

POLYPROPYLENE/SIO2 NANOCOMPOSITE WITH IMPROVED DIELECTRIC PROPERTIES FOR DC CABLES

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ABSTRACT

A new generation of nanostructured polymeric insulating material is being developed under the GRIDABLE European project framework. One of the main objectives of this project is the improvement of the dielectric properties and the life performance of High Voltage DC cables insulating materials. The dielectric performance of pre-production grade PP/SiO₂ with different formulations are evaluated in this work by means of space charge accumulation measurements, electrical conductivity tests and statistical analysis of breakdown voltage. Results are compared with state of the art XLPE and PP.

KEYWORDS

HVDC CABLES, CAPACITORS, SPACE CHARGE, XLPE INSULATION, POLYPROPYLENE INSULATION

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INTRODUCTION

High voltage direct current (HVDC) cables are recently gathering more and more interest, reaching an all-time high. The July/August 2017 issue of the Electrical Insulation Magazine focused on different aspects of the design and testing of HVDC cable systems.

The most important reason for this is probably the world wide attention for harvesting renewable energy at a scale never seen before. In Europe the cost of electricity produced by large offshore wind farms has recently dropped, as illustrated in Fig. 1, consequently accelerating the development of HVDC cables to link offshore and onshore substations.

HVDC corridors on land in Germany and China are perhaps the strongest drivers of new developments for this technology. In Germany, a large amount of offshore wind generation needs to be integrated into the grid, requiring a 525 kV corridor from North to South (Südlink). A very substantial part of this corridor will be realized with underground HVDC links because of the low public acceptance of overhead power lines. TransnetBW GmbH has estimated that Germany will require new HVDC transmission corridors with a total length of between 2600 and 3100 km and with a total transmission capacity 12 GW [1]. While many HVDC subsea systems have been installed successfully, such underground systems on land pose

considerable challenges, many of which relate to the choice of insulation system within the HVDC cable.

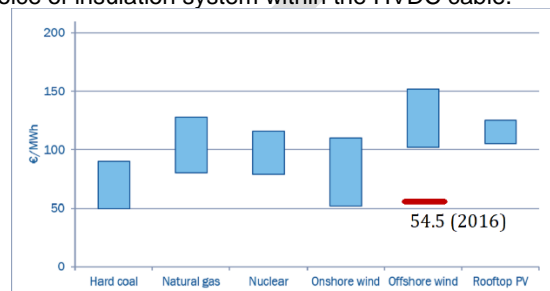


Fig. 1 - Normalized cost of electricity in Europe for different energy carriers in 2014 [2], and the cost of offshore wind in 2016 [3].

In China, the developments in the field of HVDC are further speeding up. In 2016, there are some 22 HVDC transmission systems commissioned or in operation, including the +800kV Shanghaimiao-Shandong HVDC project with a planned transmission capacity of 10 GW [4]. In May 2017, the Chinese president Xi Jinping announced further details about the One Belt One Road policy, including energy corridors connecting China and Europe [5]. In addition, strategic projects are being planned to interconnect Asian countries, see Fig. 2.

The decisions to transport electrical energy over very long distances will naturally lead to increasing voltage levels. A substantial part of the HVDC corridors will have to be installed underground, using HVDC cable technology. While major cable and cable insulation manufacturers are developing polymeric HVDC cables for higher and higher operating voltage (640 kV XLPE, 700 kV MI-PPPL), the question remains how far we can go with pushing the current technologies to even higher voltage levels.

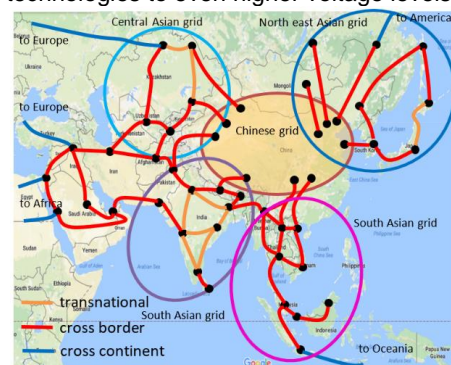


Fig. 2 - Long distance connections in Asia proposed by [6]

A new European project, that is, GRIDABLE (Polymer Nanocomposite Insulation Material Enabling Integration of Renewables and DC Storage Technologies in the AC

Energy Grid) was launched recently under the HORIZON 2020 framework funded by the European Union. Various partners, from universities and research institutions to cable and capacitor manufactures, are involved. The project aim is to develop a new generation of nanostructured polymeric materials suitable for DC cables and capacitors. In addition, the project aims in its last stage to launch, on a pre-production/model scale, industrial prototypes of DC power capacitors and cables using industrial machinery throughout the production chain.

The base material chosen for this project is thermoplastic, i.e. polypropylene (PP); having excellent electrical and thermal properties for energy applications, and good potentiality regarding mechanical properties, besides being completely recyclable. The choice to add nanofillers, specifically SiO₂ with and without functionalization, fits to the objective to improve the electrical and thermal properties and reach higher design field and temperature for the same design life and reliability of the present DC technology, that is, XLPE (cross-linked polyethylene) for cables and PP for capacitors.

Preliminary work, presented in this paper, indicates that the nanofiller can influence the degradation rate of materials, modifying the space charge assisted conduction mechanism and the space charge accumulation threshold field value. Statistical analysis of breakdown voltage shows that the presence of nanoparticles may affect noticeably the breakdown behavior. Results are compared with state of the art XLPE extruded specimens.

SPACE CHARGE AND AGING

The accumulation of space charge in electrical insulation has been recognized to be a major aging factor in DC insulation [7]-[9]. As an example, Fig.3 shows how a small amount of accumulated space charge can distort the Laplacian electric field. This will in turn influence the degradation rate and life expectancy of the insulating material. Due to the power law, which describes the aging rate under electrical stress, even a moderate increase of electrical field inside the insulation can significantly accelerate the local degradation mechanism driven by electrical stress. Indeed, the relationship between aging rate, K , the electrical stress, E , and the so-called voltage endurance coefficient, n , can be described by the inverse power life model (IPM), defined by Eq.1 [10] [11]:

$$K(E) = K_D \left(\frac{E}{E_D} \right)^n \quad (1)$$

where E_D is design field and K_D the corresponding aging rate constant. If, e.g., the electric field inside insulation locally becomes 20% higher than E_D , and considering a life of 30 years at failure probability 1% for a design field of 40 kV/mm, and $n=15$, the increase of electric field will bring to life reduction of 90%, that is from 30 to 3 years.

Hence, accumulation of space charge can be the main accelerated degradation process in DC insulation. If, in addition, voltage polarity inversions phenomena are present (as it may happen in transmission assets), the accumulation of homocharge (that is, charge having the same sign as that of the near electrode) can bring to further abnormal field distribution, causing significant field enhancement at the interface insulation-electrode, which can affect apparatus reliability and life [12].

Any material which has to be used as DC insulation,

therefore, has to be characterized to be space charge free at the operating field and temperature, and nanostructuring can help increasing field and/or temperature above which space charge accumulation becomes large enough to affect field profile and/or accelerate local degradation mechanisms [10] [13].

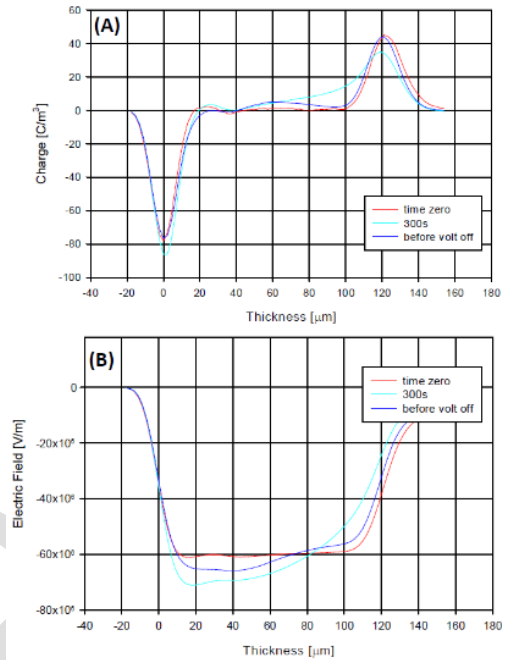


Fig. 3 - Space charge (A) and electric field profile (B) measured at the beginning, during and at the end of polarization with (laplacian) field of 60 kV/mm. The maximum field bulk material is subject to is about 70 kV/mm, after 300 s.

TESTING PROCEDURES

Space charge measurements

Space charge measurements were carried out by the Pulsed Electro-Acoustic (PEA) method. In the PEA method, a specimen is subject to the superposition of a DC voltage U_0 and a pulsed voltage $U_p(t)$. Charged particles injected by the DC field interact with the bulk material due to the pulsed voltage, producing an acoustic pressure wave that is transduced into a voltage signal by a piezoelectric sensor. The trend of this signal in time is then related to the charge distribution in space by known parameters, such as the sound velocity in the specimen, its thickness, and the applied electric field. Besides information on space charge profiles (i.e. charge density vs. distance) and their evolution as a function of the electric field, quantities were extracted from space charge profiles detected by PEA, such as threshold for space charge accumulation. This is a fundamental parameter for the characterization of insulating material for DC applications, because, as mentioned above, the presence of space charge in the insulation can modify substantially the electric field distribution and, hence, the insulation life [14]-[16]. The space charge measurements were performed on thermally pre-treated specimens (72 hours at 60° C in vacuum). This is done to remove traces of water diffused into the material that can deeply influence the final results [17]. Measurements during 3-hour polarization (while DC voltage is applied) and depolarization (while DC voltage is

absent) times are carried out in this work. Tests are done at 60°C, in controlled environment, with fields ranging from 5 to 50 kV/mm, in order to unravel the low field and high field behavior of space charge and, in particular, find out the threshold for space charge accumulation. The threshold field is obtained by identifying a bend from the linear ohmic relationship between the stored charge density at a specific field and depolarization time, $q(E, t)$, derived from the space charge profile measurements as follows:

$$q(E, t) = \frac{1}{L} \int_0^L |q_p(E, x, t)| dx \quad 2$$

where 0 and L denote the electrodes positions and $q_p(E, x, t)$ is the space charge profile for a given poling field E .

CHARGE MOBILITY AND TRAPS DEPTH

Apparent trap-controlled mobility is only a very rough approximation of the mobility as usually defined, but, even if affected by significant approximation, can be useful for material characterization and aging diagnosis. The expression of apparent trap-controlled mobility is the following [18]:

$$\mu(t) = \frac{\varepsilon}{q^2(t)} \frac{dq(t)}{dt} \quad 3$$

where L is specimen thickness, $q(t)$ is the charge density that can be calculated at any depolarization time, $dq(t)/dt$ is the slope of the depolarization curve at time t , ε is the permittivity of the specimens tested. Once known apparent trap-controlled mobility the trap depth could be estimated. This is a di-cult problem, which has not been solved yet in a totally convincing way. An approximate method to obtain the trap depth distribution, ΔU , is described in [18] and provides the following equation:

$$\Delta U(t) = KT \ln \left(\mu(t) \frac{h}{eR^2} \right)$$

where K is Boltzman constant, T is temperature, R is the mean distance between localized states, e is the electron charge and h is the Planck's constant. Therefore, the values of the trap depth can be determined from the values previously calculated for $\mu(t)$.

MATERIAL SPECIFICATIONS AND COMPOUNDING

For this paper, three nanocomposites with the same polypropylene homopolymer matrix and increasing nanofiller percentage (0-4.5%) were first tested in order to assess the amount of space charge reduction achievable by nanofilled materials. Several different compositions of cable grade insulating materials have been selected, on the basis of specific criteria (such as the elastic modulus, impact strength, thermal conductivity and melt flow index). The reference in performance is the crosslinked low-density polyethylene (XLPE) used as the base polymer for HVDC cable insulating systems at the moment. XLPE extruded samples characteristics were tested and compared with extruded samples of cable grade nanofilled polypropylene, with 1% filling. The raw materials were pre-mixed, dried for 1.5 h in oven (70 °C) and for 0.5 h in

vacuum, and thereafter compounded by a co-rotating twin-screw extruder. Continuous nitrogen gas purge and a melt filter were utilized.

RESULTS

INFLUENCE OF NANOFILLER CONTENT ON SPACE CHARGE ACCUMULATION

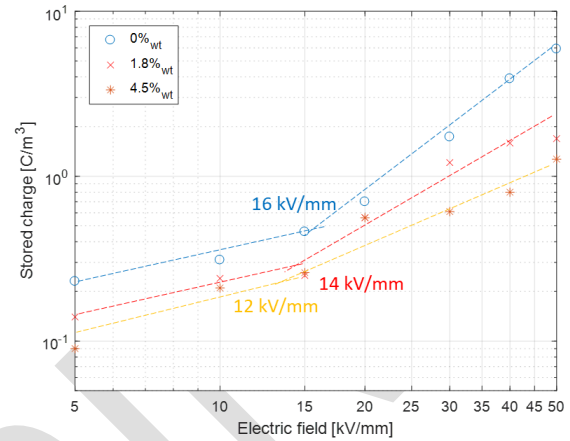


Fig. 4 - Space charge threshold characteristics for PP pure and filled 1.8wt% and 4.5wt%.

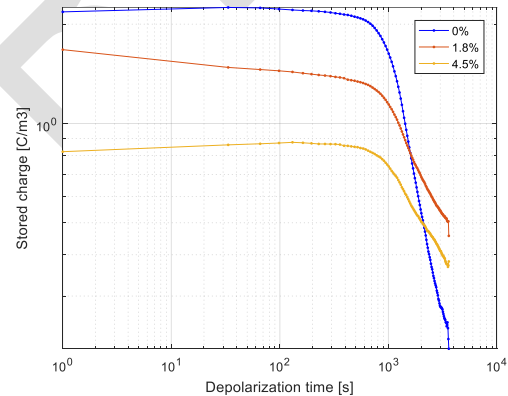


Fig. 5 – Depolarization characteristics for PP pure and filled 1.8wt% and 4.5wt%.

Fig.4 shows space charge accumulation for the tested materials at different filling percentages (from 0% to 4.5%), in poling fields from 5 to 50 kV/mm. As can be seen, the introduction of nanofiller reduces the amount of accumulated charge at medium-high fields, while similar charge at low fields is observable. The consequence is that the threshold for space charge accumulation shifts to lower values when nanofillers are introduced in PP; going from 16 to 12 kV/mm. On the other hand, the rate of charge accumulation as a function of poling field diminishes significantly from base (pure) to filled material. This behavior is more and more evident increasing filler content. Those results suggest a modification of trap density and trap depth distribution, confirmed by the depolarization space charge characteristics of Fig.5. Trapped charge is released, in fact, more slowly by the nanofilled materials, and the residual charge after long depolarization times is higher in nanofilled materials than in the base PP.

NANOFILLED POLYPROPYLENE AS AN

ALTERNATIVE TO XLPE

Space charge accumulation

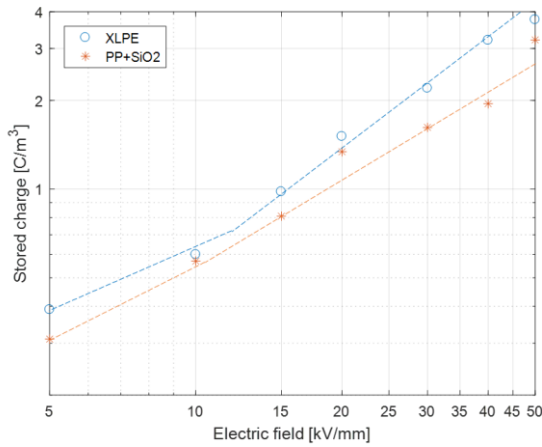


Fig. 6 - Space charge threshold characteristics for XLPE and cable-grade nanofilled polypropylene.

Fig.6 shows space charge accumulation for XLPE and the polypropylene based material, in poling fields from 5 to 50 kV/mm. As can be seen, the amount of accumulated charge at low and medium-high fields is reduced in PP nanofilled specimens. On the other hand, the rate of charge accumulation as a function of poling field diminishes from XLPE to PP based material. While a clear space charge accumulation threshold field can be clearly defined in XLPE, an Ohmic trend is observed with the nanofilled material ($n \approx 1$, after [13]). Calculations for space charge apparent mobility (Fig.8) and trap depth distribution (Fig.9) show how the polypropylene based material is characterized by deeper charge traps. In fact, charge is released more slowly than in XLPE, and the nanofilled material features higher residual charge after long depolarization times. This is a relevant issue in the case of insulations subjected to voltage-polarity inversions, such as cables interfacing with Current Source Converters. This aspect will therefore require further attention in future work.

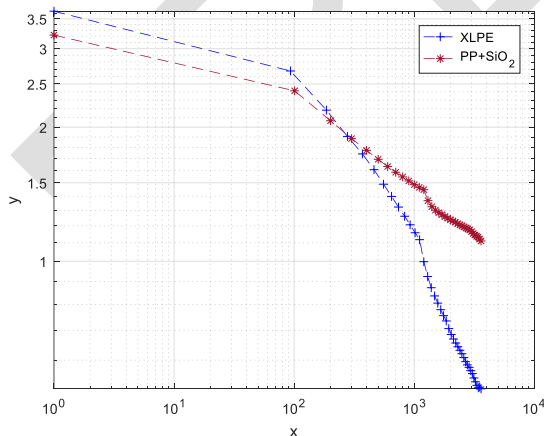


Fig. 7 - Depolarization characteristics for XLPE and cable-grade nanofilled polypropylene.

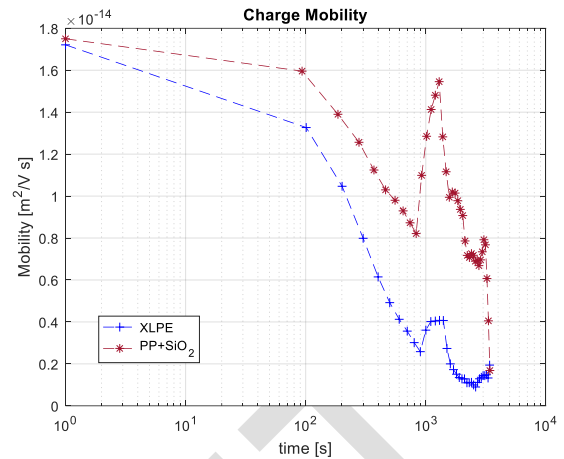


Fig. 8 - Charge mobility characteristics for XLPE and cable-grade nanofilled polypropylene (after [18]).

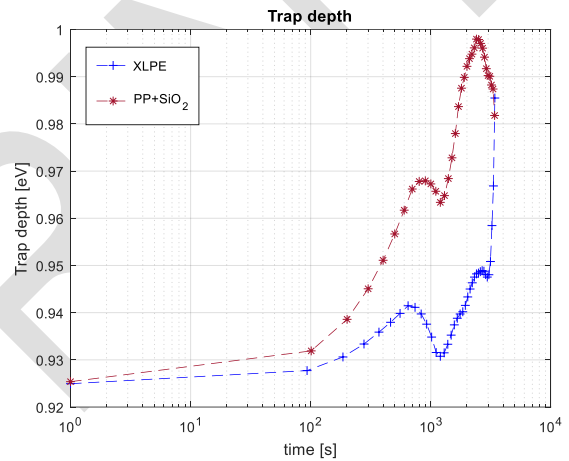


Fig. 9 - Trap depth distribution in XLPE and cable-grade nanofilled polypropylene (after [18]).

CONCLUSIONS

The addition of SiO₂ nanoparticles to a bulk of PP has revealed interesting modifications of electrical properties that may affect positively HVDC cables and film capacitors design and performance on short term and long term basis. The decrease of trapped space charge at fields close to design stress might open interesting perspectives for the future of the GRIDABLE project.

Further, long term, investigations are needed to understand the contribution of nanofillers to the modification of electrical properties, such as measurements of charging-discharging currents and space charges at various temperatures, temperature and frequency, life tests with voltage polarity inversion, but the results here reported seem to indicate that the GRIDABLE project may have an important impact on insulation technology in the near future, suggesting that HVDC cables insulating materials with better thermal performances, higher ampacity and higher reliability are a viable option using polypropylene based materials. The problematics regarding their performance in depolarization introduces a problem that will be assessed in the future.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 720858.



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