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# Application of Surface Modified XLPE Nanocomposites for Electrical Insulation of High Voltage Cables- Partial Discharge Study

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## Abstract

This paper presents the experimental results of PD test using IEC 60270 standard for 0-27.5 kV range with the PD characteristics of XLPE nanocomposites for un-modified, agglomerated and Octylsilane modified silica nanofillers using nano 1, 2, 3, 4, 5, 10 wt %. The unmodified and agglomerated nanocomposites show the lowest PD activity at nano 5 wt %. The surface modification of nanofiller helps to reduce the PD formation marginally due to improved nanofiller dispersion. Octylsilane surface modified XLPE/silica nano 3 wt % exhibits the lowest PD activity. To prove the further suitability of Octylsilane surface modified nanocomposites over unmodified and agglomerated nanocomposites, the discharge inception voltage (DIV) and breakdown voltage (BDV) have also been measured using IEC 60270 standard. The hypothetical theory has been proposed to explain the role of nanofillers in reducing PD activity and increasing DIV as well as BDV.

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*Keywords:* Crosslinked polyethylene; nanocomposites; electrical insulation; partial discharge; morphology; surface modification

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## 1. Introduction

The field of nanocomposite electrical insulations (nanofiller + electrical insulation) has gained a substantial attention of the researchers in recent years. The inclusion of nanofiller to the insulation material leads to the marginal improvement in its dielectric, electrical, thermal properties etc [1-5]. But, the agglomeration (or aggregation) of the nanofillers has questioned its reliability and application. The agglomerated nanocomposites have reported the

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adverse performances such as decreased breakdown strength and other unfavourable electrical performance. This type of behaviour biases the conclusion of different theories established to explain the role of nanofiller in the improvement of electrical, mechanical, thermal etc properties of nanocomposites. Recently, it has been found that the surface modification (generally by Silane agents) of the nanofillers acts as an adhesion between nanofillers and polymer matrix which improves the dispersion of nanofillers. This improves the dielectric properties such as AC and DC breakdown strength, electrical and water tree resistance while reducing the space charge, permittivity, dielectric loss etc [6-10]. Hence, this favours the application of surface modified nanofillers with base materials such as epoxy resin, polyvinyl chloride, XLPE etc. for electrical insulation.

XLPE is considered as a suitable insulation material for the high voltage transmission of electrical power. But, the increased voltage rating of XLPE based electrical cables has also increased the probability of formation of water tree, electrical tree, PD etc. inside the insulation. The inclusion of nanofillers improves the dielectric, electrical, thermal etc properties of the insulation materials. Recently, nanocomposite materials have been developed which procrastinate PD and avoid further consequences. The presence of nanofiller hinders the PD propagation inside the insulation. But, the dispersion of the nanofillers inside the polymer matrix plays a crucial role in this hindrance. The aggregation or agglomeration of nanoparticles has limited its application in the field of dielectrics and electrical insulation. To avoid the agglomeration, the nanofillers are modified using chemical coupling agent which improves the dispersion of the nanofiller considerably. Although the addition of nanofillers convinces its application in XLPE material to improve the foresaid properties, very less research in the field of PD has been carried out. The authors have already reported the PD study of XLPE/silica un-modified nanocomposites in [11]. In addition to this study, this paper presents the PD study agglomerated and Octylsilane modified XLPE/silica nanocomposites. It is expected that the agglomerated nanocomposites may deliver almost same performance as that of unmodified or virgin samples.

This paper is organized as follows: Section 1 explains the introduction to the PD and nanocomposite applications. Section 2 explains the methodology and characterization study of prepared nanocomposites. Section 3 & 4 comprises of experimental method followed and results of the testing. The enhancement attributed to the nanofillers is explained in Section 5 with the help of hypothetical theory.

## 2. Preparation and Characterization

XLPE/silica nanocomposites (nanosilica dimensions - 7 to 14 nm) are prepared using twin screw extruder and injection moulding for three cases using different mixing time and nanofiller as follow:

### 2.1. Case 1

PE granules with un-modified silica nanoparticles are mixed for 10 minutes and at 120 °C temperature. Dicumyl peroxide (DCP) is used as crosslinking agent. The nanocomposites prepared using this method are referred as unmodified nanocomposites.

### 2.2. Case 2

The multiple number of specimens are prepared for each wt %. It is evident from the microscopic observation that the nanofillers cannot be dispersed in homogeneous manner. Some of the specimens in each wt % show the agglomeration in the size of  $\mu\text{m}$  is observed as depicted in Fig. 1a and Fig. 1b.

### 2.3. Case 3

The same method is followed as in case 1 except the Octylsilane modified silica nanoparticles are used. Fig. 1c and Fig. 1d shows that the better (or ideal) dispersion of nanoparticles is achieved. In this case Octylsilane acts as a coupling agent between polymer matrix and silica nanoparticles. Hereafter, the nanocomposites prepared using this method are referred as Octylsilane modified nanocomposites.

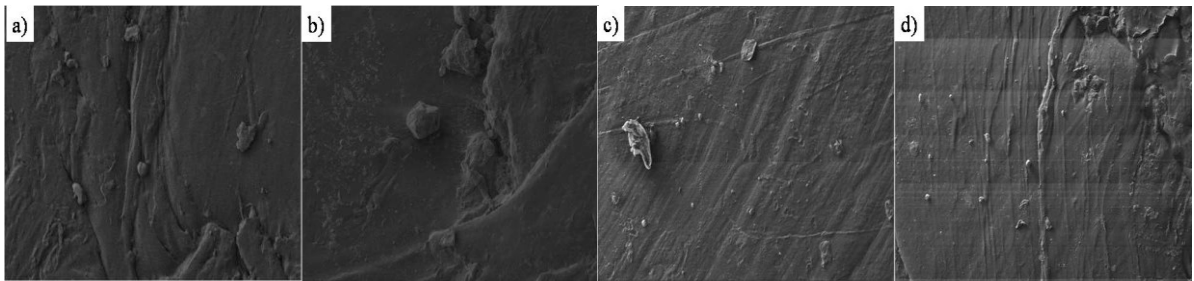


Fig. 1. SEM images of (a) XLPE/silica nano 2 wt % agglomerated nanocomposite; (b) XLPE/silica nano 3 wt % agglomerated nanocomposite; (c) XLPE/silica nano 2 wt % Octylsilane modified nanocomposites; (d) XLPE/silica nano 3 wt % Octylsilane modified nanocomposites.

### 3. Experimental Test

The PD test is carried out using needle-plane configuration test setup as shown in Fig. 2. The PD performance is monitored using the measurement of DIV at which PD activity (or pulses) starts to appear, breakdown voltage (BDV) at which the breakdown of the specimen occurs and the apparent charge (pC) Vs applied voltage (kV) characteristics following the same method reported in Reference [11]. An ideal performance of insulation is which has highest DIV and BDV with lesser PD activity. As discussed earlier, the surface treatment of nanofiller has a considerable impact on its dielectric, electrical, thermal properties etc. With this context, this experimental study investigates the PD characteristics of agglomerated and Octylsilane modified XLPE/silica nanocomposites.

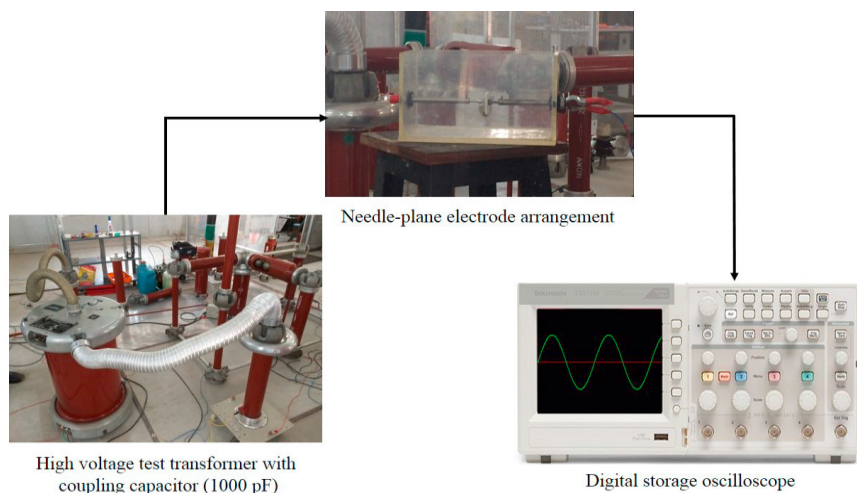


Fig. 2. Experimental test setup used for PD test.

### 4. Results and analysis

The comparison of PD activity is made with the virgin XLPE sample which is shown in Fig. 3. PD characteristics and PD activity for nano 1, 2, 3, 4, 5, 10 wt % is illustrated in Fig. 4, Fig. 5, Fig. 6, Fig. 7, Fig. 8, Fig. 9 respectively. From Fig. 4a-9a, it can be seen that the PD in all agglomerated nanocomposite samples remains almost same or less as compared to un-modified nanocomposite samples. The same can be supported by the Fig. 4c-9c respectively. The comparison clearly supports the number of PD pulses in agglomerated nanocomposites are almost as same as that of unmodified nanocomposites. This similarity is attributed to the  $\mu\text{m}$  sized agglomerates present in the agglomerated nanocomposite samples. Here, agglomerates lets the PD to reach towards the ground electrode. In case of XLPE/silica nano 3 wt % and 5 wt % samples in Fig. 6a and Fig. 8a, the PD activity present in agglomerated samples is less than the un-modified sample. This is due the point of the application of voltage i.e. the location of needle point. (explained later in the section 5: theory of PD propagation).

The importance of the results shown in Figs. 3-9 is to decide the optimal weight percentage of nanofiller which gives favorable performance towards PD study. It can be seen that the nanofiller addition clearly reduces the PD activity inside the sample. The surface modification of nanofiller has marginal influence on the reduction of PD characteristics and activity. The surface modification of the nanofiller helps to achieve the better dispersion inside the polymer matrix. This leads to the hindrance to the PD formation and propagation. It can be seen from Fig. 4a and 4d, Fig. 5a and 5d, Fig. 6a and 6d, Fig. 7a and 7d, Fig. 8a and 8d and Fig. 9a and 9d that in all wt % of Octylsilane surface modified nanocomposite samples, the PD remains well below the virgin and agglomerated nanocomposite samples. For un-modified case, XLPE/silica nano 5 wt % sample has the lowest PD activity with lowest DIV and BDV [11]. This content is considered as the optimal content for PD characteristics.

PD characteristics and PD activity for agglomerated nanocomposites is shown in Figs. 4a-9a and Figs 4b-9b respectively. It should be noted that, the PD characteristics and activity inside agglomerated nanocomposites is almost same as that of unmodified nanocomposites. In this case, the agglomeration of the nanoparticles lead to PD formation and propagation without any resistance. To quantify, the agglomerated nanocomposites have the optimal content between 4-5 wt %. In case of Octylsilane surface modified XLPE/silica nanocomposites, the nano 3 wt % sample is having the lowest PD present as shown in Fig. 6 with highest BDV and DIV as shown in Table 1. Clearly, this better performance is attributed to the dispersion of nanofiller due to surface modification. To explain further, the electrical insulation should have lowest number of PD pulses with highest BDV and DIV.

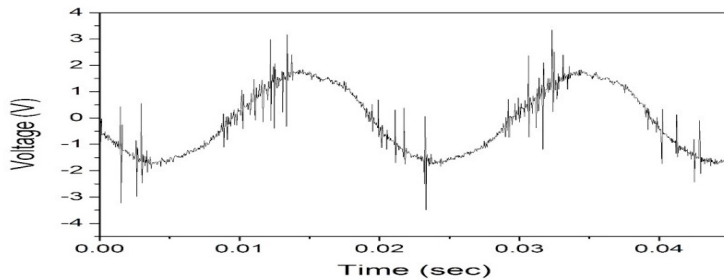


Fig. 3. PD pulses appearing at 15.5 kV in virgin XLPE.

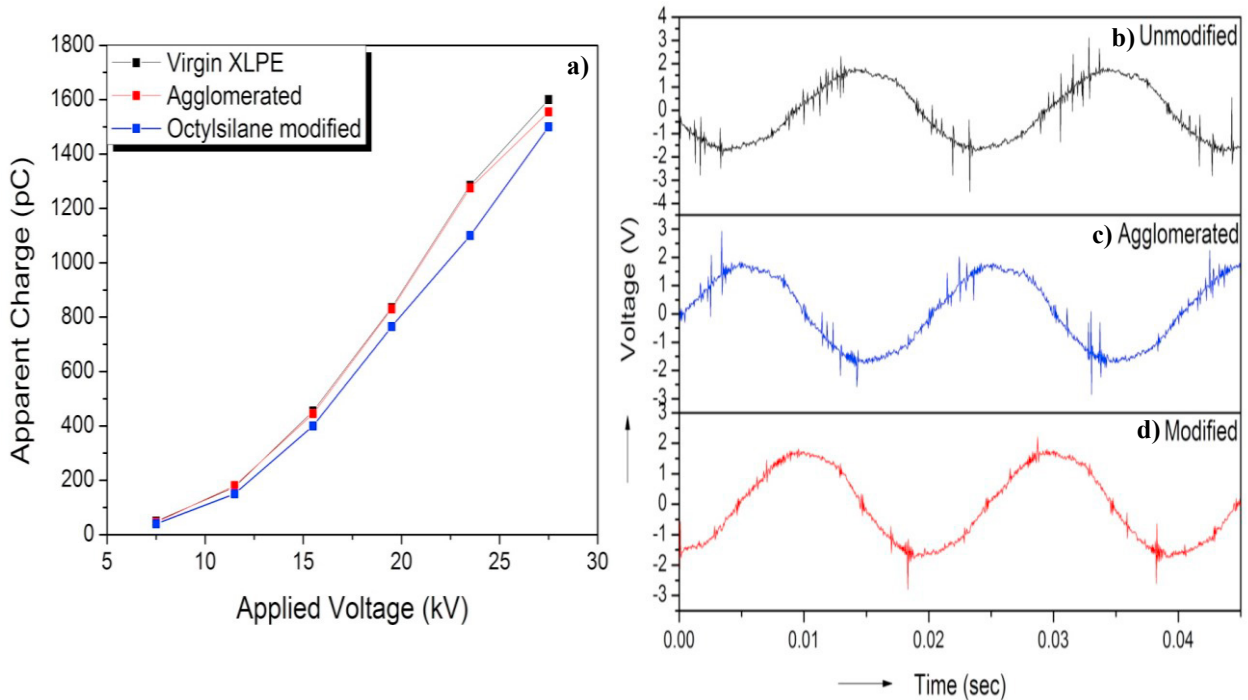


Fig. 4. (a) PD characteristics of agglomerated and Octylsilane surface modified XLPE/silica nanocomposite for nano 1 wt %; PD pulses appearing at 15.5 kV in (b) unmodified; (c) agglomerated; (d) Octylsilane surface modified XLPE/silica nanocomposite for nano 1 wt %.

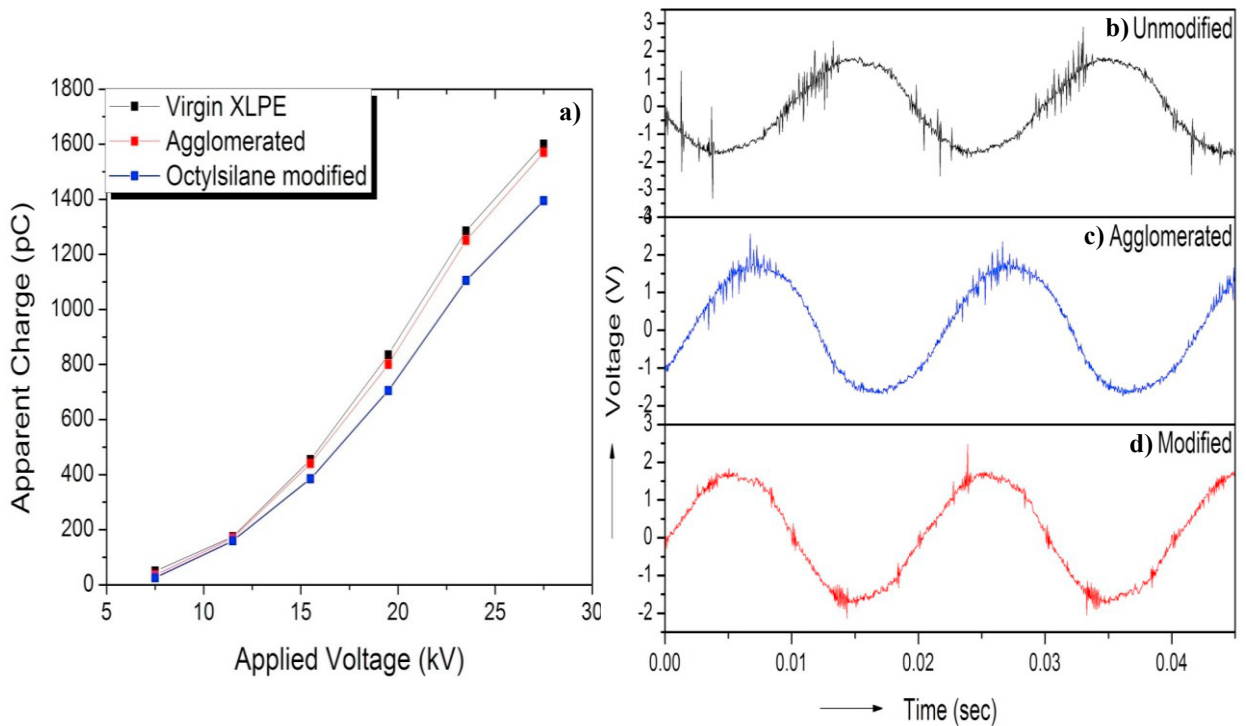


Fig. 5. (a) PD characteristics of agglomerated and Octylsilane surface modified XLPE/silica nanocomposite for nano 2 wt %; PD pulses appearing at 15.5 kV in (b) unmodified; (c) agglomerated; (d) Octylsilane surface modified XLPE/silica nanocomposite for nano 2 wt %.

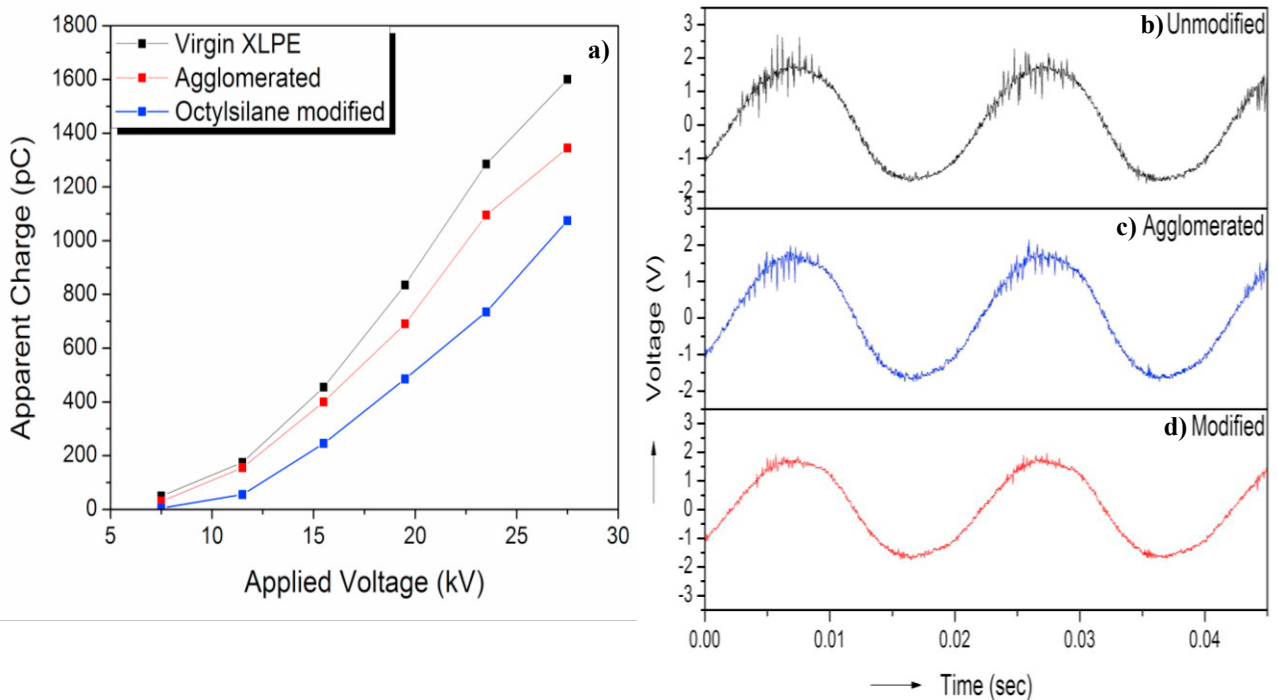


Fig. 6. (a) PD characteristics of agglomerated and Octylsilane surface modified XLPE/silica nanocomposite for nano 3 wt %; PD pulses appearing at 15.5 kV in (b) unmodified; (c) agglomerated; (d) Octylsilane surface modified XLPE/silica nanocomposite for nano 3 wt %.

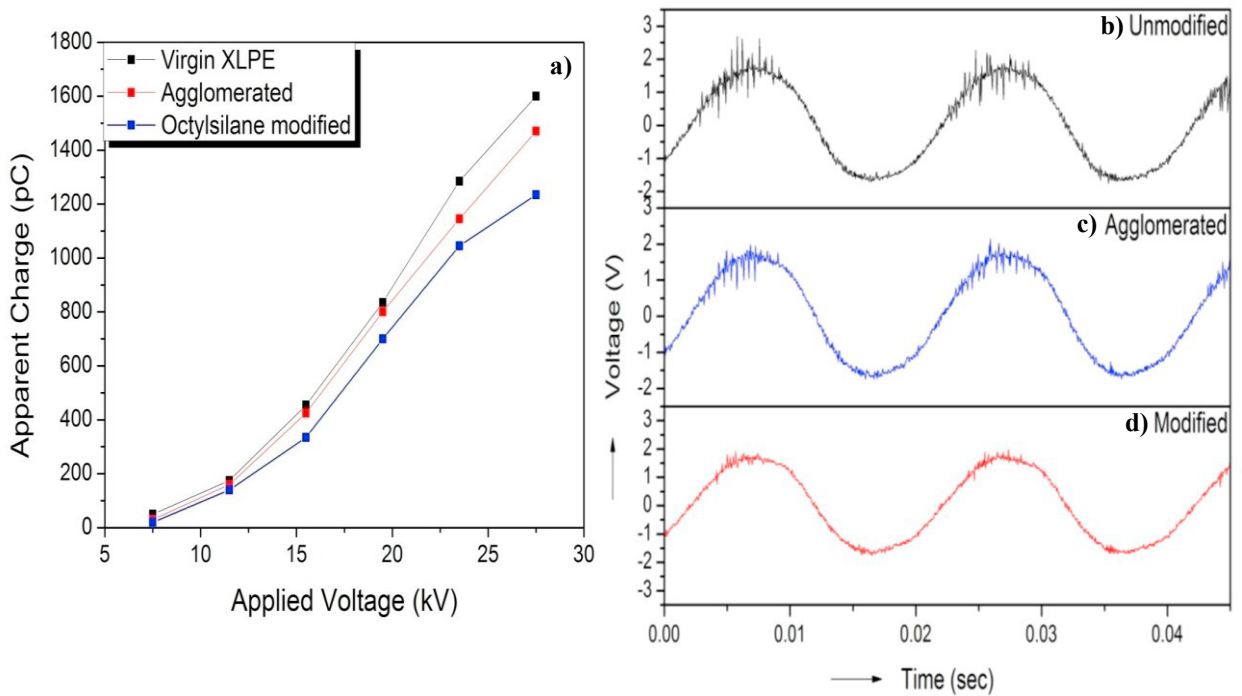


Fig. 7. (a) PD characteristics of agglomerated and Octylsilane surface modified XLPE/silica nanocomposite for nano 4 wt %; PD pulses appearing at 15.5 kV in (b) unmodified; (c) agglomerated; (d) Octylsilane surface modified XLPE/silica nanocomposite for nano 4 wt %.

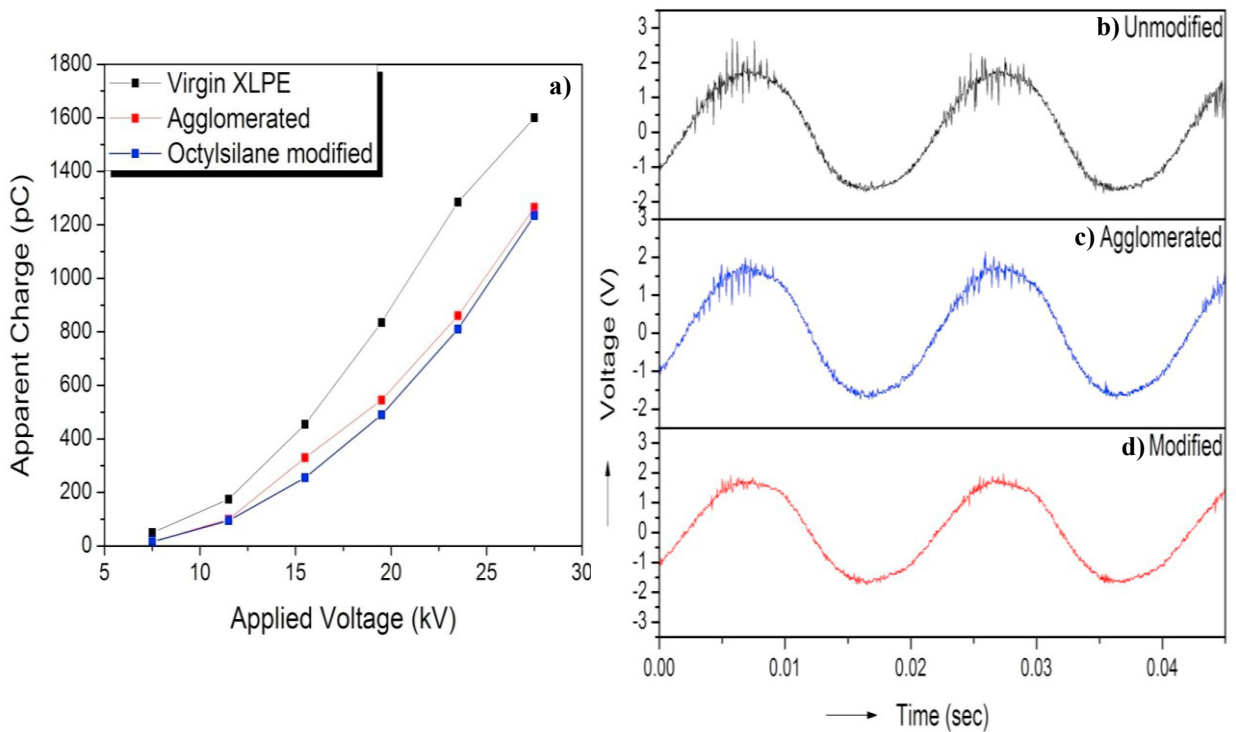


Fig. 8. (a) PD characteristics of agglomerated and Octylsilane surface modified XLPE/silica nanocomposite for nano 5 wt %; PD pulses appearing at 15.5 kV in (b) unmodified; (c) agglomerated; (d) Octylsilane surface modified XLPE/silica nanocomposite for nano 5 wt %.

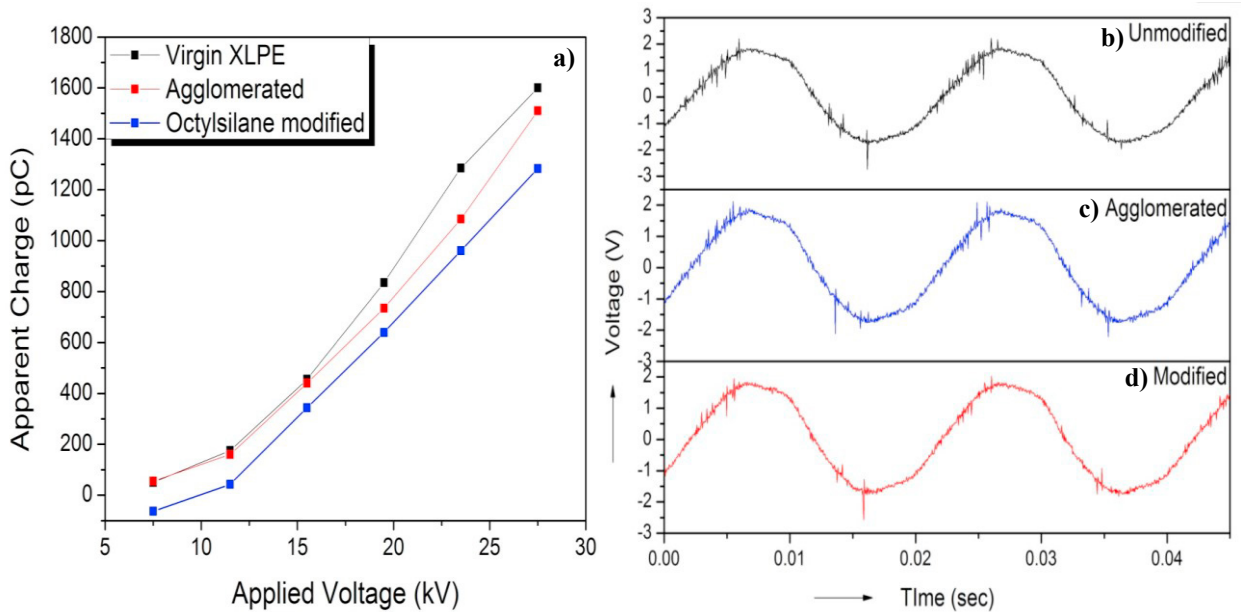


Fig. 9. (a) PD characteristics of agglomerated and Octylsilane surface modified XLPE/silica nanocomposite for nano 10 wt %; PD pulses appearing at 15.5 kV in (b) unmodified; (c) agglomerated; (d) Octylsilane surface modified XLPE/silica nanocomposite for nano 10 wt %.

In an ideal condition, it should accept the PD at high input voltages so that the probability of PD formation will be reduced. Also, it should be able to sustain the applied voltages which necessitates higher BDV value. As shown in Figs. 4-9 and Table 1, Octylsilane surface modified XLPE/silica nano 3 wt % has lowest PD formation with highest DIV and BDV. In a summary, the surface modified nanocomposites has low optimal content of nanofiller towards PD characteristics as compared to the un-modified and agglomerated nanocomposites. Hence, the surface modified XLPE/silica nanocomposites can also be considered as economically viable solution over the un-modified and agglomerated nanocomposites. Due to the limitations of the available test system, the relevant information regarding PD pulses cannot be extracted and hence not discussed here. The importance of showing PD pulses is to show the severity of the PD detection and formation.

Table 1. Discharge inception voltage and breakdown voltage values of XLPE/silica nanocomposites

| Nano filler (wt %) | Discharge Inception Voltage (kV) |                      | Breakdown Voltage (kV) |                      |
|--------------------|----------------------------------|----------------------|------------------------|----------------------|
|                    | Agglomerated                     | Octylsilane modified | Agglomerated           | Octylsilane modified |
| 0                  | 7.0                              | 7.0                  | 32.0                   | 32.0                 |
| 1                  | 7.2                              | 7.9                  | 32.4                   | 34.7                 |
| 2                  | 7.3                              | 8.3                  | 33.7                   | 35.1                 |
| 3                  | 7.8                              | 10.1                 | 35.6                   | 40.5                 |
| 4                  | 8.5                              | 9.7                  | 36.8                   | 40                   |
| 5                  | 8.6                              | 8.9                  | 37.4                   | 39.1                 |
| 10                 | 8.0                              | 9.1                  | 34.6                   | 39.5                 |

## 5. Theory of PD Propagation

It is vital to understand the role of nanofillers in hindrance of PD. Generally in PD test, the sample to be tested is held between the high voltage and ground electrode as shown in Fig. 2. It can be seen in Fig. 10a that the

unmodified silica nanofillers are not dispersed in very good manner. Due to this the frequency of encounter of PD (denoted by black color line) is very less and it is easily able to reach to the ground electrode. This may lead to the breakdown of the sample which will reduce the life of an insulation. In case of agglomerated samples shown in Fig. 10b, the nanofillers get agglomerated due to less mixing time. This leads to concentration of nanofillers at several points. Hence, PD can reach to the ground electrode easily as in case of unmodified samples.

To achieve a very good dispersion, the surface of the nanofillers is modified with Octylsilane which acts as a coupling agent and improves the dispersion as well as the distribution of nanofillers marginally as shown in Fig. 10c. This helps to delay the propagation of PD and improves the life of insulation. The surface modification of the nanofillers enhances the dispersion and avoids the agglomeration. But, it should be noted that the ideal dispersion as shown in Fig. 10d may not be achieved in case of surface modified nanofillers. Hence, it is very much important to have standardised method of preparation to get ideal dispersion.

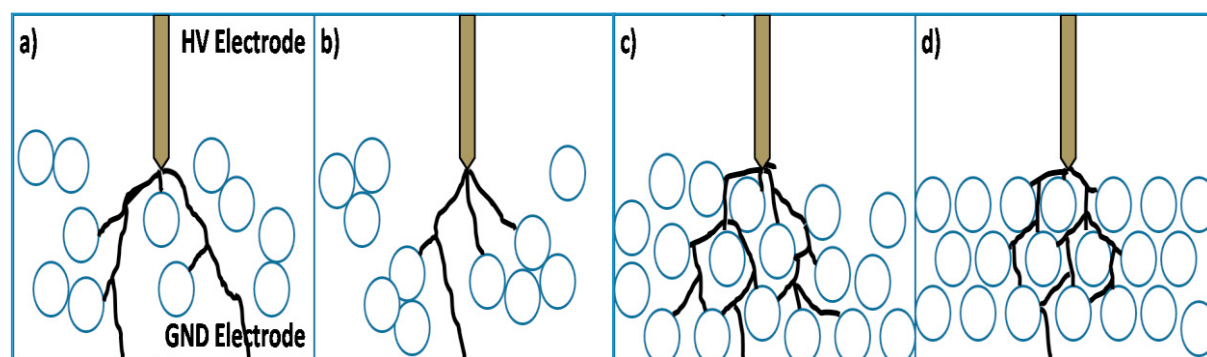


Fig. 10. Theory of propagation of PD in nanocomposites.

## 6. Conclusion

The PD study is conducted for XLPE/silica nanocomposites for un-modified, agglomerated and Octylsilane modified silica nanocomposites. From the comparison, following conclusions are drawn:

- i. PD activity can be summarized as,  $\text{Virgin} \leq \text{agglomerated} \leq \text{unmodified} < \text{surface modified}$  case.
- ii. The agglomerated and un-modified XLPE/silica nanocomposites have almost the same amount of PD present and also depends on the location of the application of voltage.
- iii. The Octylsilane modified XLPE/silica nano 3 wt % is having better PD performance than the un-modified nano 5 wt %. Hence the Octylsilane modified XLPE/silica nano 3 wt % is economically viable solution over the un-modified and agglomerated nanocomposites.
- iv. The enhancement in the PD resistance by the inclusion of the nanofiller is attributed to the larger interfacial area and enhanced interactions to the surface modification of the nanofiller.

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