Electric Power Systems Research xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Multiple enhancement of PVC cable insulation using functionalized SiO_2 nanoparticles based nanocomposites

Nagat M.K. Abdel-Gawad[a], Adel Z. El Dein[b], Diaa-Eldin A. Mansour[c,*], Hanaa M. Ahmed[d], M.M.F. Darwish[a,e], Matti Lehtonen[e]

[a] Department of Electrical Power and Machines Engineering, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt
[b] Department of Electrical Engineering (High Voltage Networks), Faculty of Energy Engineering, Aswan University, Aswan, Egypt
[c] High Voltage and Superconductivity Laboratory, Department of Electrical Power and Machines Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt
[d] Department of Mathematics and Engineering Physics, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt
[e] Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland

ARTICLE INFO

Article history:
Received 15 February 2017
Received in revised form 22 October 2017
Accepted 16 November 2017
Available online xxx

Keywords:
Power cable insulation
Nanodielectrics
Functionalized nanoparticles
Dielectric and mechanical properties
Polymer nanocomposites

ABSTRACT

Manufacturing of a new insulation material for power cables has become necessary in order to withstand electrical and mechanical stresses. The current study aims to enhance the dielectric and mechanical properties of Polyvinyl Chloride (PVC), one of the wide used power cable insulation, by the insertion of chemically modified silica (silicon dioxide, SiO_2) nanoparticles. The surface functionalization of the inserted SiO_2 nanoparticles was performed using amino silane coupling agent, and the PVC/SiO_2 nanocomposites were synthesized with different concentrations of nanoparticles. The surface morphology and chemical structure of the prepared samples were characterized by field emission scanning electron microscopy (FE-SEM) and Fourier transformation infrared spectroscopy (FT-IR). The mechanical properties of the obtained nanocomposites showed that the insertion of functionalized nanoparticles is able to increase the tensile strength and the Young's modulus of samples, however it decreases their elongation. In addition, the dielectric properties of PVC/SiO_2 nanocomposites, such as relative permittivity (ε_r) and dielectric loss ($\tan\delta$), were also measured in a frequency range of 20 Hz–1 MHz. Moreover, AC breakdown voltage of the prepared samples was measured under uniform and non-uniform field, and AC dielectric strength was evaluated using finite element method (FEM) for non-uniform and uniform field. For further evaluation, DC dielectric strength was also measured under uniform field. The obtained data revealed that PVC/SiO_2 nanocomposites with functionalized SiO_2 nanoparticles exhibited better dielectric properties compared to that with un-functionalized one or that of neat PVC. The physical mechanisms behind the obtained enhancements have been discussed.

1. Introduction

Nowadays, low and medium voltage distribution networks including large infrastructure of expensive underground power cable systems became necessary to transfer a huge amount of power into far areas. These cable systems are constructed with either oil-paper or polymer insulation materials. The use of polymer insulated cables has been expanding in the distribution networks over the last few decades.

During normal operation, underground power cables are subjected to various kinds of stresses which result in changing the insulation properties over time. In addition, the various aging processes such as exposure to heat, humidity and mechanical stress, as well as the space charges accumulation taken place in polymers under DC field, cause distortion in electric field and partial breakdown in cable insulation [1]. Moreover, by applying electric field, the polymeric material carbonizes at the region of sparking and these carbonized regions act as permanent conducting channels that result in increased stress over this region followed by treeing and complete breakdown of the insulation. This breakdown may lead to complete failure of high voltage equipment which results in large outages and disturbances across the distribution networks

---

* Corresponding author.
E-mail addresses: nagah.abdelgwad@feng.bu.edu.eg (N.M.K. Abdel-Gawad), adelzein@energy.aswu.edu.eg (A.Z. El Dein), mansour@f-eng.tanta.edu.eg (D.A. Mansour), hana.ahmed@feng.bu.edu.eg (H.M. Ahmed), mohamed.darwish@feng.bu.edu.eg (M.M.F. Darwish), matti.lehtonen@aalto.fi (M. Lehtonen).

https://doi.org/10.1016/j.epsr.2017.11.011
0378-7796/© 2017 Elsevier B.V. All rights reserved.

Please cite this article in press as: N.M.K. Abdel-Gawad, et al., Multiple enhancement of PVC cable insulation using functionalized SiO_2 nanoparticles based nanocomposites, Electr. Power Syst. Res. (2017), https://doi.org/10.1016/j.epsr.2017.11.011

[2–4]. Hence, high rating cables with good insulation properties must be performed in order to keep the system reliable and to avoid costly damages [5].

Due to their reliability, availability, ease of fabrication, and low cost, polymers have been widely used as electrical insulating materials for underground cables since the early 20th century [6]. The most commonly used synthetic polymers for cables are thermoplastic polymers such as Polyvinyl Chloride (PVC) and polyethylene (PE). Due to its low cost and good dielectric and processing properties, PVC is one of the most widely used insulating materials. It also has stable chemical properties, has excellent fire resistance due to the presence of chlorine, and is environmentally friendly [7,8]. To enhance the various properties and dielectric ability of polymeric insulation materials, suitable inorganic nanoparticles should be highly dispersed within polymer matrix producing what is called polymer nanocomposite or nanodielectric [9–13].

Nanocomposites or nanodielectrics have attracted a great attention. They are synthesized by homogeneously dispersion of inorganic particles with nanometer scale (<100 nm) within a dielectric material. Insertion of nanoparticles within polymeric materials results in a significant improvement in dielectric, mechanical, and thermal properties [12–16]. To optimize these novel properties, the dispersion of nanoparticles within polymeric matrices should be enhanced, which in turn can be achieved by chemical functionalization of nanoparticles surfaces using silanes or polyalcohol as coupling agents. This functionalization will convert the hydrophilic character of the inorganic nanoparticles into organic character, and hence, their compatibility with polymers will be improved [17–20].

The enhancement of mechanical properties such as modulus of elasticity and strength is one of the most important goals of incorporating functionalized nanoparticles into polymers. This enhancement is affected by strength of the interfacial zone and degree of surface interaction between nanoparticles and polymeric matrix [21]. This interfacial zone is considered as a key function in avoiding the agglomeration of the nanoparticles that acts as weak points at which a destructive process can initiate. Thus, agglomeration results in deterioration of electrical, mechanical, and thermal properties. To reduce agglomeration of the nanoparticles, and enhance their dispersion within polymers, chemical modification of the surface of nanoparticles is needed [22,23]. Surface modification is the most common way to lessen the surface energy of nanoparticles and to improve their compatibility with polymer matrix as well as achieving uniform dispersion of nanoparticles inside the matrix.

Many studies were interested in enhancing various properties of insulating cables by modifying the surface of nanoparticles. Roy et al. investigated the effect of nanoparticles modification by a silane coupling agent on the electrical properties of cross-linked polyethylene/silica (XLPE/SiO_2) nanocomposites [24]. It has been found that the effective dielectric constant decreased by going from micro-sized modified SiO_2 to nano-sized modified SiO_2, and the particle surface curvature played an important role in changing the amount of hydrogen bonding among silanol groups. This is resulting in a variation of surface polarity of the particle, and consequently causes a reduction in the dielectric constant of the nanocomposite. In addition, C. P. Sugumaran [25] studied the effect of insertion of calcium carbonate ($CaCO_3$) or un-functionalized SiO_2 nanoparticles with PVC matrix on the dielectric and mechanical properties. It was found that the addition of SiO_2 has an impact on mechanical properties only, otherwise $CaCO_3$ helped to improve the dielectric properties. Otherwise, Mansour et al. [26] enhanced the DC breakdown strength of PVC incorporated with 0.5 wt.% of synthesized Zinc Oxide nanoparticles compared to the base PVC. Recently, Abdel-Gawad et al. increased the AC dielectric breakdown strength of PVC insulating materials with incorporating functionalized TiO_2 into their matrix compared to that with un-functionalized TiO_2 or that of neat PVC. Moreover, the permittivity and dielectric loss were decreased by about 43% and 41%, respectively, over the neat PVC at 50 Hz [27]. In the current study, enhancement of dielectric and mechanical properties of PVC nanocomposites through using functionalized SiO_2 nanoparticles has been conducted. Functionalization of the SiO_2 nanoparticles was done using amino silane, which is a suitable coupling agent for PVC and SiO_2 particles making their surface tension values close to each other.

Dielectric quantities to be measured are real permittivity (ε') and imaginary permittivity (ε'') that reveal information about the effectiveness of a material as an insulator. A dielectric response is a result of the interaction of matter with an applied electric field that oscillates at different frequencies (f), and at given temperature. The complex relative permittivity (ε_r) is given by the equation: $\varepsilon_r(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega)$ [28], where, $i = \sqrt{-1}$, $\omega = 2\pi f$ is the angular frequency, and $\varepsilon' = t \times C_p/(A \times \varepsilon_o)$ that reflects material polarizability due to dipole re-orientation, deformation of delocalized electron distributions, or interfacial polarization. Also, $\varepsilon'' = t/\left(\omega \times R_p \times A \times \varepsilon_o\right)$ that is proportional to the energy dissipated inside the material per cycle. Here, t is the thickness of the sample, A is the area of electrodes, ε_o is the permittivity of free space, and C_p & R_p are the equivalent parallel capacitance and resistance of the samples, respectively, measured from LCR meter. It is known that when an alternating electric field is applied on a material, there is a delay between the change in the field and the change in polarization, and this delay was represented by the angle δ. The dielectric loss ($\tan\delta$) represents the ratio of the energy dissipated to the energy stored in the dielectric, and it is given by $\tan\delta = \varepsilon''/\varepsilon'$ [28].

2. Experimental setup

2.1. Materials

The materials used in this study are: compound PVC pellets (containing plasticizer, filling materials, and elastic agent materials) were provided from commercial supplier. SiO_2 nanopowder (with average spherical particle diameter between 10 nm and 20 nm as given by manufacture data sheet and with 99.5% purity) was purchased from Sigma–Aldrich. Gamma-amino propyl triethoxy silane (amino silane, with 99% purity) that used as coupling agent was purchased from Momentive Inc. Methanesulfonic acid (10%, from Sigma–Aldrich), cyclo-hexanone (99% purity), isopropyl alcohol (99% purity), and toluene (99.8%purity) were purchased from Fisher Inc., and they were used without further purification.

2.2. Functionalization of SiO_2 nanoparticles

In this sub-section, the amino silane was used to modify the surface of SiO_2 nanoparticles, and the chemical modification method was performed as our previously reported method in functionalizing TiO_2 nanoparticles [27]. This modification started with activation of SiO_2 surface to increase the surface concentration of the hydroxyl groups [29]. In this step, a mixture of 10 g of SiO_2 and 100 ml of 10% methanesulfonic acid was stirred at 110 °C for 4 h. By the end of this step, the powder was collected using Hitachi centrifuge at 1200 rpm for 10 min, then washed several times with de-ionized water before drying in a vacuum oven at 120 °C for 24 h [1,20]. The functionalization of this activated SiO_2 nanoparticles using silane coupling agent, was performed as follow: a mixture of 3 g of the surface activated SiO_2 nanoparticles and 60 ml of toluene was sonicated using water bath sonicator (Elmasonic, S-60H) at 70 °C for 30 min. Then, the solution was stirred at 70 °C for 2 h followed by addition of 10%wt. solution of amino silane in toluene, and the solution was continuously stirred at the same temperature

Please cite this article in press as: N.M.K. Abdel-Gawad, et al., Multiple enhancement of PVC cable insulation using functionalized SiO_2 nanoparticles based nanocomposites, Electr. Power Syst. Res. (2017), https://doi.org/10.1016/j.epsr.2017.11.011