

Probing the Epoxy Insulation of Smoothing Reactors With Graphene Ink

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Abstract—Electrically conductive inks (ECIs) are up to now a growing research field, to create flexible circuits for power engineering. As a result, research into screen printing of conductive electrodes onto fiberglass-epoxy-reinforced laminates (FGERLs) has emerged. In this study, an ECI based on reduced graphene oxide (rGO) is proposed for screen printing of conductive electrodes on FGERL used in insulation of the high-voltage direct current smoothing reactors (HVDCSRs). The electrically conductive reduced graphene oxide ink (ECrGOI) was fabricated by mixing rGO, hyperbranched polyglycerol (HPGL) as an adhesion promoter, and poly (vinyl alcohol) (PVA) as a binding agent. The ECrGOI electrodes exhibited adhesion strength of 3.7 ± 0.3 N/mm² and conductivity of $1.2 \cdot 10^{-4}$ S/cm at percolation threshold starting at less than 7.5 wt.% of rGO. The thermogravimetric analysis (TGA) indicates that ECrGOI exhibited good thermal stability at 400 °C. The attractive electric, thermal, and adhesive properties, combined with the ease of preparation and solution-processing capability, indicate that ECrGOI may have great potential applications in analysis of insulation produced by FGERL used in encapsulation of smoothing reactors.

Index Terms—Contacts, electrical resistance measurement, graphene, printed circuits.

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I. INTRODUCTION

RECENTLY, the use of electrically conductive inks (ECIs) has been gathering great interest as a complementary process to form electric circuits and provides the opportunity of combining the electrical properties of metals with the traditional advantages of most commodity thermoplastics such as easy and low-cost preparation and processability [1], [2].

Research on the development of ECI is a fast-growing interdisciplinary area in materials science and engineering and extensive work has been undertaken in the development of suitable electrically conductive contacts in engineering applications due to their excellent thermo-oxidative stability and good chemical inertness [3], [4], [5].

ECIs are colloidal solutions that are produced by adding various types of electrical conducting materials into polymer binding such as metal and alloys [6], carbon black [7], graphite [8], and conductive polymers [9]. Despite the achievements so far, the actual ECI technology still has some problems. The major ones are the low environmental stability and electrochemical activity limiting the practical applications of ECI in high-voltage engineering (HVE).

The high electrical conductivity and extremely high mechanical strength make graphene a promising material for the development of ECI technology for HVE applications [10], [11], [12]. However, as regards the mechanical properties of graphene films, the hardness and the adhesion strength to the substrate, such as stainless steel and polymer composites, are serious hindrances for practical uses.

One closest alternative to graphene for the preparation of colloidal conductive paints is the reduced graphene oxide (rGO). Typically, rGO consists of carbon in sp² and sp³ bonds. In relation to regions with sp² hybridization, the 2s, 2p_x, and 2p_y valence orbitals on each carbon atom form σ bonds with three other neighboring atoms creating two Bravais triangular 2-D sublattices. The fourth electron, in turn, occupies an atomic orbital perpendicular to the plane of the structure (2p_z) and gives rise to a highly delocalized π bond, which enables high electron mobility.

A search in the literature allows for an abundant survey of potential rGO applications in various areas, the one with the greatest possibility of application being composite materials, mainly with polymers. The cheapest and most scalable synthesis process compared with graphene makes rGO a suitable material as an electron transport layer in organic and flexible solar cells and also in supercapacitors and several other applications in the areas of electronics and bioelectronics [13].

Therefore, electrically conductive reduced graphene oxide ink (ECrGOI) with high electrical conductivity, high hardness, and high adhesion strength to the substrate has been desired in HVE applications.

The ECrGOI will provide an electrically conductive coating composition with the biggest advantage over any other type of electroconductive chemical-based inks due to its eco-friendly property, it is innately free of metallic particles, it avoids flux residues without cleaning, it needs a low processing temperature, and its high elasticity compensates the thermal expansion mismatch between the substrate and the conductive painted electrode. In addition, ECrGOI is nontoxic and poses less of a health risk compared with other electroconductive chemical-based paints.

Nowadays, high-voltage direct current smoothing reactors (HVDCSR) are a well-suited technology to transport large amounts of power generated in remote areas over long distances to demand centers [14], [15]. The electrostatic precipitation of submicrometer of dusty particles represents a serious threat to HVDCSR performance since they can cause local electrostatic discharges (ESDs) [16]. ESD can modify the electrical characteristics of the HVDCSR system, degrading or destroying it, or may upset their normal operation, causing equipment malfunction or even failure [17].

The successful development of the high-density laminate board based on fiberglass-epoxy-reinforced laminates (FGERLs) for HVDCSR technology requires a surface electrical resistivity in the range of 10^{10} – 10^{12} Ω /square, providing good electrostatic shielding and efficient dissipation of ESD [18].

Surface electrical resistance measurements of FGERL using ECI have been studied by numerous authors in recent years [19], [20], [21]. Many of these studies focus on using ECI based on metallic particles, carbon black, or conducting polymers. However, obtaining high electroconductive thin coatings in large areas is not easy due to difficulties in accommodating the conductive filler in the host matrix and achieving high conductivity. In addition, the poor environmental stability, stiffness, cure time, and mechanical strength of such materials limit their usefulness as conductive thin films for measurement of surface conduction on HVDCSR walls.

To the best of the authors' knowledge, there are no significant studies in the literature about ECrGOI as electrical contacts for HVE applications. This study appears to be the first to develop ECrGOI as an electrical contact for measurements of surface resistance and surface resistivity applied to composites of FGERLs used in the manufacture of HVDCSR. FGERL is an electrically insulating and very attractive material for improving the electrostatic shielding effectiveness against electromagnetic fields of HVDCSR [22].

The purpose of this work was to investigate the performance of ECrGOI as a conductive electrode for HVDCSR surface resistance measurement. The rGO was first prepared by reduction of graphene oxide with L-ascorbic acid (L-AA). Then, the ECrGOI was formulated using a green method with poly (vinyl alcohol) (PVA) aqueous solution as a film-forming macromolecular system. The structural, thermal stability, adhesive

energy, and resistivity of the ECrGOI electrodes were investigated.

II. EXPERIMENTAL: MATERIALS AND METHODS

A. Synthesis of rGO

Graphene oxide (GO) was prepared by vigorous oxidation of graphite powder (907154) using a mixture of sulfuric acid (H_2SO_4 , 258105) and phosphoric acid (H_3PO_4 , 79617) (9:1 volume ratio) and potassium permanganate (KMnO_4 , 238511) as oxidizing reagents according to the modified Hummers method [23]. Then, hydrogen peroxide (H_2O_2 , 30% v/v, 95299) and hydrochloric acid (HCl , 10% v/v, H1758) solutions were used to rinse the oxidized product. Subsequently, the product was exhaustively washed with deionized water to remove the impurities. The prepared graphite oxide solution was exfoliated into the GO using an ultrasonic bath for 10 h followed by centrifugation at 7000 r/min for 30 min to remove nonexfoliated graphite oxide. The GO was dried at room temperature (25 °C) under a vacuum for 24 h before use.

The GO reduction step was performed according to the literature, using L(+) ascorbic acid (LAA, 795437) as a reducing agent and hydrogen iodide acid (HI, 1.00344) in the ratio of 7:1 by mass of GO at 80 °C per 24 h [24]. At the end of the reduction period, the rGO dispersions were carefully washed with deionized water and centrifuged to remove impurities and dried at room temperature (25 °C) under a vacuum for 48 h before use. Unless otherwise noted, all the chemicals are purchased from Sigma-Aldrich.

B. Preparation and Characterization of ECrGOI

Reduced graphene oxide (rGO, 1–10 wt.%) was weighed and mechanically dispersed (1000 r/min) in hyperbranched polyglycerol (HPGL, $M_w = 9.5$ kDa, Sigma-Aldrich, 806250) by sonication in ultrasonic bath (SP Labor) at room temperature (25 °C) of 12 h. The PVA (Sigma-Aldrich, P8136) solution (10 wt.%) was prepared in water with a sonication of 12 h. The PVA solution was mixed with HPGL-rGO solution and stirred for 10 h followed by sonication of 10 h at room temperature (25 °C).

Fourier transform infrared (FTIR) spectra of the ECrGOI films were recorded using Shimadzu IR Tracer 100 spectrometer in the wavelength range (500–4000) cm^{-1} with a resolution of 4 cm^{-1} .

The extent of sp^2 conjugation in rGO was measured by an ultraviolet–visible (UV–Vis) spectrometer (Varian, Cary 50) at room temperature (25 °C). The estimative of the extent of reduction in rGO was made from Raman spectra obtained in a Raman spectrometer (LabRam HR800) using a 514-nm laser as source of excitation energy.

C. Electrical Properties Measurements

Two strips of adhesive tape were applied (as a mold) onto a glass slide with a gap between these two strips. The ECrGOI was then spread within the glass slide space and the narrow sides of the film followed by casting at 90 °C for 60 min. The thickness of ECrGOI was measured by a micrometer. The

resulting ECrGOI contacts were smooth and continuous before and after electrical tests.

The electrical conductivity of ECrGOI films was measured using a four-point probe accessory, attached to a Keithley 2612A source-measure unit (SMU) controlled through a computer. The ECrGOI sample to be tested was placed on the base plate of the four-probe arrangement, and the probes were allowed to rest in the middle of the sample. To minimize damage to ECrGOI films, each probe has a hemispherical shape with a diameter of 0.3 mm and is supported by a spring load. The probes were lowered onto the ECrGOI films in such a way that they only contact the conductive surface and not the insulating FGERL underneath. Voltage was measured at currents of 0, 0.5, 1, 1.5, and 2 A. Sample conductivity was calculated using the following equation [25]:

$$\rho = \frac{V}{I} \cdot \frac{w \cdot h}{l} \quad (1)$$

where ρ is the resistivity ($\Omega \cdot \text{cm}$), (V/I) is the measured resistance, l is the length of the film, w is the width of the specimen, which corresponds to the gap between the two adhesive strips, and h is the thickness of ECrGOI.

Three specimens were tested for each experimental condition, and the resistivity measurement was repeated several times to confirm the accuracy and reproducibility of the results. An average bulk resistivity and standard deviation for each sample were calculated for each sample. DC electrical conductivity (S/cm) was calculated as the reciprocal of resistivity ($1/\rho$).

D. ECrGOI Adhesive Energy

The substrates used in ECrGOI adhesion studies were commercial samples of FGERL. Before coating, all the substrates ($120 \times 15.1 \times 91.6$ mm) were chemically cleaned in acetone (Sigma-Aldrich: 1.00012) by ultrasonic for 10 min at room temperature (25 °C) followed by rinsing in isopropanol (Sigma-Aldrich: 34 863, 30 min) and drying at 60 °C under vacuum for 24 h.

The peel strengths of the ECrGOI/FGERL interfaces were measured using a 90° peeling angle on an Instron with a 1000-pound load cell at a crosshead speed of 12.7 mm/min and 23 °C while the applied force was measured, according to ASTM D903-49 [26], [27]. The measurement was stopped when all the ECrGOI has been peeled off the samples. The average force was calculated by choosing a representative interval of the graph. Six pull-off tests were conducted on each sample.

E. Thermal Stability of ECrGOI

Thermogravimetric analysis (TGA) was used to monitor the mass change of ECrGOI that is subjected to a controlled temperature ramp within the atmospheric environment. The mass change is a function of time and temperature. By comparing mass changes at certain temperatures, the thermal stability of ECrGOI was estimated. The instrument used was a Shimadzu TGA-50 50 in 40 mL/min of airflow at a heating rate of 10 °C/min up to 1000 °C.

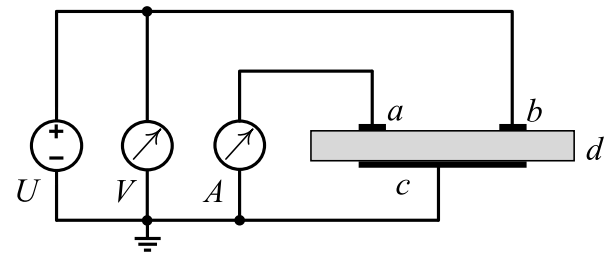


Fig. 1. Three-terminal electrode arrangement for measurement of surface resistance of FGERL. U , V , and A are the dc source, voltmeter, and ammeter, respectively. On the electrode: a , b , c , and d , are electrode 1, electrode 2 (shielded), electrode 3 (protective), and specimen, respectively.

F. Surface Resistance Measurement Method of FGERL

To measure the electrical resistance of commercial FGERLs, specimens used in the manufacture of HDVCSR were cut from flat sheets according to IEC 62 631-3-2:2015 [28]. FGERL specimens were prepared for resistance measurement test by coating a thin layer of ECrGOI onto each face using a template during the spraying. A conventional spray deposition process was used using a Steula BC 66-08 airbrush with a 1.0-mm hole nozzle and an electrical circuit to control the deposition time. The parameters used for ECrGOI coatings were: dispersion concentration of 1 mg/mL, carrier gas pressure of 1.7 atm (25 psi), distance from the substrate to the tip of 20 cm, and substrate temperature of 25 °C. Coating thickness was monitored during coating and determined using an electronic probe universal micrometer Mitutoyo QuantuMike 0–25/0.001-mm thickness gauge. The homogeneity of ECrGOI coating was monitored by an SPLabor MTM17T inverted microscope at 1000× magnification.

The ink film was cured by air-drying at 60 °C at room humidity (RH) of 90% for at least 8 h before the measurements. All the measurements for the samples were also performed in the climate room at the above-mentioned conditions.

For measuring the surface resistance of FGERL samples, the schematic illustration of the measurement circuit is presented in Fig. 1. In a three-electrode system, the surface resistance R_s is measured between electrodes E_1 and E_2 , whereas electrode E_3 serves as a guard electrode. The dimensions of E_1 and E_2 were 25 mm in length and 3 mm in width, and the guard electrode E_3 has a width of 25 mm and a length of 25 mm. The electrode E_3 consists of the reduction of the normal component of the electric field, occurring between electrodes E_1 and E_2 , to a value close to zero, which significantly reduces or eliminates the value of the volume component of conduction current I_1 . Current I_2 , measured by ammeter A , is then determined mainly by the surface current I_s . The surface current is enforced by the tangent component of the electric field occurring between electrodes E_1 and E_2 , which are placed on the same surface as the sample tested.

The surface resistance was measured between terminals E_1 and E_2 with the guard cable connected to E_3 . For this purpose, the measurement cables were fixed on ECrGOI electrodes with copper adhesive tapes. The equipment used was a standard insulation resistance tester. The voltage applied was set to

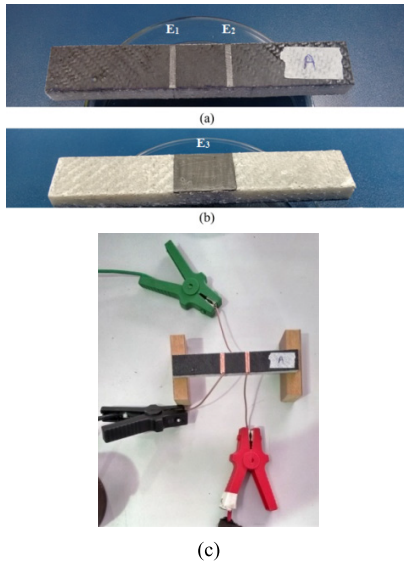


Fig. 2. (a) and (b) Painted ECrGOI electrodes onto FGERL from HDCVSR and (c) connect cables for surface resistance measurements.

500-V dc, and the time to steady-state current waited was 4 min. Fig. 2 shows the painted ECrGOI electrodes and all the electrical connections on FGERL surfaces for the electrical surface resistance measurements.

The arrangement of electrodes E_1 , E_2 , and E_3 permits the calculation of the surface resistance and surface resistivity through the following equation:

$$R = \frac{\rho L}{tW} = R_S \frac{L}{W} \quad (2)$$

where t is the thickness, and W , L and ρ are the width, length, and resistivity, respectively.

Since $L = W$ (square of any dimension), the result is $R = R_S$. Therefore, R_S is the surface resistance according to the following equation:

$$R_S = \frac{\rho}{t}. \quad (3)$$

The dimension of (3) is $[\Omega]$, and the FGEL resistivity $[\Omega \cdot \text{m}]$ can be calculated if the thickness of the sample is known.

III. RESULTS AND DISCUSSION

A. Preparation and Characterization of ECrGOI

The FTIR spectra of pure PVA and ECrGO films were obtained, and the results are shown in Fig. 3.

The spectra (Fig. 3) show a strong broad absorbance at 3380 cm^{-1} for pure PVA and 3430 cm^{-1} for the ECrGOI. This band could be assigned to O–H stretching vibration of hydroxyl group of PVA. The band corresponding to C–H asymmetric stretching vibration occurs at 2930 cm^{-1} for PVA and at 2939 cm^{-1} for the ECrGOI. The FTIR spectrum of PVA films (Fig. 3) also shows absorption bands at 1435 and 1334 cm^{-1} , which can be attributed to bending and wagging of CH_2 vibrations. These bands are shifted to 1495 and 1398 cm^{-1} in ECrGOI films, respectively. The shift in the corresponding FTIR bands for ECrGOI suggests that there is the formation of hydrogen bonding between rGO and PVA

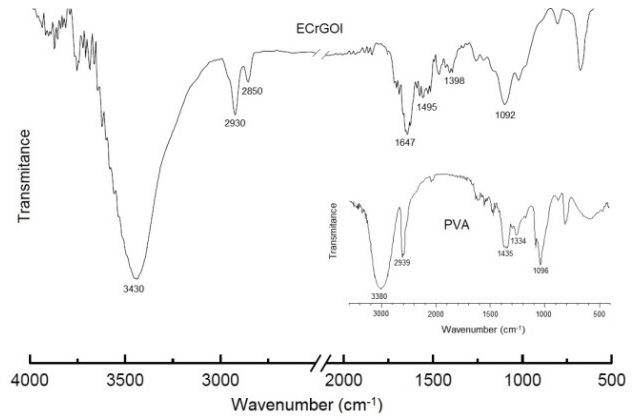


Fig. 3. FTIR spectra of ECrGOI and PVA films measured at room temperature (25°C).

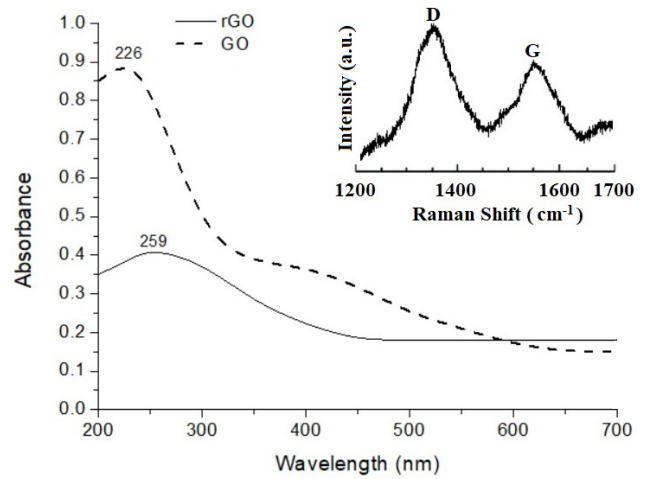


Fig. 4. UV-Vis and Raman spectra (top right) of rGO measured at room temperature (25°C).

chains. It is also notable that the peak at 1647 cm^{-1} for ECrGOI corresponds to the sp^2 hybridization of carbon bonds ($\text{C}=\text{C}$) of rGO and was consistent with the literature [29].

A UV-Vis spectrum of rGO is shown in Fig. 4. The GO showed λ_{max} at 226 nm presumably due to the $\pi \rightarrow \pi^*$ transition of the C–C bond and a shoulder around 400 nm corresponding to the $n \rightarrow \pi^*$ transition of the $\text{C}=\text{O}$ bonds. The rGO renders a red shift of λ_{max} at 259 nm, reflecting increased π -electron concentration and structural ordering, which is consistent with the restoration of sp^2 carbon in graphene [29].

The Raman spectrum of rGO displays the characteristics D and G peaks at 1350 and 1550 cm^{-1} , respectively (Fig. 4). The D peak is characteristic of the presence of defects, related to sp^3 hybridized carbon and defects characteristics of the bulk material (graphene). The G band is due to the vibration of the sp^2 carbon atoms in the plane and corresponds to the doubly degenerate (E_{2g}) vibration mode of the phonons in the center of the Brillouin zone of graphene. The full width at half maximum (FWHM) of the D and G peaks at Raman spectrum was determined and I_D/I_G ratio calculated. The intensity I_D/I_G ratio is around 1.25, significantly higher than in GO ($I_D/I_G = 0.85$). The increase in I_D/I_G ratio of rGO relatively to GO

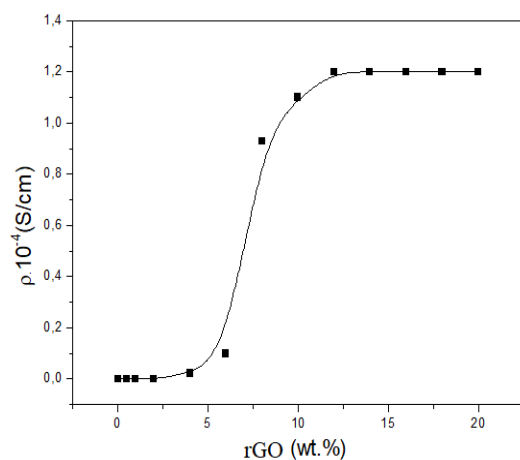


Fig. 5. Electrical conductivity of ECrGOI as a function of rGO loading.

is indicative of the reduced sp^2 lattice size formation and suggests the recovery of graphene backbone phase.

In this study, various samples of ECI were prepared by the mixing different concentrations (wt.%) of rGO into the fixed volume of PVA/HPGL blend solution. The organic polymer blend PVA/HPGL is the insulator while rGO is a good electronically conducting polymer. It is well-known that polymers that are normally insulating undergo a percolation transition where the electrical conductivity of the composite jumps up above a critical concentration changing its electrical property from an insulator to a conductor and establishing a continuous path in the polymer matrix [30].

The relationship between the conductivity of ECrGOI and the wt.% of rGO is shown in Fig. 5. The percolation threshold varies with rGO composition starting at less than 7.5 wt.%. This behavior is attributed to the formation of a conducting network through the insulating matrix material when the filler content is at or above the percolation threshold [31].

In this work, ECrGOI is an aqueous coating using PVA as the film-forming polymer on the surface of the substrate material. The main function of PVA is to make an elastic film of electroconductive ink preventing the formation of shrinkage cracks. For the ECrGOI to be useful, it must achieve good adhesion to the substrate surface. Adhesion depends largely on surface phenomena and ECrGOI must flow out on and appropriately interact with the surface where the electrical contact should be established.

To promote ECrGOI adhesion onto FGERL, HPGL was used as an adhesion promoter for the optimization of the electrical contacts. Fig. 6 demonstrates that the adhesion of ECrGOI could be considerably increased by the addition of HPGL compared with the ECrGOI without the addition of HPGL. In addition, the surface functional groups of HPGL, such as $-O$ and $-OH$ can cause a highly adhesion of ECrGOI to FGERL and may be interesting for formulations of electrically conductive coatings.

The relative electrical resistance increased (R/R_0) with every peel-off attempt (Fig. 6). After the first peel-off, R/R_0 increased about 1.5 times, and it increased around 4.5 times after the seventh assay. After seven peeling attempts,

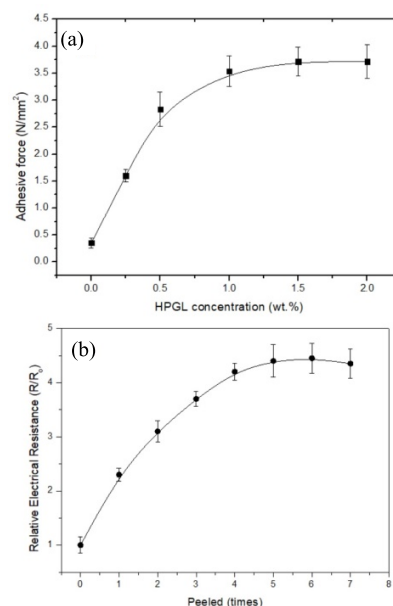


Fig. 6. (a) Adhesive force of ECrGOI onto FGERL surfaces measured through 90° peeling at 23°C according to ASTM D903-49 and (b) electrical resistance change during seven peel-off assay at 23°C .

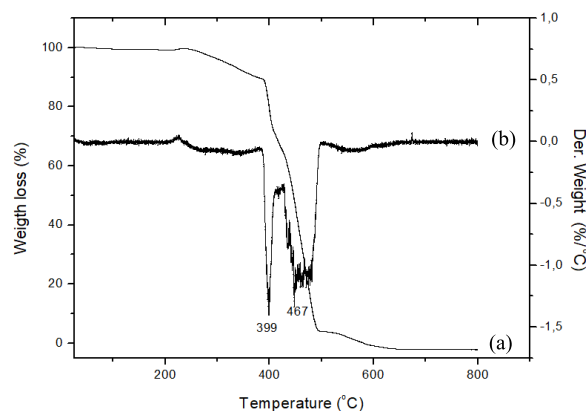


Fig. 7. (a) TGA and (b) derivative TGA of ECrGOI.

no damage to coating was observed, which suggests that adhesion between the ECrGOI and the FGERL was strong.

The amount of heat generated in electric contacts due to ohmic heating may degrade significantly the ECrGOI. Thus, thermal degradation and mode of decomposition under the influence of heat are highly recommended for the optimization of painted electrodes onto FGERL. TGA is a convenient and reliable technique to characterize the ECrGOI. Fig. 7 shows the TGA curves of ECrGOI, together with their derivative (DTG) curve. TGA data (Fig. 7) show two significant weight losses, at maximum temperature (T_{\max}) of 399°C and 467°C , respectively. T_{\max} (temperature for maximum weight loss) is the main criterion to indicate the thermal stability, and the high values observed suggest that will be greatly useful as electrically conductive paint for contact electrodes in HVE.

B. Measurement of Surface Resistance

In terms of electrical measurement, surface resistance is part of insulation resistance, and often, the measured resistance

will be converted into resistivity and then it will be compared with the bulk resistivity of the material [27]. It is generally desirable to have the insulation resistance as high as possible with acceptable mechanical, chemical, and heat properties. In this work, the ECrGOI is used to measure the surface resistance of FGERL with semiconductive resin with two important properties. First, the electrical charge accumulated on HVDCSR should be dissipated on the surface. Second, the material must present enough electrical resistance to withstand the dielectric ac and impulsive tests [32].

According to the IEC 62631-3-2:2015 [29], the measurement methods of surface resistance (R_S) and surface resistivity (ρ) of electrical insulation depend on materials of interest. In the case of surfaces with a curved shape, a small line electrode could be used. Spring-loaded electrodes provide easy measurements on samples that have to be conditioned before the test. The standard presents five electrode arrangements, and the line electrode arrangement is recommended if there is no information available.

Parasitic resistances in parallel to the electrode arrangement could influence the results and should be avoided. This influence is pronounced for measured resistances higher than $10^{10} \Omega$ and shielded cables or shielded measuring equipment shall be used. Considering the band measurement expected between $10^{10} \Omega$ and $10^{14} \Omega$ on the samples tested, the measuring equipment presents at least $\pm 20\%$ accuracy [27]. The voltage source is dc and should be stabilized to guarantee negligible current variations during measurements.

Being a nondestructive test, the surface resistivity (S_R) and surface resistance assays (S_R) may be considered to be a sustainable approach toward determining the electrostatic shielding and efficient dissipation of ESD by FGERL used in the manufacture of HDCVSR since it decreases the consumption of resources and raw materials. With the implementation of S_R assays, significantly fewer samples would have to be collected by the quality control professionals.

Surface resistivity has generally been the property used to describe the conductive, dissipative, or insulated range of static control material [33] while surface resistance would be used to evaluate the static dissipative property of the material [34]. Surface electrical resistance is considered an effective measure in HDVCSR power machines for identifying the risk of the development of ESD.

Table I summarizes the results of surface resistance measurements on nine samples of different FGERL shielding. The column “N° LAT” refers to the internal code of the laboratory, and the column “name” refers to the manufacturer reference. This reference is confidential and involves the development of the final product, the HDCVSR. For each sample, three measurements were performed, and the mean result is presented in column R_S . Through (3), it is possible to obtain resistivity ρ and compare it with the limits imposed for this kind of fiberglass application. The limits are calculated based on $10^{10} \Omega < R_S < 10^{12} \Omega$ and the thickness of each sample which results in $5 \times 10^7 \Omega \cdot m < \rho < 1.26 \times 10^{10} \Omega \cdot m$. The environment temperature for all the measurements varies between 24 °C and 25 °C and from 58% to 62% relative humidity.

TABLE I
MEASUREMENTS OF SURFACE RESISTANCE
ON FGERL SHIELDING SAMPLES

Samples		R_S Mean (Ω)	t Thickness (mm)	ρ Resistivity ($\Omega \cdot m$)	Results
N° LAT	Name				
L1	A (with guard cable)	2.64×10^{11}	12,3	3.25×10^9	Ok
L2	A (without guard cable)	1.12×10^{11}	12,3	1.38×10^9	Ok
L3	1	3.80×10^{12}	7,7	2.93×10^{10}	-
L4	3	5.06×10^8	7,4	3.74×10^6	-
L5	B	1.93×10^{10}	12,6	2.43×10^8	Ok
L6	X	1.30×10^6	7,4	9.62×10^3	-
L7	X (painted)	1.60×10^6	7,5	1.20×10^4	-
L8	C	7.00×10^3	7,3	5.11×10^1	-
L9	X initial	5.26×10^{11}	5,0	2.63×10^9	Ok

The differences among the FGERL samples are basically in their composition. In these cases, the variations are protected by the customer. On the other hand, the measurements L1 and L2 evaluate the difference in the use of guard cable and can be observed its influence on the results by adding some volumetric resistivity on L2. Even approved within the limits, this result was not used for project decisions. On L6 and L7 measurements, the main objective was to evaluate the influence of covering paint on smoothing the reactor. It is noted that X initial sample L9 presented acceptable results compared with L6 and L7 samples.

IV. CONCLUSION

In power engineering where the tendency is to maximize the integration of components to develop more and more efficient HVDCSR, the electrically conductive graphene oxide ink developed in this work will be of great interest. This work aimed to study the performance of ECrGOI systems in the characterization of the dissipative properties of FGERLs used in the manufacture of HVDCSR. The use of ECrGOI is very promising as they are easy to produce (only two components, a polymer matrix, and eco-friendly conductive filler) and to handle (ease of the process of fabrication). They also offer the advantage of being quite a low cost compared with the other electroconductive inks, such as those based on metallic particles, avoid flux residues without cleaning, have low processing temperatures, and their nontoxic nature and pose less of a health risk compared with other electroconductive chemical-based inks. The method recommended by IEC 62631-3-2 standard was easily implemented and had a low cost due to the use of only ECrGOI, copper adhesive tapes, and conductors. Some different electrode arrangements demand special holders with metal contacts and extra costs. The adhesive and conductive property of ECrGOI offers a facile and versatile electrode preparation for analysis of the electrical insulation of the fiber-reinforced composites used in the encapsulating of smoothing reactors.

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