A Review: Polymer-based Insulation Material for HVDC Cable Application

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Abstract. Demand on the usage of HVDC cables in the past was very low, this is because at that time most its application is only for underwater cable installations. However, when there are an increased in demand for using renewable energy such as solar energy, the use of polymer-based as insulator material for HVDC became increased. This have attracted more cable manufacturers try to improve this cable quality and attract more market penetration in order make the development costs recoverable. This paper presents a review the used of polymer-based material for HVDC cable application. Comparison and discussion from previous researcher and manufacturer was done in term of material properties and quality was presented and discussed. The review was focused 4 types of polymer-based material which are: cross- linked Polyethylene (XLPE), low-density polyethylene (LDPE), high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE). Each material tests result were discussed for the best usage as HVDC insulation systems. The review found, polymer based material with additional of nana filler or difference type polymer can improve dielectric properties of HVDC cable insulator. This is because these material have very good indication of the conductivity and dielectric strength of high voltage insulation for HVDC application.

Keywords: HVDC Cables, Polymer-Based Insulation, XLPE, HDPE, LDPE, LLDPE

1. Introduction

The design of insulation is the most challenging issues for HVDC cable application. The design has the goals to develop materials with high electrical resistivity, high breakdown strength in particular superimposed impulse conditions and insensitive to temperature and polarity reversals.
Indeed, high thermal conductivity, low coefficient of thermal expansion, low dielectric constant are also the properties that this material must have and the production must at low cost to compete with other material. Nowadays, many researches try to improve performance of the insulation materials for high voltage application. This material was used as shield from conductor to the ground or to another conductor. Figure 1 show the typical HVDC extruded cables with an XLPE insulation system produced with copper or aluminum conductors. There are several type of polymer material that have been used as insulation material for HVDC cable. In this paper only 4 types of common polymer-based material for HVDC cable was reviewed. These 4 material are: cross-linked Polyethylene (XLPE), low-density polyethylene (LDPE), high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE). The objective of the review is to come out the best material usage for HVDC cable.

![Figure 1: Typical extruded HVDC cable](image-url)

2. Polymer as insulation material

The polyethylene (PE) is the simplest hydrocarbon in polymer and a typical example of synthetic polymer that obtained from the polymerization of ethylene. This polyethylene consists of linear, branched and cross linked polymers. The polyethylene commonly used for HV insulation process is XLPE which is LDPE cross linked with organic peroxide. The LDPE is the polyethylene that vary in molecule weight and degree of branching with the highest branching while the others have unbranched, high density polyethylene (HDPE) and short branched linear low density polyethylene (LLDPE) [7]. The polyethylene commonly uses as a cable sheath material in the industry since its produce good electrical characteristics, ease of processing, and acceptable cost, and have therefore been popular extruded dielectric materials but still have several defect such as low thermal conductivity that need to be consider. The aims of the studies are to enhance the insulating performance using several methods like blending method, adding some filler with certain percentage, add additive, using bridge material and so on.

Beside polyethylene there are researchers that had study polypropylene (PP) as based material for HV insulating material. C. W. Reed [1] had study polypropylene as insulating material for high voltage application. This based material is similar to polyethylene, is a simple polyolefin synthesized following the cracking of petroleum. The poly-ethylene has chains of adjacent -CH-groups, in either (mainly) linear or branched configuration, in the poly- propylene chains have methyl (-CH\(_3\)) alternate carbon atoms side groups. These methyl groups that increase the thermal qualities occurs the intermolecular van der Waals forces (crystalline melting point and glass transition temperature) of polypropylene over those of polyethylene, offering thermal capabilities in excess of 100°C, possibly as high as 140°C for limited periods of time. However, the researchers also found that the polypropylene does have certain weak properties such as low temperature brittleness, requiring innovation via blends or co-polymers with polyethylene or other polymers to correct such weaknesses. The polyethylene samples had a higher dielectric strength than the polypropylene samples. This paper summarizes the polyethylene and polypropylene samples. The average breakdown
of HDPE, LDPE and PP, were 70, 79, and 55 kV/mm, respectively. The breakdown strength of Polypropylene was increased when compounded with LDPE and also with HDPE. The mixture of PP containing HDPE or LDPE showed enhanced breakdown of PP. The breakdown strengths were still lower than those of pure HDPE and LDPE [15].

Tracey L. Hanley and et.al [9] state that spherulites (best described as a collection of lamella crystallites) surrounded by amorphous regions consist in polyethylene (typically 15-40 percent crystalline). The spherulite size, influence the mechanical and electrical properties of the material that depends on the processing temperatures and the cooling rates. The annealing produce larger spherulites and higher crystallinity, the quenching produces smaller spherulites and lower crystallinity. In an inert atmosphere, the heating and cooling of extruded cables is very thoughtfully controlled under high pressure so that the possibility of void formation is minimized. In water, under the same pressure as the previous step, the additional cooling is performed.

As above finding, for now polyethylene is the most favourable based material used as high voltage insulating material. There are several type of this material was used in this application. The material was classification based on how the polyethylene was prepared and assembled. Below is review on most comment types of polyethylene that being used in HVDC cable.

3. Cross-Linked Polyethylene (XLPE)

XLPE is cross linked polyethylene that is the dominating material used in the insulation system of extruded DC cables. Since XLPE includes peroxide decomposition products (PDP), understanding their role on conduction behavior of the insulation system has been of great interest. It was start being used as HVDC insulating material since 1963. Most XLPE HVDC cable have voltage range from 500-600kV. The researchers [18] investigated the effect of thermal aging conditions on the performances of XLPE, insulation material used in MV 18/30 kV cables. Significant degradation of the material was obtained under severe stress conditions simulating overload and short circuit occurring in insulated power cables at the temperatures of 135°C and 150°C respectively. The temperature effect on the material performances let to presume a thermal degradation mechanism (decomposition reactions, chains break, and oxidation). This degradation is characterized by the dissipation factor and mass loss increase and the decrease of volume resistivity, dielectric strength, elongation at rupture and tensile strength [18].

In overcome the issue faced by pure XLPE in HVDC cable application, researcher [17] had introduced XLPE with addition of nano filler material to improve this material properties. The researcher add organic nano filler silicon oxide, SiO2 into XLPE . This filler was found plays the role improving the heterogeneous nucleation, accelerating the crystallization rate, reducing the crystal size and the crystal distributing is even more evenly. Researcher [16] had done study on comparison of conduction currents under different temperature on XLPE with Aluminium Oxide (Al2O3/XLPE) nano filler and without nanofiller and on XLPE with filled polymer . This research found that Al2O3/XLPE has higher conductivity than filled polymer XLPE. The thermal activation energies for pure XLPE is 0.84eV, 0.99eV for nano Al2O3/XLPE composite and 1.35eV for polymer filled XLPE. This research finding show that the addition of nano filler does not change thermal activation energy as much as the polymer filler does.

4. High - Density Polyethylene (HDPE)

HDPE is high density polyethylene which is polymer based produced from the monomer ethylene. HDPE has high crystallinity, large spherulite radius and little change in the dielectric constant according to to frequency. However, pure HDPE as cable insulator have faces several problem
because of its brittleness, its mechanical properties such as flexibility and bending strength need to be reinforced. The researcher [20] found had modified HDPE cables have to outstanding DC characteristic and improve breakdown characteristic similar to those of Polypropylene laminated paper (PPLP) Cables. The modification HDPE contains phenolic antioxidant and chlorine catcher. This modification has resulted in an increased intrinsic breakdown strength due to the high crystallinity of the base polyethylene and space charge suppression based on the small amount of grafted modified groups. It also have excellent thermal characteristic, especially thermal resistance which is about 80% of XLPE and 60% of oil-impregnated paper. Permitting an increased current loading. The bending elastic modulus of modified HDPE is about 2.5 times larger than that of XLPE but the bending rigidity(EI) of the cable core. [20]

Meanwhile researcher [21] had done experiment to examine the dielectric properties of HDPE with Alumina Nano Fillers. The experimental results from this study showed that 3 wt% compositions of HDPE with Al₂O₃ nano filler have improved capacitance value of HDPE properties. This composition of Al₂O₃/HDPE dielectric constant is 3.332 which is 20.18 % increased compared to pure HDPE which at 2.774. The dissipation loss of 7 wt % Al₂O₃/HDPE was found to have 1 value compared with pure HDPE. Alumina by nature has higher thermal conductivity property, higher addition this material helps to dissipate the heat, thus which reduces the dissipation factor. This study also had found that, the breakdown voltage of 5 wt% composition of Al₂O₃/HDPE is 16.3 % higher compared with pure HDPE. HDPE with additional of nanofiller Al₂O₃ at right weight percentage can improve its dielectric properties this material. The write amount of nano filler added is important due to higher the incorporation of additives creates higher conductive ions, which leads to a quicker break down. It is concluded that at 5 wt % Alumina with HDPE is showing highest break down strength with increased dielectric constant and less dissipation compared to pure HDPE.

5. Low – Density Polyethylene (LDPE)

LDPE is low density polyethylene that made from monomer ethylene. This material was used as HV insulating material since 1939 as an insulator for radar cable. Pure LDPE have an outstanding flexibility, a high fatigue life and high-impact strength but difficult in controlling the high temperatures and high pressure of the materials. This had motive researcher [22] to examine the LDPE based nanocomposites reinforced by Magnesium Oxide (MgO), Polyhedral Oligomeric Silsesquioxanes (POSS) or Zinc Oxide (ZnO) either by mechanical alloying or by melt mixing. The dielectric properties were investigated in producing enhanced dielectric properties for low loadings from 0 to 5 wt% in order to assess the efficiency of the compounding procedure. The inclusion of MgO nanoparticles, treated or untreaded, led to an improvement of the material resistance to space charges accumulation under a moderate field close to the operational field in power cables under a much higher electrical field, but the ZnO or POSS was found not giving significant improvement on the material space charges behaviour.

Measurements of dielectric properties were carried out in this paper [23] for nanocomposites of LDPE and MgO. The resistivity increases by the filler addition up to 5 phr, but decreases at 10 phr, in the temperature range from 278K to 363K. It is reasonable that this order is exactly opposite to that of tan δ, since the conductive current is one of the main reasons of tan δ. The addition of a proper quantity of nano-fillers which help electronic or ionic charge carriers escape from traps by hopping the molecular motions. While, researcher [24] found that the presence of nanofiller resulting in reduce the space charge accumulation of the material. The nanocomposite sample containing MgO nanoparticles acquire less space charge that investigated under different conditions of poling (applied electric field and duration) than the reference sample. Both MgO and POSS polyethylene composites showed the ability to overcome space charge accumulation after the application of a moderate electrical field. The nanocomposites also produced by melt mixing with silane-treated nanoparticles accumulate less space charge than their untreated counterpart in case of high applied electrical field and long poling duration.

Researcher [25] had tested LDPE blends with fillers. The test result found the pure blends
have higher Voltage Endurance Coefficient (VEC) compared to the composites and give indicating a better behaviour in the long term. The amount of filler content presents very low performance at the highest voltage. It due to the percolating effect that are common when the larger amount of filler incorporated and an exfoliated structure obtained.

6. Linear Low Density Polyethylene (LLDPE)

LLDPE is linear low density polyethylene that blended form of LDPE where the film has much more flexibility, tensile strength, and more conformability. It is more pliable and softer. LLDPE is used for pond liners or blended into other films to give them more flexibility and extra strength and the difference between LLDPE with LDPE is the thermal resistance and melting point of LLDPE is higher more than 20°C compared to those for LDPE. As LDPE most researcher try to improve this material dielectric properties by adding or mixed with other material. Researcher [26] had tested the mixed films with LLDPE and ethylene-vinyl acetate (EVA) with ratios of 80:20, 70:30, 60:40 and 50:50 wt%. The physical properties and dielectric strength was study and compared with to pure LLDPE. The result shows the specimens of 70:30 and 50:50 is excellent at insulating performance, dielectric strength. The pure LLDPE’s is less stable at varying temperature and thickness than the two sample. For each specimen, dielectric strength of virgin LLDPE is highest, and that of virgin EVA is lowest. Even though dielectric strengths of mixed film are somewhat lower than that of virgin LLDPE, it is more stable at varying temperature. Its conclude that the mixture with LLDPE and EVA enable performance of PE to be improved [26].

Researcher [27] had stated that the I - V characteristics of the material was transform when the nano alumina was added to the LLDPE. The alternation depends tediously on the amount of nano alumina particles. For a small amount such as 1% by weight, I - V characteristics of the material is improved. Further increase in nano alumina particles leads to a lower conduction current at lower applied voltage but rapid increase in conduction current at higher applied voltage. The addition of small amount of alumina give the implication to the movement of charge in the bulk of the material. As the amount of alumina increases the conduction current in the polyethylene (PE) increases [27].

Finding from study by researcher [28] shown that LDPE-based material can withstand larger DC field strength than LLDPE-based material at 30°C. But, when the temperature reaches 70°C, the DC breakdown strength of LDPE-based material reduces more than 50% and DC breakdown strength decreases at 90°C. The LLDPE-based material, has lower DC breakdown strength than LDPE-based material at the temperature of 30°C. But when the temperature increases, the DC breakdown strength of LLDPE-based material only decreases slightly. The LLDPE-based material has better performance than LDPE - based material as of the temperature stability [28].

The addition of nano particles into the LLDPE nano composites can reduces the PDC values while the different amount of the fillers contribute to different result. It has been found that the conduction current shows a minimum at a 1% b.w. concentration nano alumina and titanium particles. The researchers [11] reveal that the volume resistivity of LDPE is increased by addition of MgO nanofiller. The conductivity analysis shows that addition of nanofiller into the polymer improved its insulation properties. The nanofiller exhibits the significant reduction in DC conductivity with certain amount, it is not varying with the other fillers to the others materials.

LLDPE was found by [29] to have a weak dependence of the dielectric permittivity on frequency in the range of $10^{4}$ - $10^{6}$ Hz. Researcher [29] stated that when increasing the alumina concentration to the LLDPE, the dielectric permittivity increase. This is because the LLDPE has the lower dielectric permittivity than the alumina concentration. While others researchers [30-37] have done research on adding different nanofiller to the base LLDPE-NR material. From the observation, the both composite gain larger in size when adding the percentage (wt%) of nanofiller. The dielectric of the LLDPE will improve by adding the titanium oxide, TiO$_2$ composite while SiO$_2$ composite will
make it worse. The LLDPE-NR/SiO$_2$ at 5 wt% has been found to be the best composition for HV insulation in terms of the lowest polarization and depolarization current values as well as the lowest conductivity level.

The researcher [38] conclude that the melting point of LLDPE is 125°C while for LDPE it is 104°C. The average value for breakdown strength (Eb) and breakdown voltage (Vb) compared to LDPE is increased around 12-15% from the sample test. The usage of LLDPE rather than LDPE allows the thermal, electrical and mechanical properties of large size to be considerably increased.

7. Mixed Two type of Polyethylene

These group of researchers [2-5] studied the DC Conductivity and DC breakdown test with DC dielectric properties of HDPE/LLDPE blend. The blend is closely related to the temperature and applied electric field. DC conductivity rises up exponentially with temperature increases with the temperature range near the operating temperature. DC conductivity increases with power-function as applied electric field rises up. The breakdown strength goes down with temperature because of less content of polar additives. As a result, at the cable operating temperature, the 30HDPE/70LLDPE blend produce higher breakdown strength than XLPE, the breakdown strength is nearly two fold higher than XLPE. Except the permittivity, other properties of the blends seem better than XLPE at high temperature. For cables service temperature is about 70-90°C, dielectric behaviours of insulation materials at high temperature are of significantly importance. 30HDPE-70LLDPE blends exhibits good properties and stability at high temperature. The 70LLDPE-30HDPE blend exhibits better heat resistance than XLPE below 130°C, but morphological structure transformation caused by crystal melting limits its applications at higher temperature grade. The co-crystalline structure leads to a shorter average hopping distance, which contributes to a lower conductivity.

The researchers [8] reveal that the addition of small amount of high density polyethylene (HDPE) to a low density polyethylene (LDPE) resin has resulted in radical reduction in DC conductivity of high voltage. The HDPE content in LDPE as low as 1 wt% that contribute to small population of thicker crystalline lamellae that finely scattered throughout the overall material. A decrease in DC conductivity respond by the change in nanostructure by approximately 1 order of magnitude and elevated in temperature. This performance of the LDPE/HDPE blends is an alternatives design insulation material that limited by its residual electrical conductivity.

The researchers gaining to improve the breakdown strength by up to 15 % on a blend comprising 20 wt% HDPE in an LDPE matrix which are the effect of imparting a controlled thermal history. As the LDPE softens, the benefit of controlled crystallization is less obvious: the advantage is rather to impart extra mechanical stiffness to the blend via the reinforcing framework of space-filling HDPE lamellae. It is likely that this same framework will include an increased level of inter-lamella tie molecules which will also structurally reinforce the material [14].

The intrinsic thermal conductivity of the polymer matrix and fillers, filler loading, filler size and shape, filler aspect ratio, filler dispersion and orientation, as well as many other factors affect the thermal conductivity of polymer composite. The researcher propose that it is not possible to conclude that the thermal conductivity of a composite depends on a specific parameter without taking into consideration all other parameters. They also found that the thermal conductivity of the polymer is not increase with the increasing of the filler size [10].

The researchers [13] studied on DC breakdown properties and morphology of PE blended with polystyrene (PS). The results of breakdown test exhibit a clear negative temperature dependence breakdown strength of all the blends. DC breakdown strength enhancing with the blending PS with PE at high temperature region (70°C and 90°C) by ~20%. The addition of PS into LDPE does not change the crystallization behaviors significantly while PS particles with the size of several micro meters dispersed in the inter-spherulitic region could contribute to the improvement of DC breakdown strength under at 70°C and 90°C.
8. Conclusion

Design of the Insulation for HVDC cable poses a greater challenge due to a lot of factor. The main factor is the material usage and the mixed composition used. From the review, the summarize can be made that the conductivity, dielectric and other performance is determined by the intrinsic of the polymer matrix, the composite of the polymer, percentage filler loading, filler size, filler aspect ratio, filler shape and many other factor. One cannot conclude that the thermal conductivity of a several composite depends on a specific parameter without taking into examination on all other parameter also percentage of weightage include. The increasing of filler size or weightage in one composite are not increase the thermal conductivity of polymer composites.

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