procedures for diagnosing ET under DC voltage. PD characteristics and ET growth under DC constant conditions at different temperatures were carried out using PD q-t histograms to evaluate the insulation status based on grey-level correlation. The increase in

temperature promotes the growth of ET and PD intensity, and the results reveal that the insulation status for XLPE insulation status based on this grey level correlation has high accuracy [102].

Prior studies have not encountered high-precision development, non-destructive, and three-dimensional (3D) in situ imaging technologies for micro-scale damage in polymers. The research conducted by [192] discovered that applying an electric field to silicone gel can generate an electric tree, which in turn triggers a self-excited fluorescence phenomenon. This method can perform successful high-precision, non-destructive, and 3D in situ fluorescence imaging of polymer flaws. This groundbreaking finding establishes the possibility of achieving accurate and non-destructive three-dimensional imaging of internal damage in polymers. This advancement can potentially address the challenge of visualizing internal damage in insulating materials and precision equipment.

5.2. Self-Healing Due to ET

Improving insulation material techniques, such as grafting, SH, and voltage stabilizers, can directly increase the strength of ET and indirectly enhance dielectric properties. The addition of filler is an improvement material that is commonly used today. Filler materials that function as SH agents will become trendy and in demand because they have a direct impact due to ET degradation, which has long been considered the end of a cable's lifetime. Challenges related to competitive degradation due to ET with SH, including electroluminescence (EL) as a trigger for SH, and the challenges of insulation materials that possess SH properties and are also self-adaptive dielectric (SAD) and self-reporting (SR), will be discussed in this research.

The competitive relationship between ET and SH in polymer insulation materials (epoxy resin) is discussed, divided into two stages: the first stage focuses on the design of self-healing (SH) strategies, while the second stage examines the functioning of SH polymers. The emphasis is on the effectiveness and consistency of SH, as well as the frequency of maintenance required for healing. The outcome achieved is an accelerated restoration of the insulating characteristics, as measured by the PD amplitude, detected while applying the suitable healing voltage. Nevertheless, the SH ability might be forfeited when the voltage exceeds a certain threshold, confirming the antagonistic correlation between electrical degradation and SH. These results are expected to be an initial reference for higher damage resistance due to ET and longer service time [193].

SH-generated EL was started by Biomimetic in 2001. The majority of polymer insulation problems are ET, and generally, the material cannot be SH. Gao et al. [146] conducted research on SH due to ET using microcapsule-TiO₂, which is unlike other research that uses external methods such as heat, pressure, and magnetic fields. However, this research has several limitations; the healing time takes 16 hours, and healing can only be done for ET smaller than 500 micrometers. Alternative design solutions

must be adopted since microcapsules used in thermoplastic matrices can potentially burst during processing. Then, in self-healing natural systems such as living cells, injured cells can substitute themselves for ones that are irreversibly damaged or damaged through self-replication. Regarding this, artificial SH polymers still have a long way to go. This can be corrected by changing the material composition to increase the EL intensity [194].

Finally, there are challenges associated with smart dielectric materials, namely SAD, SR, and SH. It is anticipated that smart dielectric materials, akin to dielectric creatures, will be developed and produced for next-generation electrical isolation with bioinspired and autonomous functionalities. Using smart materials lowers production and manufacturing costs while improving the electrical equipment's stability and durability [195].

5.3. Physical Lifetime Model

RUL prediction is necessary to ensure the reliability of DC cable insulation material, which can be achieved more accurately with a physical lifetime model than a phenomenological lifetime model. The physical lifetime model of DC cable insulation has three main problems: practicality and the assumption of homogeneous insulation, availability of standards, and models that do not accommodate various ageing and degradation factors.

This practical problem can be seen from the model generally applied to estimate the lifetime of full-size DC cables by referring to Cigre TB 496: 2012 [196] and TB 852: 2021 [197] using a phenomenological lifetime model. Due to the lack of data on DC cables, the improvement strategy carried out on AC cables by simulating directly on 3D large insulation towards breakdown is impossible [198]. Another strategy, using simple extrapolation and the assumption of homogeneous isolation, uses a phenomenological model that refers to international standards and shows validity beyond its scope [40]. So, in [199], an improvement in the lifetime estimation of full-size HVDC cable under electro-thermal transient caused by load cycles was carried out using the relevant DMM physical lifetime model with prequalification in Cigre TB 852. This was achieved by randomly examining elementary bonds in insulation through DMM kinetic equations, comparing the phenomenological lifetime parameters of the HVDC cable model with the physical lifetime model [200][201].

Apart from that, the standard problem in CIGRE TB 852:2021 [197] does not accommodate IEEE standard 1732:2017 [202] for SC measurements on HVDC cables and IEEE standard 2862:2020 [203] for PD DC cable measurements using a robust AC voltage test, and has been used for decades. This indicates an area for improvement in the physical lifetime related to testing standards, particularly SC and PD [204]. Finally, physical lifetime models that accommodate various ageing and degradation factors are also challenging for future research. In general, the ageing factor is TEAMS stress, while the degradation trend in current research is under time-varying electro-thermal stresses, thermal transients due to load cycles, temporary overvoltage TOVs, and steady state,

superimposed switching impulses SSIs, voltage polarity reversal VPRs [40][205]. However, the majority still rely on phenomenological lifetime models. Apart from that, improving the physical lifetime model, which accommodates the ET phenomenon without SH or with SH, is also a breakthrough in revealing the veil that is still tightly closed, along with the current development of insulation material technology. This discussion reveals significant areas for improvement in the physical lifetime model.

5.4. Recycle

The demand for reliable, cheap, and environmentally friendly transmission with higher power and voltage will challenge DC cable insulation material technology in the future. For this reason, various methods are used to find alternative materials that meet these criteria.

Recently, a review of the development of polymer HVDC cables was carried out regarding novel cable insulating materials that, in place of traditional XLPE, have high working temperatures, excellent performance, and are recyclable. Due to its outstanding qualities and potential for HVDC insulation, polypropylene (PP) has garnered a lot of interest. Key elements of PP-based nanocomposites for HVDC cable insulation were discussed in [54], emphasizing how different nanofiller parameters affect the dielectric characteristics of PP-based HVDC cable insulation. The challenge of HVDC cable insulation reliability has two main problems that must be resolved. First, the electric field inversion in HVDC cable insulation is caused by the polymer insulating material's temperature-dependent DC volume resistivity and electric field. Second, SC behavior under multi-field coupling, including charge injection, transport, accumulation, and dissipation characteristics. It is necessary to pay attention to the future with nanoparticle doping and recycling technology to overcome these two problems in future HVDC cables [206].

Thermoplastic PP as an alternative to HVDC insulation has become increasingly prominent and convincing in research in recent years. This is due to meeting the dielectric properties with nanofiller, recyclability, ease of processing, and the absence of by-products due to the crosslinked process, thereby minimizing SC accumulation and degassing costs [207]. Likewise, [42] discusses environmental friendliness, economics, and reliability of PP insulation for high voltage. As the core of electric power equipment and electric transportation assets, insulating materials face unprecedented challenges and opportunities. Although XLPE is the most popular HV cable insulation material to date, it fails to meet the requirements for reliable, cost-effective, and recyclable large-capacity power and voltage transmission, as well as sustainable development requirements. So, there is no doubt that the potential insulation material to support the 2050 carbon-neutral vision that meets sustainable development is thermoplastic PP [208].

6. SUMMARY AND FUTURE WORKS

Numerous research works on HVDC XLPE extrusion power cables explain that failure is often caused by ET.

Comprehensively, this needs to be handled before and after ET, starting from a comprehensive evaluation of polymer extruded electrical cables that cause ET, material improvements, physical lifetime, and recycling of insulation materials. Some of these studies have been reported previously, but further review of a comprehensive ET evaluation is needed. Preconditions and triggers of ET occurrence in DC cable insulation have been revealed in this review, focusing on handling before ET occurs, namely improving insulation material and diagnosis of ET, as well as after ET occurs, namely lifetime and material recycling. The study of DC cable lifetime due to ET has made its relevance to the issue of electric power transmission reliability, which is necessary in the era of Industrial Revolution 4.0 and an ecologically friendly system, have researchers interested in investigating it. The major conclusions of this review are outlined below.:

- Because DC voltage will be widely employed to support NZE, diagnosing ET-PD on HVDC cable insulation requires serious attention. ET is the primary phenomenon causing breakdown, which is often influenced by factors such as AC/DC, voltage level, grounding, harmonics, the combination and increase of TEAM stresses, space charge, lightning impulse, switching surges, polarity, and short circuit.
- PD pattern diagnosis can be used as an entry point to evaluate ET on HVDC cables. Hence, it needs to be carried out comprehensively, namely, the type, length, shape, and time of ET associated with the PD pattern. This diagnosis is essential so that the results are accurate and specific for the isolation condition. However, experimental standards for PD diagnosis at DC voltage are not yet available, so the journey for ET-DC diagnosis is still long and uphill.
- ET evaluation is helpful to improve materials that can be carried out during manufacturing, such as filler, blending, degassing, and annealing, as well as other methods, such as grafting, self-healing, and voltage stabilizer.
- Researching efficiency in improving material insulation, including the selection of accompanying materials, experimental treatment, and sample number, requires considerable time, cost, and energy; the Taguchi method can overcome this.
- Insulation materials before and after improvement need to be comprehensively compared, starting from the manufacture, the occurrence of PD, ET, and breakdown phenomena, to the recycling process.
- Self-healing after ET or breakdown has a significant impact on extending the lifetime of DC cables, so that it can be of concern to both microcapsule materials and self-healing agents for future research.
- Current physical lifetime models generally only accommodate time, from the time a small void occurs until it is assumed that ET is triggered. Despite its limitations, recent physical lifetime models are available for when ET occurs.
- Lifetime models before and after material improvement need to be compared, especially after treeing occurs, and the performance of the self-healing agent.

- In the end, insulation breakdown cannot be avoided by choosing insulation materials that can be recycled and reliable, such as PP, which is a potential material and seems to be a choice in the future.

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Competing Interests

I declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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