High Current Tests over Conductive Fabrics

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***Abstract*— Lightning, as a powerful natural phenomenon, is dangerous for living beings, equipment, structures, and buildings. The protection principle against lightning currents is to divert and conduct them safely into ground. Therefore, materials and components of lightning protection systems (LPS) must be able to bear lightning currents on the order of tens of kiloamperes. On the search of light materials for LPS, we performed several laboratory tests with high-current lightning-type impulses over some different types of commercial conductive fabrics. The samples used as object under test (OUT) were pieces of 10 cm x 10 cm from four different types of conductive fabrics, including rip-stop, plain-weave and non-woven commercial ones. The OUTs were subject to four 4/10 µs impulsive currents up to 20 kA generated by an Impulse Current Generator. Were taken images of before and after tests and both current and voltage on the OUTs were recorded. Moreover, Scanning Electron Microscope inspections were performed after the tests, to understand some particular patterns presented on the fabric surfaces. A rip-stop type of conductive textile looks that withstands better the four impulses applied. The results of carried out tests suggest that is possible to use some conductive fabrics as part of a LPS, particularly in lightweight and portable applications required in outdoor conditions, such as in the cases of mobile shelters and tents.**

Keywords— conductive fabrics, high-current tests, lightweight lightning protection system, shelter

I. Introduction

Consequences of lightning strikes on living beings, equipment, structures, and buildings can be severe depending on several factors, such as the struck object, point of impact, lightning parameters, current path, or soil conductivity. As the lightning activity in the world has an uneven distribution, there are places more prone to lightning strikes than others, as shown on lightning maps. Places with high annual frequency of lightning activity have more accident occurrence probability related to this phenomenon. The 100 places of the world with the highest lightning activity present a density that ranges from 83,45 to 232,52 flashes per square kilometer [1]. Colombia has 7 of the top 10 places of South America with highest lightning activity ranging from 77,02 to 172,29 flashes per square kilometer with several related accidents. Just for the Colombian Army, lightning accidents account for 72 fatalities and 210 injured people in 8 years between 2003 and 2012 [2].

Lightning protection systems (LPS) are used to protect living beings, structures, and equipment against lightning effects. LPS are intended to intercept, conduct and disperse safely into the ground the lightning currents [3, 4]. Since lightning currents could reach tens of kiloamperes, materials and components of LPS should be able to bear effectively these currents. Particularly, the standard IEC62305 presents methodologies to guarantee risk reduction in order to avoid physical damage and life hazards. IEC62305-3 gives guidance in the use of materials and components, which are considerably heavy in most of cases. However, the conditions imposed by outdoor activities on remote and isolated places, constrain the use of weighty materials and equipment, necessary to an adequate LPS. So, most outdoor people remain frequently exposed to a catastrophic risk. In order to protect mobile campsites in places with lightning strike risk are required lightweight LPSs, desirable in a quick and easy to use form.

On the quest of lightweight materials to use as part of LPS different materials should be considered and assessed. It is also necessary to analyze existing data and carry out electrical tests to found what the best ones. For instance, nonfatal lightning accidents reported reveals the possibility of some light metallic elements could help to preserve the people's lives [5].

Some technical fabrics with high electrical conductivity have interesting potential to apply in the personal protection against weak and strong electromagnetic fields. These materials are lightweight surfaces (sheets), easy to handle and with low resistivity. Most of the conductive textiles are intended for shielding low power electromagnetic fields such as non-ionizing low and high frequency radiations. In this work we are assessing the behavior of some conductive fabric samples tested under 4/10 µs impulsive high currents through high-voltage laboratory tests and microscopy observations.

II. Conductive Fabrics

A. Brief Overview

The most common structure of the fabrics are woven or nonwovens ones [6]. Woven fabrics are formed weaving threads of several yarns made of individual fibers. On the other hand, nonwoven fabrics have a structure made by bonding short and long fibers together, using mechanical, chemical, thermal or solvent means, and combinations thereof. The final application of each fabric type depends on both structural design and properties of constituent yarns and fibers [7].

A conductive fabric can be considered a special type of technical textile with the ability of conduct electrical currents because to their low electrical resistivity. The group Messe Frankfurt through the Techtextil Exhibition Trade Fair has 12 application areas of technical textiles [8, 9], fitting in the "Protech" classification the developments in personal and

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property protection. Typical applications of conductive textiles include their use in antistatic, e-textile, wearables, medical and EMI shielding [7] .

B. *Types of Conductive Fabrics*

Conductive fabrics comprise fibers, yarns or threads made of conductive materials, or those that are made with non-conductive or low conductive substrates coated or embedded with electrically conductive materials. Such materials could be either metallic as nickel, copper, silver, or alloys or non-metallic as conductive polymers, carbonaceus and graphenes [6, 7].

On the other hand, there are several types of conductive fabrics depending on the knitting or woven type, weave pattern, base material, conductive metal layers, number of plies, number of threads, weight, thickness, etc. Fig. 1 shows micrographs of two weave types, one of a woven conductive fabric and the second of non-woven one, both made with electrically insulating core fibers of polyester metalized with an outer nickel-cooper layer.

In woven type textiles, there are several weave patterns according to its final use. The rip-stop fabrics have a special weave array with a reinforcing technique that makes them resistant to ripping and tearing. Other woven types are for example plain, denim and silk.

C. *Conductive fabric as a film conductor*

Conductive textiles have a macroscopic geometry analog to a thin film conductor which electrical resistance is considered as a sheet resistance instead to bulk resistance admitted for wire conductors. The regular three-dimensional resistance of a thin film conductor with a geometry as shown in Fig. 2 can be written as

$$R = \rho \frac{Lenght}{Area} \tag{1}$$

that becomes

$$R = \rho \frac{w}{t.w} = \frac{\rho}{t}\frac{w}{w} = \frac{\rho}{t} \quad [\Omega] \tag{2}$$

for a square of width sides w and thickness t, with a current I in direction going through the cross-sectional area $A=w\cdot t$.

Equation (2) is valid for a square of film conductor, denoting the sheet resistance as R_{sh}, frequently expressed in units of ohms per square [Ω/□] to emphasize the fact that the estimated resistance corresponds to a square of material, independent of the side length [6]. Then, resistance in a square of film conductor depends on the material resistivity and on the thickness of the film.

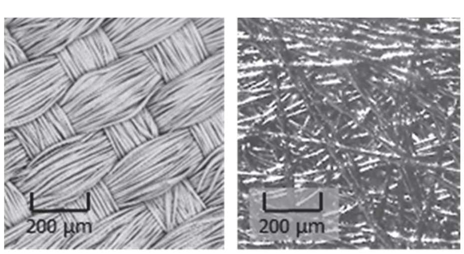

Figure 1. Micrographs of conductive woven (left) and nonwoven fabrics (right). Individual fibers of each fabric are similar in size and composition.

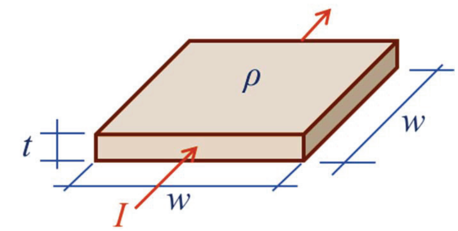

Figure 2. Sheet resistance geometry of a square film conductor

III. SETUP AND METHODOLOGY

A. *Fabrics used as samples under test*

Specimens used as object under test (OUT) to carry out the impulsive high current tests, were pieces of 10 cm x 10 cm of different weave types of commercial conductive fabrics, which include rip-stop, plain-weave and non-woven, all coming from the same manufacturer. The main characteristics of the fabrics used are shown in Table 1. Each material Mat1, Mat2, Mat3 and Mat4 was tested over three samples.

TABLE I. CHARACTERISTICS OF TESTED CONDUCTIVE FABRICS

Item	unit	Mat1	Mat2	Mat3	Mat4
weave pattern	type	rip-stop	rip-stop with FR[(a)]	plain	non-woven
weight	g/m²	90±10	245±10	130±10	90±10
thickness	mm	0,10±0,01	0,16±0,02	0,15±0,02	0,08±0,01
sheet resistance	Ω/□	≤ 0,05	≤ 0,07	≤ 0,07	≤ 0,05
Material	type	Ni-Cu	Ni-Cu+FR	Ni-Cu	Ni-Cu

a. (a) Flame Retardant level UL94V-0

B. *Setup of the bench test*

The DUT samples were subjected to impulsive currents with peak amplitudes in the order of tens of kiloamperes with wave shapes of 4/10 µs coming from an Impulse Current Generator (ICG) of the laboratory of electrical tests LABE of the Universidad Nacional de Colombia – Sede Bogotá. In addition, were also conducted tests in the High Voltage Teaching Laboratory of the Electrical and Electronic.

The schematic of the ICG bench system of the LABE, used for this work, is represented in Fig. 3. Measurements of both current and voltage were made with the oscilloscope of two channels of the ICG system, leading the signals from a shunt resistor and a capacitive divider. On the other hand, the setup 2 of the HV Teaching Lab is represented in Fig. 4.

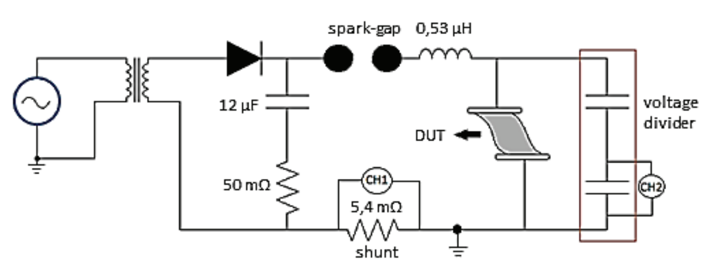

Figure 3. Setup 1 of the Impulse Current Generator (ICG) with measurement of current by a shunt resistor

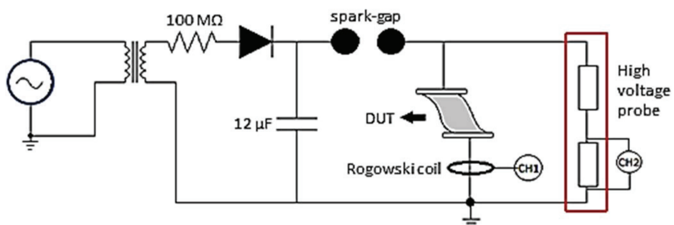

Figure 4. Setup 2 with measurement of current by a Rogowski coil

In the setup 2, the measurement of the current was conducted through a Rogowski coil with passive integrator. The measurement of the voltage was conducted using a high-voltage probe, as shown in Fig. 4. Both current and voltage signals were lead to a two channels of an external oscilloscope.

In both setups (Fig. 3 and Fig. 4), the OUT was placed with appropriate 12 cm length copper electrodes to provide physical support and electrical contact to the sample.

Changing the separation between the spheres of the spark-gap the voltage shot was changed, so the current amplitude of the impulses for the tests. The ICG of the Setup 1 was adjusted for four consecutive tests to (2,1; 4,1; 6,2 and 8,2) kV.

Three samples of each four materials type (Mat1, Mat2, Mat3 and Mat4) were subject to the four current tests, with an interval of 5 minutes between each impulse. In all of these tests, the current was applied lengthways over the fabric through the copper electrodes placed in opposite sides. The resistive impedance of the sample fabrics as OUT, considering the square pieces, corresponds to the value of sheet resistance given in Table 1.

After current tests, the samples were observed in an optical microscope to compare the fabrics after and before the tests and to analyze how the fabrics were altered by the high current flow. Moreover, some small sections trimmed from OUT were examined by a scanning electronic microscope (SEM) to improve the visualization capacity and give more details about the physical changes over the textile surface.

IV. Some Preliminary Results

A. Previous optical observations

Fig. 5 shows some pictures of the initial optical microscopy visualization performed over untested samples.

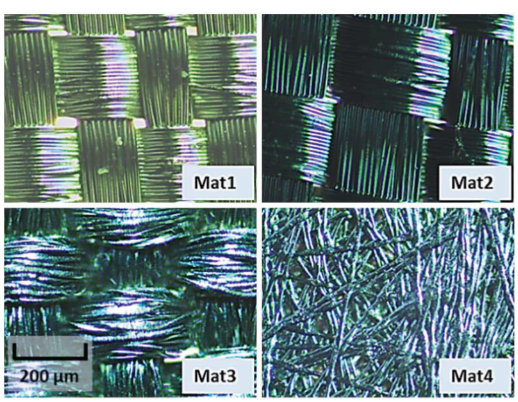

Figure 5. Optical micrographies of the four type of fabrics

The woven differences between the samples are more easily appreciable with the magnification of the optical microscope. Fig. 5 shows Mat1 and Mat2 that correspond to rip-stop and rip-stop with flame retardant, Mat3 to plain-weave and Mat4 to non-woven conductive fabric, as given in Table 1. The flame retardant composite of Mat2 is a coating applied over one side of the fabric increasing the total fabric thickness and its weight. Woven fabrics have a patterned structure whereas the nonwoven has a random arrangement of the fibers.

B. Impulsive current tests

After the impulsive current tests over each sample, the fabric surface exhibited different patterns depending on the weave type and the current, more evident in the last impulse with larger current peak. Fig. 6 is related to the fourth test on a nonwoven sample Mat4, showing at the left side the current and voltage signals on. The inverted recorded current signal shows a crest value of -18,5 kA and the voltage signal a crest of 1,98 kV over the sample, from a 8,2 kV charge of the generator according to the setup parameters. As shown at the right side of Fig. 6, close to the electrodes, the current let burn marks and a horizontal scratch on the MAT4-3 fabric surface.

The voltage vs. current data at peak current values were plotted as shown in Fig. 7 for the three samples of Mat4 (Mat4-1, Mat4-2 and Mat4-3). It was observed that the impedance of the setup remains similar without major apparent electrical change for the three firsts impulsive tests. The Mat4 material, considering just the crest value for the current and its corresponding voltage, gives an impedance average value of 0,03 Ω, consistent with the sheet resistance of the Table 1.

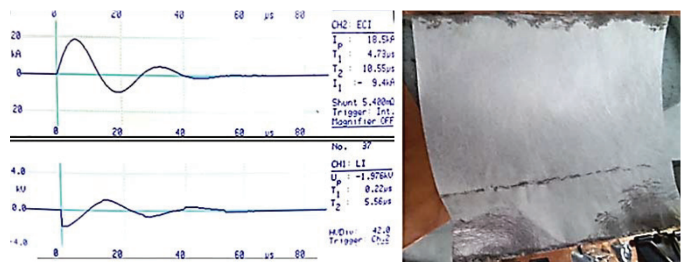

Figure 6. Last impulsive test over the third sample of Mat4 (Mat4-3). The *left side* is the picture of the fourth pulse with (up) the inverted signal of the current due to the connection of the shunt resistor and (down) the voltage records; the current peak value gives 18,5 kA with a corresponding voltage value of 0,9 kV. On the *right side*, the fabric after the four impulsive current tests showing some marks by overheating.

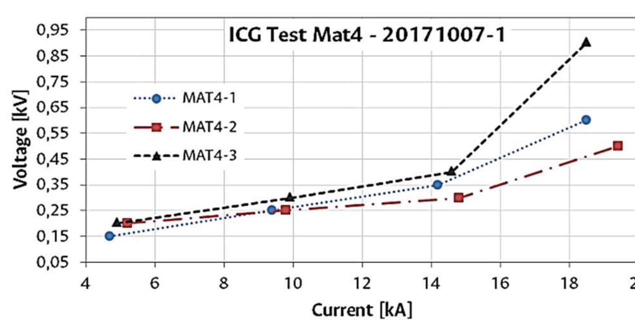

Figure 7. Current tests with the ICG (Setup 1) over Mat4 samples. The each colored line (blue, red, black) indicates the sample tested at the 4 conditions.

For the all tested samples was observed a similar behavior with constant impedance from the first ~ 5 kA to the fourth ~ 20 kA impulsive test. However, after each test, we noticed a change in the color of the fabric samples suggesting material overheat due to the crossing current that could cause the dispersion on the last impulse of larger current for the three samples. Based on the Joule heating effect related to the current and voltage just for the first peak of the last impulse current signal on the Mat4 tests, the estimated power dissipated was approximately 104 J.

C. *Visual inspections*

If an electrical current crossing through a material is high enough, can produce changes in its physical properties due to the joule heating effect. Fast impulsive high currents are able to melt the conductive material. In this case, the rapid heating can be considered as an adiabatic process neglecting the heat losses [3, 10]. The impulsive current applied over the textile samples, produce some pattern-like effects not always easy visible by the naked eye.

After the current tests, selected samples were observed through optical and scanning electronic microscope (SEM) to observe the changes in the surface morphology of the materials, zooming-in over some surface fabrics scratches. Fig. 8 shows two views of a Mat1 sample after tests, one of the entire piece and the other, a micrograph out of the SEM inspection. It is easy to see the parallel pattern formed perpendicular to the impulsive current flow in both images. With the increased magnification and detection of the SEM were revealed particular details related to the weave type structure and current effects on the fabric surface.

Some of the tested samples after the current impulses show, through the SEM inspections, the fabric fibers constitution, each with two basic layers in coaxial arrangement. For the four fabrics the threads have the same conformation with filament cores of polyester coated by a nickel-copper layer. As shown in the Fig. 9, after tests, some parts of the metallic coating of the threads were melted disclosing their core. For the tested conditions, the effects of the current on the woven fabrics are similar, showing parallel scratch-like patterns particularly in the intersections of the weaves. The rip-stop Mat2 fabric shows in the side with flame retardant (FR) composite an ablation pattern parallel to electrodes. For the nonwoven sample Mat4 (Fig. 6), the surface displays concentric scratches, parallel-like to the electrode and also, some longitudinal dark fibers.

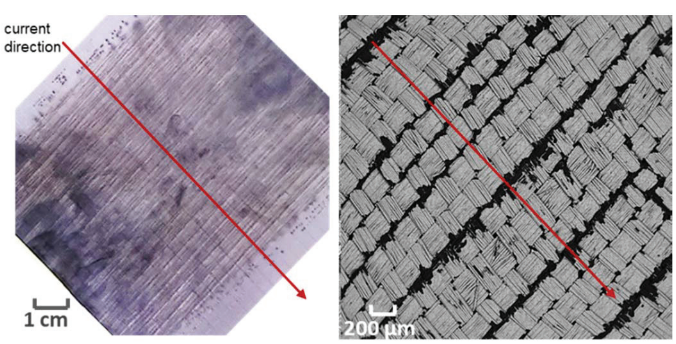

Figure 8. Complete and SEM micrography views of a Mat1 conductive fabric sample after impulsive tests indicating the current direction.

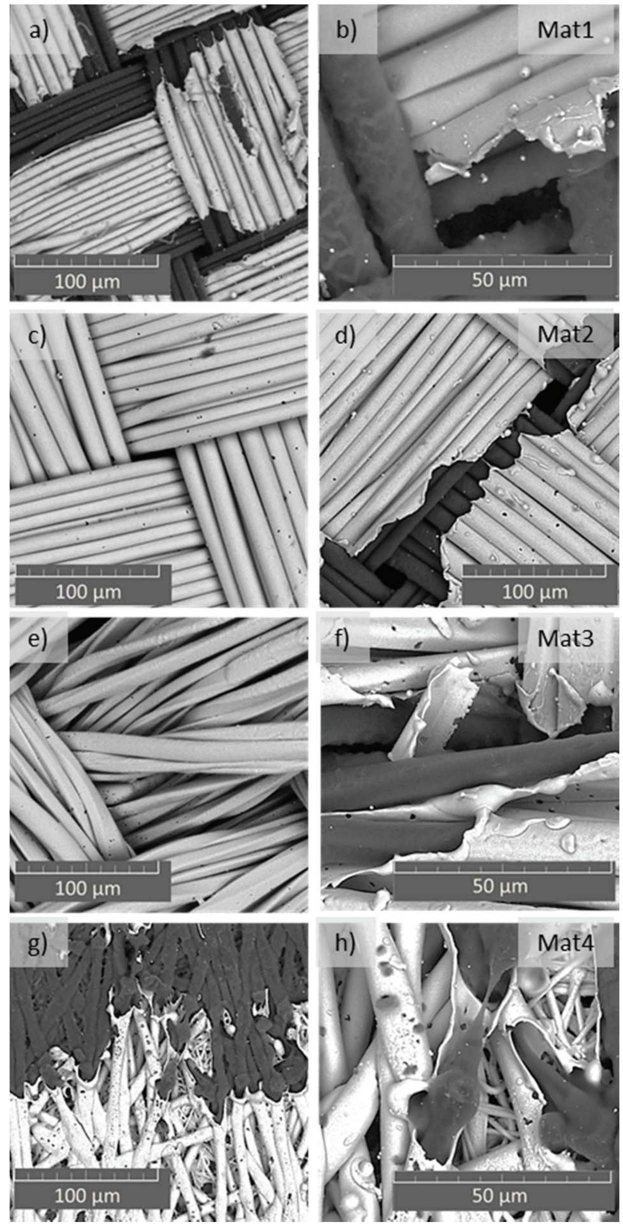

Figure 9. Micrographs of sample fabrics after impulsive current tests that melted the conductive outer layer, a) and b) of the rip-stop Mat1, c) and d) of the rip-stop with FR Mat2, e) and f) of the plain-weave Mat3 and g) and h) of the nonwoven Mat4 fabric. Note that dark inner fibers correspond to the polyester core and clear sheath, the conductive outer layer.

V. Discussion

Considering just the conductive surface of the tested samples as a homogeneous layer, the electrical resistance could be taken as a sheet conductor, in units of Ω/□. That resistance value rules the Joule heating effect, dependent also on the square of the crossing current. As all the tested samples were squares, independent of their sides' length, the resistance value is that given in Table I. Then, for those materials with resistance of 0,05 Ω/□, the instantaneous peak power value dissipated in the test as I^2R was around 17 MW. Nevertheless, the energy for the first pulse of the current signal applied to the textile sample, according to the registered data and to the relation

$$W = R \cdot \int i^2 \, dt \quad [\,\mathrm{J}\,] \qquad (3)$$

with W as the thermal energy, R the resistance, i the current and t the time, was circa 104 J. The total thermal energy dissipated on the Mat4-3 fabric sample was estimated on about 130 J.

The samples of the technical textiles tested under the conditions of impulsive currents used for this work show an effect of burn up forming parallel patterns perpendicular to the current flow. For the four tested weaves samples the current let like horizontal scratches on the surface due to the melting and vaporization of the outer metal conductor coatings of the fibers. The surface scratches, perpendicular to current flow as shown in Figures 6, 8 and 9, are more evident. This is due to the effect of larger currents following the weave pattern for woven fabrics. In non-woven fabrics (Mat4) is noticeable the horizontal melting effect not just as lines, but also areas in a parallel to electrode and in concentric contact points way.

The metal sheath over the base fabric fibers forms a net of little conductive tubes able to conduct high currents. Despite the loss of conductive material in the initial impulse tests, the fabrics continue to conduct currents in subsequent tests through existing conductive paths. For the nonwoven fabric Mat4, the SEM images (Fig. 9 g and h) even show the non-conductive core base fiber melted, going out of the little sheath formed by the outer metal layer around it.

Discarding the mechanical affectation of the fabric and taking into account just the optical and electrical effects of the current tests, the rip-stop weaves showed a better endurance to support the impulsive currents like lightning-type ones. Nonwoven looks as more fragile because previous folds or wrinkles producing evident scratches on the surface after tests.

Regarding to the lightning parameters accepted in the IEC 62305-1, the 50% value of a first negative stroke peak current of 20 kA with a probability P =0,8 [3] suggest that the tested conductive fabrics have potential to conform a lightning protection system intended to light and portable stuff as tents and other outdoor shelters, in order to mitigate the risk.

It is very important to have in mind that not only the high direct currents of the lightning cause injuries but the indirect too. Step potential has a larger incidence in fatal accidents accounting more than 50% of primary fatality mechanisms, with low currents able to produce cardiorespiratory arrest [11]. The outcome of this work shows that at least for this lightning injury mechanism, the use of conductive textiles is possible to develop light personal protective systems. Nevertheless, it is important to test other materials, composites and arrangements under different current parameters and setups. Although it is necessary further research to have more accurate information, the use of electrical conductive technical textiles shows great potential in the personal lightning protection field.

VI. Conclusion

In this paper it has been presented part of the preliminary results of experimental work in high-voltage laboratories and microscopic observations over four types of conductive textiles, using three samples per fabric type. Over each sample square of 10 cm x 10 cm were applied currents in four consecutive high impulsive current tests from about 5 kA to 20 kA. The samples reported endure the trials but letting in the fabric surface burn scratches. Besides this, were done some inspections through optical and scanning electronic microscopy (SEM) to enhance the observation capacity before and after tests. The outcomes from this experimental research suggest that is possible to use conductive fabrics in lightweight and portable lightning protection systems (LPS), in spite of further investigation is necessary about this. Rip-stop conductive fabrics could be used as part of light LPS, intended for outdoor conditions as tents, mobile shelters and other personal protective equipment to mitigate the lightning risks.

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