Research Article

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Understanding the Lightning Impulse Breakdown Strength of Carbon Quantum Dots-Modified Silica Nanofluids

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ABSTRACT

The study provides an understanding of lightning impulse characteristics of the mineral oil used in transformers and other high voltage applications. The withstanding capabilities of the mineral oil were studied under different experimental conditions such as electrode gap distance, electrode type, type of nano-filler and concentration of fillers. Experiments were conducted for electrode gaps of 5 mm and 10 mm. Different electrode configurations such as needle-sphere and needle-plane electrodes were used. Nanofillers such as SiO_2 and Carbon Quantum Dots-treated SiO_2 nanoparticles were used in various concentrations of 0.01 % wt., 0.05 % wt. and 0.1 % wt. of mineral oil. Comparisons were made for positive and negative polarities of lightning impulse test voltages. Experimental results were shown to understand the influence of nanoparticles to deliver better results in impulse-withstanding capabilities of commercially used mineral oil with improved performance in lightning impulse-withstanding strength.

Keywords: Lightning impulse studies; mineral oil; breakdown voltage; streamer velocity; carbon quantum dots; Nanofluid.

1. INTRODUCTION

Reliable electric power transmission and distribution depends on the effective operation of the equipment associated with it. The reliability of power transformers is a vital aspect of uninterrupted power delivery. Any form of transient load like lightning, can have a severe effect on the stability of the power transfer system (Kuffel and Zaengl, 1984). Transformers are more prone to lightning strokes which lead to system failure, resulting in the breakdown of the electric power supply. The equipment failure is a sequential result of transformer insulation breakdown caused by abnormalities like flashover caused by lightning. The transformer uses solid, liquid and gaseous insulations, among which the use of liquid insulation is predominant (Ushakov *et al.* 2007). Hence a liquid insulation system with better lightning impulse breakdown strength is a wise choice for ensuring continuous operation of the electric power network. Experiments and real-time lightning impulse testing of electrical insulation systems are considered a pivotal choice for the quality check of insulation systems. Information from lightning impulse (LI) discharge pulse shape is used to study the lightning breakdown mechanism (Thien *et al.* 2006). LI pulse is widely affected by various factors such as electrode geometry, as the electrode geometry subjects the strength of the electric field at the head of the propagation channel which affects the propagation velocity and dielectric strength of liquid insulation (Thien *et al.* 2016). Apart from electrode geometry, lightning impulse strength is much sensitive to changes in applied voltage, the polarity of applied voltage, electrode gap distance, properties of dielectric liquid and additives to insulation liquids which can affect the breakdown strength of insulation (Kuffel and Zaengl, 1984; Ushakov *et al.* 2007; Thien *et al.* 2006).

The application of mineral oil in high voltage equipment has been in practice for several decades because of its better stability under severe lighting conditions and superior dielectric properties as compared to other insulation liquids. Studies have reported that the addition of nano-sized particles can improve the breakdown characteristics of insulation liquids (Lv *et al.* 2014; Jin *et al.* 2015; Nagendran and Chandrasekar, 2018; Cavallini *et al.* 2015). Prior works have reported that the addition of SiO_2 nanoparticles results in better insulation properties in AC, DC and lightning impulse breakdown characteristics; in addition, the dielectric breakdown strength of nanofluids is higher under all forms of voltages and either of the polarities (Ramu *et al.* 2012). It is reported that the addition of surface-treated SiO_2 nanoparticles can improve the breakdown strength of mineral oil (Jin *et al.* 2014). The new findings (Dao *et al.* 2016; Guo *et al.* 2015; Uthirakumara, et al. 2018; Ma *et al.* 2013; Kasi Viswanathan, *et al.* 2020; Kasi Viswanathan, *et al.* 2019) about the properties of Carbon Quantum Dots (CQDs) for its various applications urges the interest in using it for surface treatment applications for nanoparticles like SiO_2.

The effect of adding nanoparticles on lightning impulse-withstanding strength was studied for liquid insulation samples such as mineral oil, SiO_2 nano-modified mineral oil and nanofluids of mineral oil by surface-treated SiO_2 nanoparticles using CQDs at varying concentrations levels. To examine the effect of electrode geometry and distance, needle-sphere and needle-plane electrodes with gap distances of 5 mm and 10 mm were used and the samples were tested for both positive and negative polarities of impulse voltages. A lightning impulse voltage generator with a digital storage oscilloscope was used to record, analyze and compare the LI test results. The resultant waveform determines the rise time, tail time and streamer velocity of LI waveforms. These test results make it possible to understand the dependency of lightning impulse strength of insulating liquids on electrode geometry, electrode gap distance, the polarity of applied voltage and the effect of adding nanoparticles in insulating liquids. The pure mineral oil used in the study was referred as 'MO', SiO_2 nanofluid as 'S1, S2, S3' and the CQDs-nanofluid as 'C1, C2, C3'.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1 Preparation of Nanofluid

Carbon quantum dots were used for the surface modification of nanoparticles of SiO_2 by laboratory processes using a solvent. The solution was stirred to coat the surface of SiO_2 nanoparticles and dried after chemical processes. The quantum dots form a 5-10 nm layer on the SiO_2 nanoparticles. Commercially available mineral oil was bought and filtered using micro-sized porous layer microfilter paper; the obtained nanoparticles were added to virgin mineral oil at 0.01 % wt. A magnetic stirrer was used to blend the mixture for about 45 minutes. Then the samples were subjected to ultra-sonication in an ultra sonicator for about 15 minutes. Prepared samples were thermally treated in a hot air oven for about 48 hours at a higher temperature to remove the moisture present in the prepared samples. All the samples prepared were left undisturbed for 36 hours to ensure the absence of nanoparticle agglomeration, by which the mixed nanoparticles tend to settle down at the bottom of the fluid.

2.2 Test Cell used for Lightning Impulse Experiment

The test cell used for the LI test consists of a liquid insulation specimen of 180 ml filled in a transparent test cell which contains needle-sphere electrode with an electrode gap distance of 5 mm/10 mm. Fig. 1 shows the photograph of the test cell used. The needle electrode was connected to the lightning impulse source and the sphere electrode was connected to solid ground; the needle sphere electrode configuration and gap distance were maintained to measure the lightning impulse capabilities of base mineral oil, SiO_2 nanofluids and CQD-SiO_2 nanofluids. Needle plane electrode configuration of 5 mm/10 mm gap distance was also used for the test as shown in Fig. 1(b).

2.3 Lightning Impulse Experimental Setup

The block diagram representation of the lightning impulse test setup is shown in Fig. 2. The complete test setup for the lightning impulse test is shown in Fig. 4. The LI test setup consisted of a 3-stage 300 kV high-voltage lightning impulse generator, based on a Marx circuit and capable of delivering 1.2/50 μs standard lightning impulse voltage. A high voltage capacitor of 400 pF was used for measurement purposes and the capacitor was connected to the digital storage oscilloscope by which the impulse waveforms were obtained at the PC interface. The software-assisted PC was used for controlling, monitoring, data acquisition and analysis of impulse waveforms; all the oil samples were tested under room temperature.

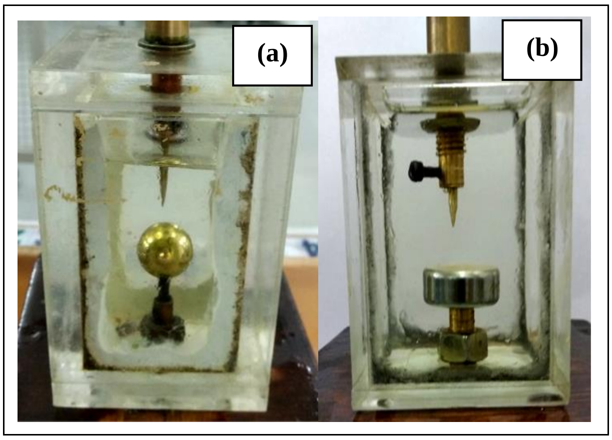

Fig. 1: Photograph of test cell

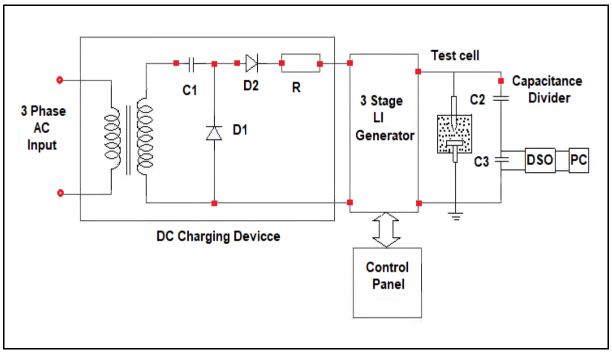

Fig. 2: Schematic diagram of Lightning impulse voltage test

3. RESULTS AND DISCUSSION

3.1 Positive LI Test for Needle Sphere Electrode Configuration

The positive polarity Lightning impulse voltage is used to study and compare the virgin mineral oil and nanofluids of SiO_2 and CQD-covered SiO_2. Similarly, the average peak value of applied voltage (Up), along with the front time (T1) and tail time (T2) of the lightning impulse voltage, is also shown in the results. Fig. 3 and Fig. 4 show the typical positive LI withstand (left) and breakdown waveforms (right) of S-3 and C-3 samples, respectively. It can be observed from Fig. 5 that the virgin mineral oil sample has the capability to withstand Lightning impulse voltage up to 101 kV peak, whereas it tends to break down when the applied LI voltage peak goes beyond 103 kV. Tests were conducted for 20 different oil specimens to calculate the minimum, maximum and average LI breakdown voltage.

Similarly, Fig. 3 shows the typical average positive lightning impulse withstands and breakdown voltage of 0.1 wt. % sample of SiO_2 nanofluids. The S3 sample shows higher LI withstand strength, which was about 108 kV and breakdown began occurring at nearly 113 kV. A significant increase in breakdown strength was observed with an increase in nanofiller concentration when compared with MO sample and similar results were also obtained with 0.01 wt. % and 0.05 wt. % concentration samples of SiO_2 nanofluids. Fig. 4 shows the typical average positive lightning impulse withstands and breakdown voltage of 0.1 wt. % sample of CQD-covered SiO_2 nanofluids; it shows 123 kV peak lightning impulse withstand strength and when the LI voltage reached above 125 kV, the insulation was tending to breakdown. It clearly shows that the addition of CQD-SiO_2 nanofiller in the base oil improved the lightning impulse withstand property, as there were 22 kV improvements in C3 sample than MO, which is 21% higher than MO's LI withstand strength and 16 kV improvement than S3 sample which is 15% higher than S3's LI withstand strength. It is quite evident from the waveforms that CQD-SiO_2 nanofluid shows improved withstand and breakdown voltage values. Similar results were also obtained with C1 and C2 concentration samples of CQD-SiO_2 nanofluids.

3.2 Negative LI for Needle Sphere Electrode Configuration

In this case, the test procedure remains similar to that of the positive LI test, but the specimens were subjected to negative polarity lightning impulse stress of 1.2/50 μs period. Fig. 5 and Fig. 6 show the typical negative 1.2/50 μs LI withstand (left) and breakdown waveform (right) of pure mineral oil SiO_2 and CQD-SiO_2 nanofluid. It is clearly understood from the result that virgin mineral oil exhibited an average maximum of 153 kV peak lightning impulse withstand strength. In contrast, it was tending to breakdown when the applied LI peak value exceeded 158 kV.

The results of 0.1 wt. % concentration of SiO_2 nanofluid sample are shown in Fig. 5. This sample revealed that while adding nanofiller, the breakdown strength started to increase above the virgin mineral oil. The withstand capability of 0.1 wt. % SiO_2 nanofluid was 161 kV and the breakdown occurred at 165 kV.

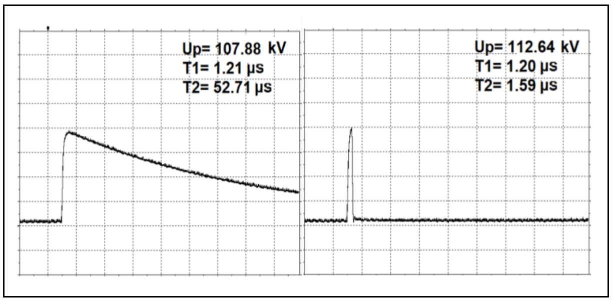

Fig. 3: Typical Positive LI withstand (left) and breakdown (right) waveforms of 'S3' sample

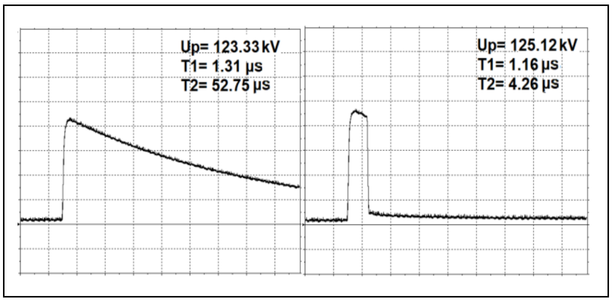

Fig. 4: Typical Positive LI withstand (left) and breakdown (right) waveforms of 'C3' sample

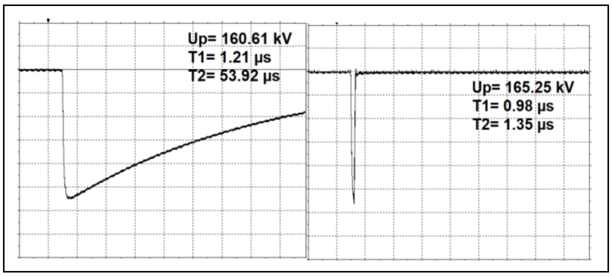

Fig. 5: Typical Negative LI withstand (left) and breakdown (right) waveforms of 'S3' sample

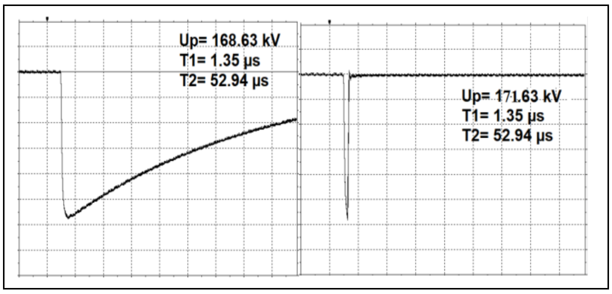

Fig. 6: Typical Negative LI withstand (left) and breakdown (right) waveforms of 'C3' sample

This shows that the addition of SiO_2 nanofiller to base mineral oil was influenced by the negative polarity and was tending to remain higher than MO's LI withstand strength. In the case of CQD-SiO_2 nano-modified 0.1 % wt. mineral oil, shown in Figure 6, the LI withstand strength was above 169 kV and when the voltage reached above 171 kV, the insulation breakdown occurred. It clearly shows that the addition of CQD-SiO_2 nanofiller in the base mineral oil has improved the lightning impulse withstand capability, as there was 16 kV improvement in C3 sample than MO, which was 11 % higher than MO's LI withstand strength and 8 kV improvement than S3 sample which was 5 % higher than S3's LI withstand strength. When compared with positive polarity results, it was observed that withstand and breakdown capacity of nanofluid insulation is considerably higher in the negative polarity case.

3.3 Positive LI Test for Needle Plane Electrode Configuration

Fig. 7 and Fig. 8 report the typical positive 1.2/50 µs LI withstand and breakdown waveform of S2 and C2 samples for needle-plane electrode configuration. In this case, the withstand voltages were found to be in the range of 69 kV, 79 kV and 109 kV for MO, S3 and C3 samples and the breakdown voltages were in the range of 73 kV, 93 kV and 105 kV, respectively; this shows that CQD-SiO_2 oil sample shows the higher withstand level than the virgin mineral oil and SiO_2 nano-sample.

3.4 Negative LI Test for Needle Plane Electrode Configuration

The LI withstand and breakdown voltages for S3 and C3 samples are reported in Fig. 9 and Fig. 10. The withstand and breakdown voltages of samples in needle-plane configuration were found to be considerably lesser than that of needle-sphere electrode configuration and this shows that the LI withstand capabilities of insulation systems depends on electrode configuration and distance between them which can be practically related to the component design and insulation clearance between conducting elements.

The LI withstand voltages were found to be 91 kV, 115 kV and 131 kV for MO, S3 and C3 samples and the breakdown voltages were found to be around 73 kV, 93 kV and 105 kV, respectively; the results clearly show that the CQD-treated SiO_2 nanoparticles have better influence in the LI withstand capabilities of mineral oil. The withstand capabilities of nanofluids vary according to the nanofiller type and concentration of nanofiller. The withstand voltage obtained for negative polarity LI are higher than positive polarity LI, according to the results obtained for Needle-sphere electrode configuration. Hence the insulation system design for LI withstand capabilities should consider the type of nanofluid, concentration of nanofiller, the polarity of LI, clearance and type of conducting live elements of the power equipment.

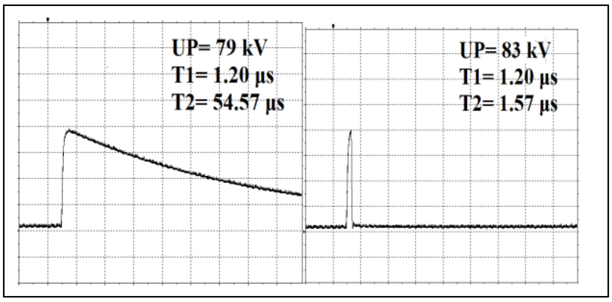

Fig. 7: Typical Positive LI withstand (left) and breakdown (right) waveforms of 'S3' sample

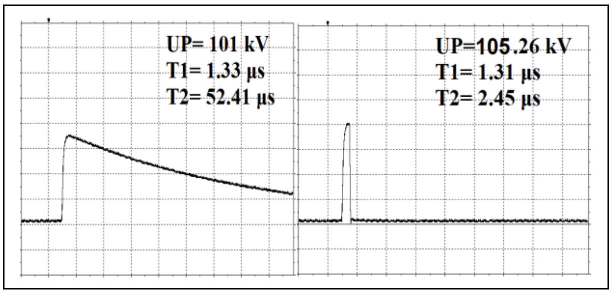

Fig. 8: Typical Positive LI withstand (left) and breakdown (right) waveforms of 'C3' sample

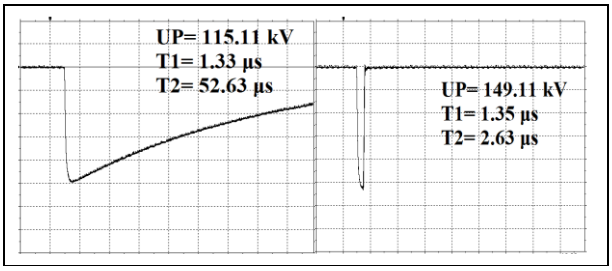

Fig. 9: Typical Positive LI withstand (left) and breakdown (right) waveforms of 'S3' sample

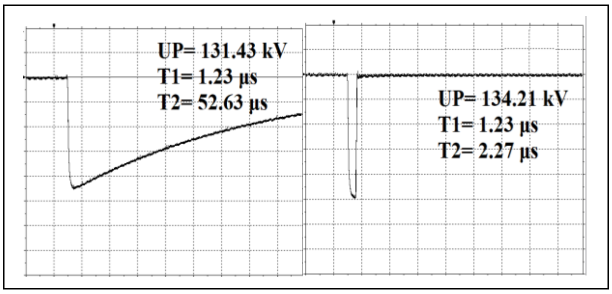

Fig. 10: Typical Positive LI withstand (left) and breakdown (right) waveforms of 'C3' sample

3.5 Probability Distribution

It is difficult to evaluate the correlation between the dispersion of LI breakdown voltages between the mineral oil and nanofluids to determine the safety level while designing electric equipment insulation. LI Breakdown strength of liquid insulation is a statistical parameter that depends on several physicochemical properties of the material. This study uses two-parameter Weibull distributions to determine the appropriate LI breakdown strength. The LI withstand strength (kV), which is the characteristic life at which 63.2% of failure is of expected probability, represents the electrical breakdown strength of oil samples. With the measured LI withstand values noted for oil samples at different electrode gap distances and polarity, a probability distribution graph is plotted in Fig. 11 and Fig. 12, to get the maximum chances of occurrence. Hence, a set of 20 values were considered for each sample in needle–plane and needle-sphere gap electrode configurations and were plotted in a probability distribution graph using MATLAB.

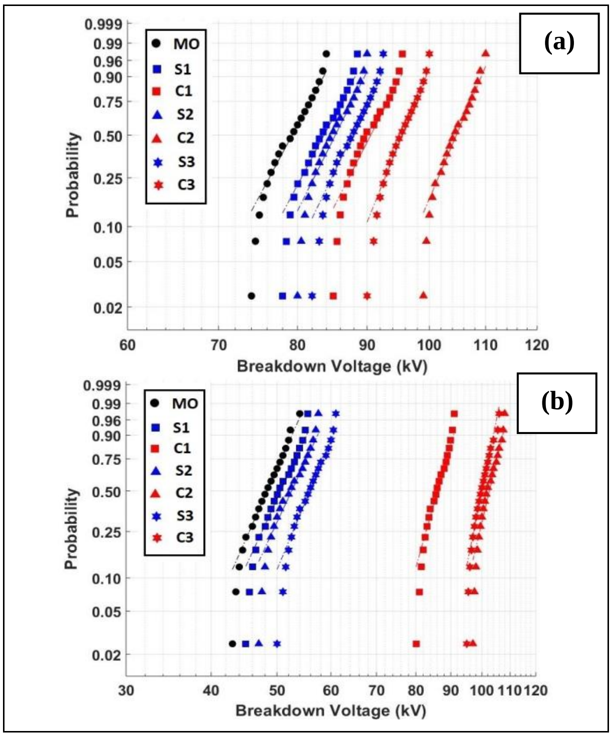

Fig. 11: Probability distribution for positive and negative LI needle-plane electrode.

Fig. 11 and Fig. 12 show the probability distribution for 10 mm needle–plane and needle-sphere electrode in mineral oil and nanofluids under positive and negative lightning impulse polarity. As shown in Fig. 11, the LI withstand capability of surface-treated SiO_2 nanofluids is much improved than that of pure MO and SiO_2 nanofluid and the most effective CQD-SiO_2 nanoparticle concentration is 0.05 %. Similar kinds of results were observed for needle-sphere as well as needle-plane electrode configuration. The scale parameter values of surface-treated SiO_2 nanofluids were higher than other tested samples, irrespective of the polarity of waveform, which indicated lower dispersion of data.

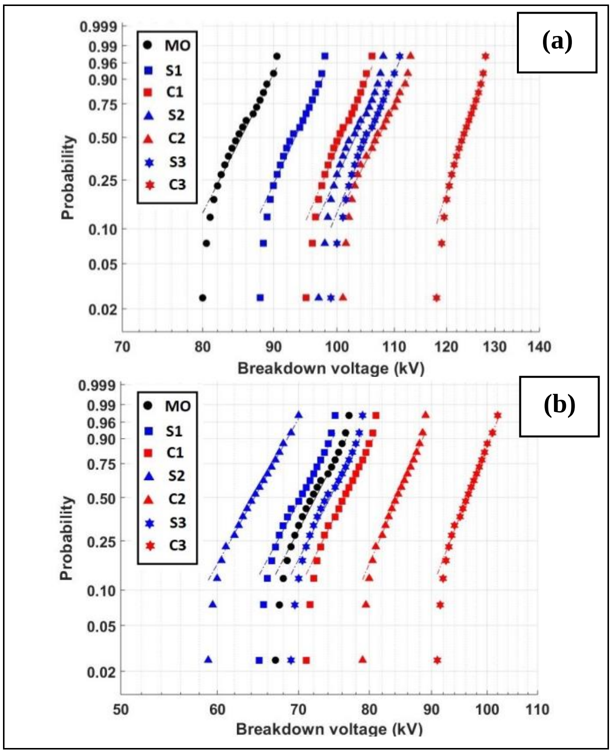

Fig. 12: Probability distribution for positive and negative LI needle-sphere electrode.

4. CONCLUSION

From the experimental studies, it can be understood that in needle-sphere electrode configuration for positive and negative LI, the quantum dots-treated SiO_2 nanofluids of mineral oil has shown higher LI withstand strength compared to other samples. The withstand strength is observed to be high in negative LI than positive polarity of LI testing. Lightning impulse testing of needle-plane configuration has shown that LI withstand strength was depending on electrode configuration, which in practice resembled the physical structure of conductive windings or live parts of electrical equipment. The LI withstand strength in negative polarity of oil samples remains higher than positive polarity impulse waveforms in a overall manner. The lightning impulse-resisting strength of liquid insulation depends on several factors, such as electrode configuration distance between conducting materials accommodating the insulation.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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