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Experimental and simulation analysis for insulation deterioration and partial discharge currents in nanocomposites of power cables

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ABSTRACT

Partial discharge (PD) has a well-established relationship with the lifespan of power cables. This paper has been treated the polyvinyl chloride (PVC) with specified nanoparticles for enhancing dielectric degradation and reducing partial discharge current to extending lifespan of power cables. It has been succeeded to creation new polyvinyl chloride nanocomposites that have been synthesized experimentally via using solution-gel (SOL-GEL) technique and have high featured electric and dielectric properties. The validation of nanoparticles penetration inside polyvinyl chloride during synthesis process have been constructed and tested via scanning electron microscope (SEM) images. The partial discharge current mechanisms in polyvinyl chloride nanocomposites have also been simulated in this work by using MATLAB® software. This paper has explored the characterization of partial discharge current for variant void patterns (air, water, rubber impurity) in polyvinyl chloride nanocomposites insulations of power cables to clarify the benefit of filling different nanoparticles (Clay, MgO, ZnO, and $BaTiO_3$) with varied patterns inside power cables dielectrics. A comparative study has been done for different partial discharges patterns to propose characterization of partial discharges using nanoparticles of appropriate types and concentrations.

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1. INTRODUCTION

Partial discharge is a physical process that occurs in a solid dielectric-bounded cavity and serves as a warning sign to monitor insulation degradation. Partial discharges behave stochastically for several reasons, including the free electron supply, discharge generation, and surface charge fading. The partial discharge resistant property of polymer insulation can now be improved effectively by incorporating inorganic nanoparticles into the polymer matrix [1]. Device safety and reliability are strongly dependent upon partial discharge, the operation of the devices. A partial discharge is described as a localized electrical discharge that can be created by a distorted local electric field and partially penetrates in the insulation [2]. In light of this, partial discharge has been recognized as a crucial element that contributes to polymer degradation and causes it to age sooner than it is designed. Doping nanosized inorganic particles into polymer matrix improves polymer resistance to partial discharge, resulting in nanocomposites. The use of nano-sized fillers has been demonstrated to improve partial discharge resistance [3]–[5]. Partial discharges are named cavities, void partial discharges or internal partial discharges, and have attracted much attention mainly due to two reasons. Using current polarization and depolarization to measure the dielectric response of power apparatus can be a useful diagnostic tool for determining insulation status. The aim of this paper is synthesis and characterization of electric degradation for traditional and new polyvinyl chloride nanocomposites and multiple nanocomposites at variant nanoparticles (type and concentration) and so variant high voltages levels. In addition, the simulation model on MATLAB® software has been focused on estimating partial discharges currents in polyvinyl chloride nanocomposites insulation of single-core power cables that is a main problem to be investigated in this study. Finally, this paper deduced new pattern design of specified nanoparticles for enhancing dielectric degradation and reducing partial discharge current to extending lifespan of power cables.

2. EXPERIMENTAL SETUP

2.1. Material design and fabrication

Polyvinyl chloride is made from ethylene and anhydrous hydrochloric acid and it is the polymerized vinyl chloride that is most frequently used for cables, thermoplastics, and polymerized vinyl chloride. The interphase region depends on the surface area, volume fraction, and thickness of the interphase zone that surrounds each nanoparticle particle [6]–[9]. A closer approach to nanoparticles reveals an overlap of interphase areas around nanoparticles as shown in Figure 1; the comprehensive analysis of the interphase thickness estimation has been found in [10]–[13]. The electrical characteristics of several industrial insulation materials and their effects on electrical applications have recently been explored theoretically and experimentally [14], [15]. Recent studies have been reported the effective dielectric constants of both interphase and inclusion areas of several nanocomposite models [6], [8], [15].

Spherical nanoparticles characterization shape (Dia.:10-50nm) have been used in our test sample preparation. Polyvinyl chloride is a commercially available material already in use in the manufacturing of high-voltage (HV) industrial products. Whatever, the preparation of polyvinyl chloride nanocomposites has been used solution-gel (SOL-GEL) method fabrication [16]–[19].

Scanning electron microscope (SEM) images have been used to detect nanoparticle penetration inside polyvinyl chloride, as shown in Figure 2. Figures 2(a) and 2(b) represent SEM images for penetration of clay and zinc oxide nanoparticles inside polyvinyl chloride respectively. On the other wise, Figures 2(c) and 2(d) represent SEM images for penetration of multiple nanoparticles (Clay+$BaTiO_3$) and (ZnO+$BaTiO_3$) inside polyvinyl chloride respectively.

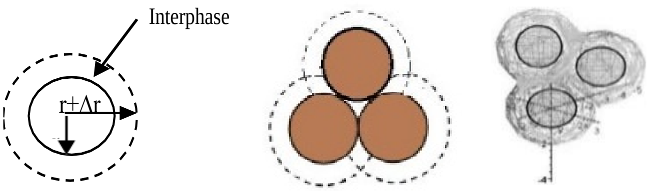
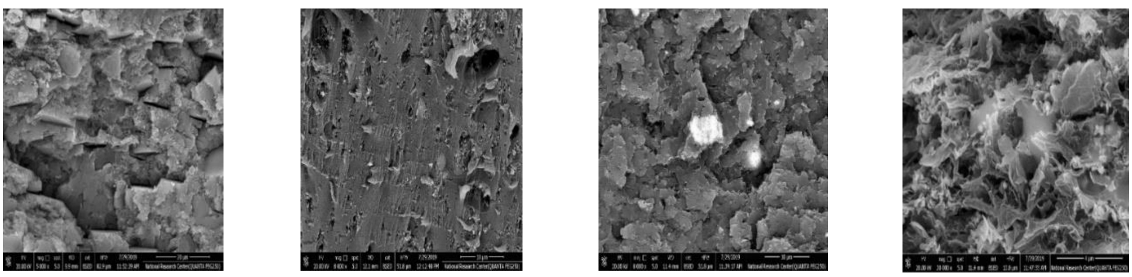


Figure 1. Interphase zone surrounds the multi-nanoparticle particles in multi-nanocomposites system



(a) (b) (c) (d)

Figure 2. Samples of SEM images (a) clay/polyvinyl chloride (PVC) nanocomposites, (b) ZnO/PVC nanocomposites, (c) (Clay +$BaTiO_3$)/PVC nanocomposites, and (d) (ZnO+$BaTiO_3$)/PVC nanocomposites

2.2. Characterization of nano-metric materials

Among nanoparticles industrial materials, clay is a very effective catalyst that reduces the density of products and is free of cost. Also, there are numerous industrial applications for zinc oxide (ZnO) and fumed silica (SiO_2), which are an inorganic white powder. Additionally, magnesium oxide (MgO) offers high thermal conductivity and low electrical conductivity, while Barium Titanite ($BaTiO_3$) is used as a capacitor dielectric.

Titanium dioxide (TiO_2) is used in electrical ceramics, metal patinas, catalysts, electric conductors and chemical intermediates. The HIOKI 3522-50 LCR Hi-tester device measured the characterization of nanocomposite insulation industrial materials. It has been characterized all nanocomposites and multi-nanocomposites made from polyvinyl chloride as shown in Table 1.

Table 1. Electric and dielectric properties for new polyvinyl chloride nanocomposites and multi-nanocomposites materials

Nanoparticles and nanocomposites	Dielectric constant	Multiple nanocomposites	Dielectric constant
Pure PVC	3	(5wt.% ZnO+3wt.% Clay)/PVC	2.758
Clay	2	(5wt.% ZnO+5wt.% Clay)/PVC	2.707
ZnO	1.8	(5wt.% $BaTiO_3$+3wt.% Clay)/PVC	2.907
$BaTiO_3$	3.8	(5wt.% $BaTiO_3$+5wt.% Clay)/PVC	2.876
MgO	9	(5wt.% $BaTiO_3$+7wt Clay)/PVC	2.901
TiO_2	10	(5wt.% $BaTiO_3$+7wt ZnO)/PVC	2.835
5wt.% Clay/ PVC	2.801	(10wt.% $BaTiO_3$+15wt.% Clay)/PVC	2.507
5wt.% ZnO/PVC	2.831	(5wt.% $BaTiO_3$+15wt.% MgO)/PVC	4.336
5wt.% $BaTiO_3$/PVC	3.084	(5wt.% $BaTiO_3$+15wt.% TiO_2)/PVC	4.888

2.3. Specifications of devices and measurements

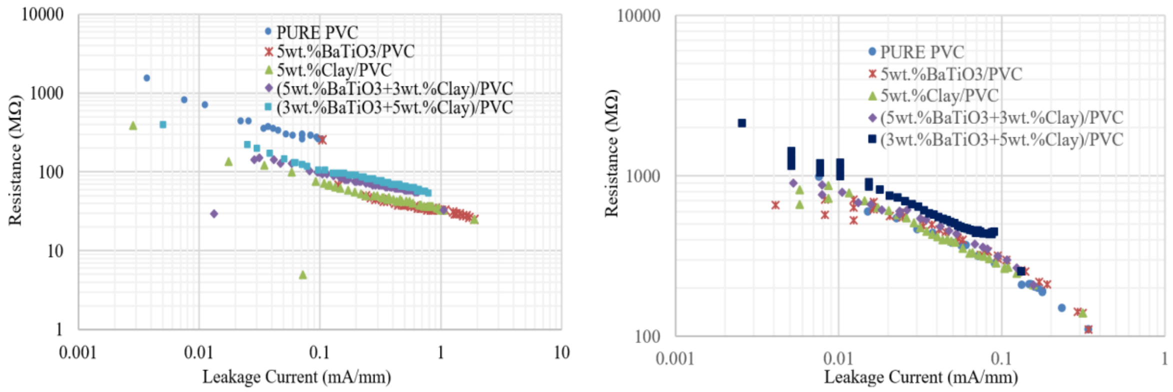
The distribution of the electric field along the thickness of the insulation layer of various nanocomposite materials has been studied using the HI-POT tester model ZC2674 device; the electrical specifications of the Hi-tester gadget are as follows: 1 kVA, 20 kV, and 10 mA, alternating current (AC) and direct current (DC) power sources. During uniform electric field measurements, a test sample of 35 mm diameter is sandwiched between two good contacts of copper cylindrical electrodes (50 mm). On the other wise, in the case of non-uniform electric fields, the insulation test sample sandwiched between a flat copper plate and a tip electrode pin with a diameter of less than 0.5 mm. The performance test of the dielectric degradation is carried out in the laboratory using a set-up, HI-POT tester model ZC2674 device. Expert evaluation of nanocomposite materials in uniform and non-uniform electric fields is critical. Thus, two parallel plates were employed to compress a nanocomposite specimen in order to disseminate equal electric field distribution.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Under uniform and nonuniform electric fields, the measurements of breakdown characterization of industrial insulation materials made of pure and nanocomposite materials are shown in Figures 3 to 5. In Figures 3(a) and 3(b), constant and non-constant electric fields at 25 °C are used to show dielectric degradation of pure materials and nanocomposite materials. It has been obvious that adding individual nanoparticles (Clay, ZnO, and $BaTiO_3$) changes resistance of polyvinyl chloride, especially, in case of adding two different types of nanoparticles together in polyvinyl chloride base matrix materials. It has been noticed that type and concentration of nanoparticles are changing resistance degradation and conduction current in polyvinyl chloride nanocomposites specimens compared with the traditional polyvinyl chloride dielectrics under uniform electric fields. The dielectric degradation reduces the conduction current under electric fields with an increasing percentage of clay nanoparticles. Whatever, the dielectric degradation has been increased with increasing percentage $BaTiO_3$ nanoparticles under electric fields.

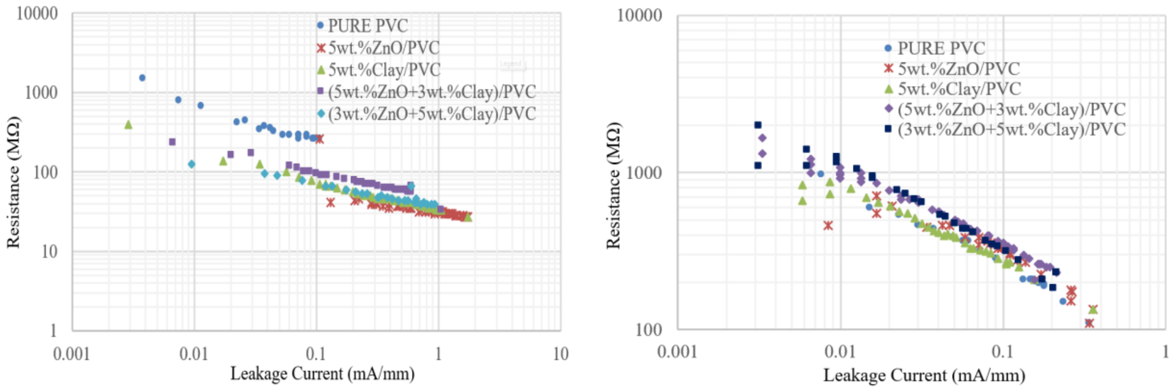
On the other hand, Figures 4(a) and 4(b) display the dielectric degradation characterization of the polyvinyl chloride test samples as a function of leakage current inside specimens under uniform and non-uniform electric fields. It is clarified that the dielectric degradation reduces the conduction current under electric fields with an increasing percentage of zinc oxide nanoparticles.

Additionally, Figures 5(a) and 5(b) displays the dielectric degradation characterization of the polyvinyl chloride nanocomposites test samples as a function of leakage current inside specimens under uniform and non-uniform electric fields compared to virgin samples. It has been clarified that dielectric degradation reduces the conduction current under electric fields with increasing percentage of zinc oxide nanoparticles. Whatever, the dielectric degradation has been increased with increasing percentage $BaTiO_3$ nanoparticles under electric fields.



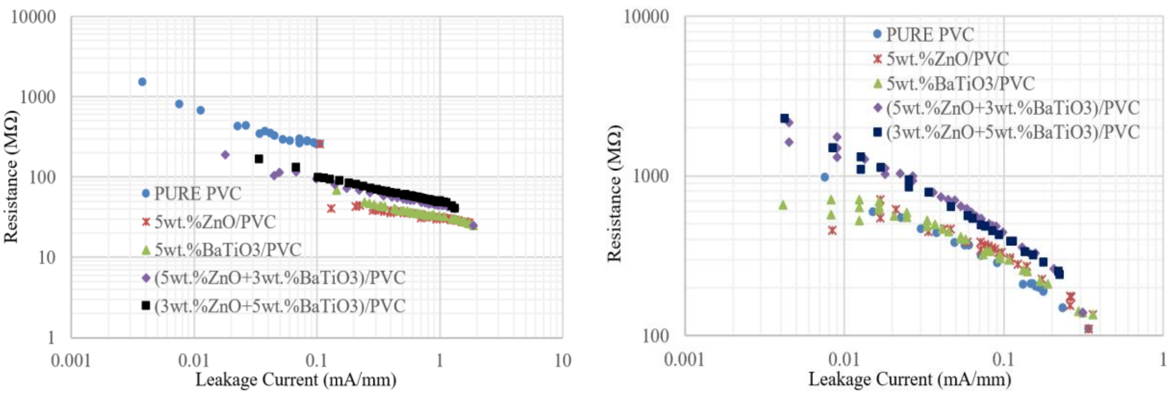
(a) (b)

Figure 3. Samples of resistance degradation characteristics for ($BaTiO_3$ and Clay)/PVC nanocomposites (a) under uniform electric fields and (b) under non-uniform electric fields



(a) (b)

Figure 4. 3 Samples of resistance degradation characteristics for (ZnO and Clay)/PVC nanocomposites (a) under uniform electric fields and (b) under non-uniform electric fields



(a) (b)

Figure 5. Samples of resistance degradation characteristics for (ZnO and $BaTiO_3$)/PVC nanocomposites (a) under uniform electric fields and (b) under non-uniform electric fields

4. SIMULATION MODELS

A power cable with polyvinyl chloride insulation, voltage rating of 11 kV with void (spherical) is considered here the parameters which includes calculating the resistance and capacitance of the insulator and void. To simulate partial discharge and produce void outcomes, MATLAB® Simulink is employed. The partial discharge activity in insulators with void expressed by a capacitance equivalent circuit designed by Gemant and Philippoff [20]–[23]. Similar to electric field-based approaches [24], [25], this model simulates the temporal characteristics of the electric field inside the void. Partial discharge must be taken into account to assess how well insulating systems work; therefore, the most partial discharges take place in electrically weak spots of solid dielectric materials.

The discharge current's value is determined by the input voltage, and the input voltage has been raised as a result. Due to its consideration of both the contents of nanocomposites and the impact of local charge accumulations brought on by prior discharges, the partial discharge equivalent circuit is more accurate in its presentation of voids in nanocomposites materials. A power cable's insulation material's dielectric constant may change if nanoparticles are added; whether or not this affects the insulator's self-capacitance, it will have an effect on the partial discharge current in the void. A single-core power cable configuration is illustrated in Figure 6 as well as a model configuration that complies with Nexans energy networks limited's design standards 6622-BS 7835 [26]. Table 2 illustrates the model parameter of single-core power cables and it has been considered that the void diameter between the conductor surface and the insulation's inner surface is 1 mm [27]. The simulation lasted 0.02 seconds and used the ode23tb (stiff/TR-BDF2) solver in MATLAB® Simulink with a variable step-size and non-adaptive algorithm configuration. The algorisms and techniques applied to use ODE solvers vary in order of accuracy [28], [29] to solve different types of systems (stiff or non-stiff).

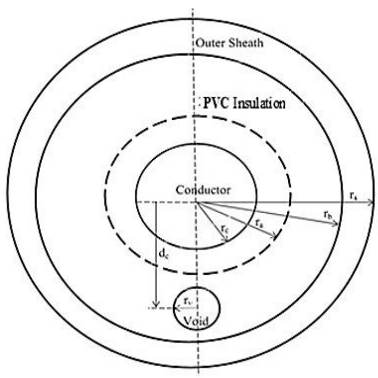


Figure 6. Cross-sectional area single core cable with circle void

Table 2. Characteristics of single-core power cable [27]

Specifications	Rating
Rated voltage (kV)	11
Core number	1
Cross-sectional area of conductor (mm^2)	150
Diameter over conductor (mm)	14.3
Diameter over insulation (mm)	22.2
Overall diameter (mm)	38
Insulation dielectric constant (PVC)	3.3
Relative permittivity of water	81
Relative permittivity of air	1
Relative permittivity of rubber impurity	1.6
Permittivity of vacuum(F/M)	8.85E-12
Specific air-void conductance (mho/m)	1.00E-08
Specific insulation PVC conductance (mho/m)	7.33E-14
Specific water-void conductance (mho/m)	5.5E-06
Specific impurity-void conductance (mho/m)	5.96E+07

5. SIMULATION RESULTS AND DISCUSSION

The discharge occurred once because of the non-repetitive switching mode of the breaker; It is important to swap out the breaker with a circuit designed for repetitive switching in order to increase the frequency of switching. A new dielectric material is needed in order to enhance electric applications. In this way, the partial discharge current can be controlled by varying the relative permittivity of the insulator material by adding nanoparticles to the dielectric material. In the following results, partial discharge currents are illustrated inside pure and variant nanocomposites of power cables model containing voids (air-water-rubber impurity).

The partial discharge current inside air void has been presented that is located at 25% from nanocomposites insulation materials thickness with conductor voltage 11 kV in single-core cable. Figure 7 illustrates the simulation model behavior of partial discharge current inside the air cavity by using pure and nanocomposites of polyvinyl chloride insulation materials. It has been observed that partial discharge current reaches 0.03421 mA by using pure polyvinyl chloride insulation material but a 10% concentration of $BaTiO_3$ nanoparticles in polyvinyl chloride further reduced partial discharge current to 0.01057 mA. It has been discovered that adding a concentration of (10wt%$BaTiO_3$+15wt%Clay) nanoparticle to polyvinyl chloride reduced the partial discharge current to 0.006377 mA due to the influence of clay nanoparticle on dielectric constant reduction. Whatever, adding concentration of (10wt.% $BaTiO_3$+15wt.%TiO_2) nanoparticle to polyvinyl chloride has been increased the partial discharge current to 0.04796 mA due to the effect of high dielectric constant of TiO_2 nanoparticles as shown in Figure 7.

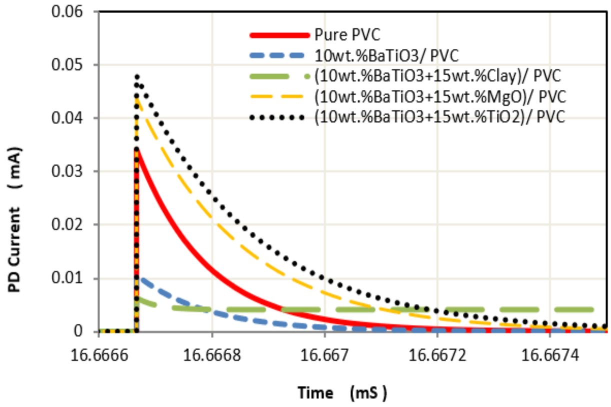


Figure 7. Partial discharge current for $BaTiO_3$/PVC nanocomposites in case of containing air voids

On the other hand, it has been presented that the partial discharge current inside water void which is located at 25% from nanocomposites insulation materials thickness with conductor voltage 11 kV in single-core cable. So that, Figure 8 illustrates the behavior of partial discharge current inside the water cavity by using pure polyvinyl chloride and nanocomposites insulation materials. It has been observed that partial discharge current reaches to 0.02085 µA by using pure polyvinyl chloride insulation material. Furthermore, due to the high dielectric constant of $BaTiO_3$ nanoparticles, adding a concentration of (10wt.%$BaTiO_3$) nanoparticles to polyvinyl chloride boosted the partial discharge current to 0.05038 A. The high dielectric constant of TiO_2 nanoparticles led to a 0.0385 partial discharge current when added with (10wt% $BaTiO_3$+15wt% TiO_2) nanoparticle into polyvinyl chloride, as shown in Figure 8. In addition, the simulation model has been presented that the partial discharge current inside rubber impurity void which is located at 25% from nanocomposites insulation materials thickness with conductor voltage 11 kV in single-core cable.

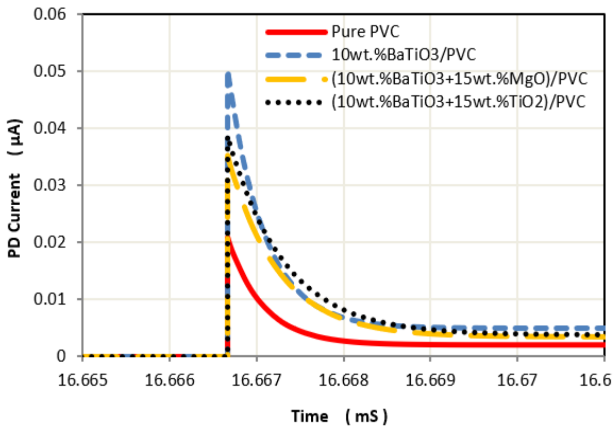


Figure 8. Partial discharge current for $BaTiO_3$/PVC nanocomposites in case of containing water voids

Figure 9 illustrates the behavior of partial discharge current inside the impurity cavity by using pure and nanocomposites polyvinyl chloride insulation materials. The partial discharge current has reached 1.923 zA in case of using pure polyvinyl chloride insulation material. Whatever, the addition of a concentration of (10wt.%$BaTiO_3$) nanoparticle to polyvinyl chloride increased the partial discharge current to 4.658 zA because the $BaTiO_3$ nanoparticles improved the dielectric constant. Also, the addition of (10wt% $BaTiO_3$+15wt% TiO_2) nanoparticles to polyvinyl chloride increased the partial discharge current to 3.556 zA due to TiO2 nanoparticles' effect on increasing high dielectric constant.

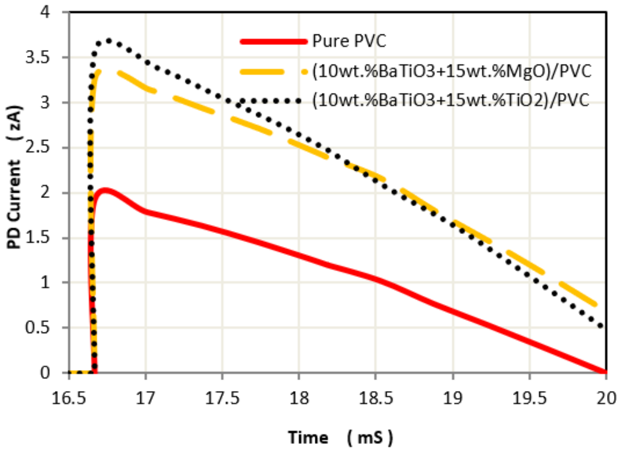


Figure 9. Partial discharge current for $BaTiO_3$/PVC nanocomposites in case of containing rubber impurity voids

6. IMPACT OF NANOPARTICLES ON DIELECTRICS

It is crucial to acquire new dielectric materials because of the industrial need to improve electric applications. Thus, by adding a single or a number of nanoparticles to dielectrics, the relative permittivity of the insulator material can be changed to regulate the partial discharge current. Adding clay nanoparticles decreasing the dielectric constant to prevent accumulating charges inside polymer matrix specimens; moreover, zinc oxide nanoparticles are effective for decreasing the dielectric constant and preventing accumulating charges inside polymer nanocomposite matrix. On the otherwise, adding $BaTiO_3$ nanoparticles of aid to increasing capacitive charges via increasing the dielectric constant of polymer nanocomposite matrix. Nanocomposite and pure materials suffer from higher dielectric degradation when subjected to a non-uniform electric field than they do when subjected to a uniform electric field. The experimental testing is performed on a laboratory-scale and has been concluded that the dielectric degradation reduces the conduction current under electric fields with increasing percentage of clay and zinc oxide nanoparticles. Regardless, the dielectric degradation has increased with increasing percentages of $BaTiO_3$ nanoparticles. According to this study, the dielectric deterioration of pure and nanocomposite materials in non-uniform electric fields is greater than in uniform electric fields. The laboratory experiment result strengthens the simulation result that the PVC nanocomposites is more efficient to avoid the partial discharges than the traditional PVC. Therefore, the simulation MATLAB® software model is successfully deployed as a tool to improve the design material of power cables. The simulations reveal that the partial discharges of nanocomposites are reduced by using certain concentrations of clay and zinc oxide nanoparticles compared with traditional materials. Table 3 has been depicted the maximum partial discharge current for variant voids located at 25% from inside pure and nanocomposites insulation materials thickness with conductor voltage of 11 kV single-core cable.

Table 3 Maximum partial discharge current for variant voids

Material	Max. PD current (A) Air void	Max. PD current (A) Water void	Max. PD current (A) Rubber impurity void
Pure PVC	3.421E-05	2.085E-08	1.923E-21
10wt.%BaTiO3/PVC	1.057E-05	5.038E-08	4.658E-21
(10wt.%BaTiO3+15wt.%Clay)/PVC	6.377E-06	2.664E-05	9.775E-18
(10wt.%BaTiO3+15wt.%MgO)/PVC	4.385E-05	3.522E-08	3.249E-21
(10wt.%BaTiO3+15wt.%TiO2)/PVC	4.796E-05	3.856E-08	3.556E-21

7. CONCLUSION

Design aspects of employing nanoparticles to improve the dielectric strength of single-core power cables lead to optimal selection of types and concentrations of nanoparticles for prevention partial discharges. Experimental and theoretical characterization have been created and evaluated for electric degradation and partial discharge of modern PVC nanocomposites. It has been investigated on partial discharge currents of PVC nanocomposites under various uniform and non-uniform electric fields and via variant void patterns (air, water, rubber impurity). A change in insulation deterioration is occurring with regard to the types and concentrations of nanoparticles (Clay, ZnO, and $BaTiO_3$) if they are embedded in traditional power cable insulation under uniform and non-uniform electric fields, especially in case of using two different nanoparticles types in base matrix materials. Partial discharge monitoring is critical to evaluating the effectiveness of insulation systems since it primarily occurs in areas of solid dielectric material that are electrically weak. The dielectric constant of power cable insulation material is affected by nanoparticles, causing self-capacitance, and then partial discharge current inside void patterns (air, water, and rubber impurity). Adding clay and zinc oxide nanoparticles decreases the dielectric degradation and prevents accumulating charges inside polymer matrix specimens. On the otherwise, adding $BaTiO_3$ nanoparticles of aid to increasing capacitive charges and dielectric degradation of polymer nanocomposite matrix. Dielectric degradation of pure and nanocomposite materials in non-uniform electric field are higher than dielectric strength of pure and nanocomposite materials in uniform electric field. The partial discharge current is reduced or increased when nanocomposite materials are used instead of pure PVC insulation material. In addition, the high partial discharges occur due to air voids in pure and polymer nanocomposites with respect to water or rubber impurities; it is more penetration inside insulation and more effective on polymer dielectric strength and degradation. Especially, it has been deduced that an excess values resistance property via using individual and multiple nanoparticles (Clay, ZnO, and $BaTiO_3$) in polyvinyl chloride under non-uniform electric fields measurements.

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