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Conductive Fabric Potential Rise due to Lightning Impulse Currents

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***Abstract*— In this laboratory experimental research work, the potential rise of conductive fabrics due to lightning impulse currents is investigated. The potential rise is obtained by measuring the voltage drop across the following representative human body lying face-up position contact points: head-to-heel, head-to-coccyx or head-to-scapula. With the conductive fabric potential rise, the energy transferred to the 1 kΩ human body model is calculated. This investigation let us to assess the possible use of a conductive fabric sheet to protect the human life against ground lightning currents.**

Keywords—Lightning personal protection, shelter, conductive fabrics, conductive fabric potential

I. INTRODUCTION

Currently, international lightning safety standards are intended mainly to protect structures disregarding its effects on human and living beings. There are not standards with recommendations of equipment to reduce the lightning risks for people or living beings exposed to the lightning hazards. Despite of prevention is always the pinnacle measure of personal lightning protection, there are many human activities that make the exposition to lightning risk unavoidable. The technical report IEC/TR 62713 "Safety procedures for reduction of risk outside a structure" introduces the lightning strike prevention and gives some precaution measures when this type of risks exist [1]. However, that report does not propose any technological tool to reduce the lightning current effects outside of structures.

There are several technical and media reports that show the possibility that a single lightning event can left several people injured or death. Sheltering of a storm into an unappropriated housing or under a tree can left several living beings inured and deaths, as it is the case of dozens of reported cattle fatalities [2]–[6]. To reduce lightning risks adequate shelter with a suitable lightning protection system is imperative.

Electromagnetic Compatibility Research Group and *Análisis de Falla, Integridad y Superficie* (Failure, Integrity and Surface Analysis) Research Group of the Universidad Nacional de Colombia – EMC-UN and AFIS –, are performing laboratory investigations to search and verify materials able to form part of portable lightning protection [7]. In laboratory conditions, some samples of conductive fabrics showed that they could withstand 20 kA, 4/10 µs and 8/20 µs lightning current impulses. In this paper, we are reporting some preliminary results of laboratory research tests with high amplitude lightning current impulses on larger samples of conductive fabric, intended to be part of portable lightning protection shelters.

II. BACKGROUND

A. Conductive Fabrics

A conductive fabric can be considered a special type of technical textile able to conduct electrical currents. Most of the conductive textiles are intended to shield low power electromagnetic fields. These fabrics are lightweight, easy to handle and with low resistivity [7]. The conductive textiles structure can be woven or nonwoven. Woven textiles can be, among others, plain, rip-stop or knitted. The rip-stop fabric refers to a plain-weave type with squared texture, woven with stronger or large interleaved yarns to improve the mechanical resistance to tearing.

Conductive fabrics are part of the research area related to E-textile [8]. Manufacturing of conductive textiles includes various processes and methods, such as melt spinning, percolation, polymer and solvent combinations, sol-gel process, chemical and physical vapor deposition between others, to obtain intrinsic conductive materials or surface coatings with conductive materials [9]–[13]. Through generation and control of plasma it is possible increase the temperature of thermoplastics fibers, very thermally sensitive, and then apply a conductive material to form a conductive layer [13], [14].

To characterize the electrical resistance of film conductors' squares, commonly is used the parameter "sheet resistance" expressed in units of ohm per square [Ω/□]. This unit emphasizes the fact that the estimated resistance corresponds to a square of material, independent of the side length [10].

Fabrics with high conductive surfaces can potentially be used in personal protection against lightning currents. However, currently there are not standards related to lightning impulse current tests on conductive fabrics.

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B. *About previous laboratory work*

In previous lightning impulse current laboratory experiments performed on 10 x 10 cm conductive fabrics, it has been observed that some fabric types can endure both electrical and mechanically stresses produced by the subsequent 4/10 µs or 8/20 µs lightning current impulses with amplitudes from 5 to 20 kA. A possible explanation of this behavior is the low electrical resistance of conductive fabrics, the materials type and the high mechanical strength of its structure [7], evidenced through electrical measurements and microscopy observations. That work [7] suggests that conductive fabrics could be used to mitigate the lightning risks under outdoor conditions in mobile shelters as part of lightweight lightning protection system.

C. *Some aspects about lightning risk*

The lightning activity and particularly the cloud-to-ground discharges are not uniformly distributed over the world. Some places are more prone to lightning activity than others [15], as it is easy visible in the world lightning maps published in the literature [16]–[18]. Beside many factors, lightning data have shown a strong seasonal and day time dependence of the lightning activity [19]. Thus, there are locations associated to human activities and presence of living beings with increased lightning risk. The consequences can be soft disturbances, hard trauma, or even fatalities. The global lightning casualties may be as high as 24,000 deaths and 240,000 injured people per year [2].

Outdoor human activities in stormy weather and lightning-vulnerable sheltering increase the risk to suffer a lightning-caused trauma. Farming, shepherding, leisure or recreational camping and trekking, open air sports, military and security outdoor operations and other activities expose people to the lightning risk [15]. Even more, in much cases people is expose to lightning without any other possible measure than to stay in squatting position adopting a “lightning crouch posture” [20].

There are five electrical primary mechanism that can cause injuries in humans: Ground current, side flash, contact potential, upward leaders and direct strike. The ground current coupling mechanism between lightning and humans is considered the responsible of about 40–50% of all lightning-caused deaths in a developed country. Direct strike is reported as the less causing death mechanism, estimated in 3–5% of all fatalities [2]. Therefore, lowering the risk caused by ground currents can reduce the entire lightning risk.

D. *Step potential*

When lightning strikes directly on a tall object or on the ground surface, the diverted current through the ground produce hazardous potentials that can lead to traumas. As it is explained in Fig. 1, two points of the human body away from each other, in contact with two different potentials, could force the conduction of electrical currents inside the body. Vital organs could be affected depending on the electrical current path, amplitude and duration. Considering a homogeneous soil, the lightning current diverts in a regular pattern into the ground. If a person is lying down, standing or walking near the striking point, it can be subjected to a potential difference *Us*, which can be calculated according to (1),

$$Us = I\frac{\rho}{2\pi}\frac{s}{d(d+s)} \tag{1}$$

where I is the current amplitude, ρ the resistivity, s the span between contact points and d the distance from the strike point to the closer point of contact [21]. This relation considers neither that common soils are anisotropic and can have multiple different layers, nor that soil electrical parameters are dependent of composition, moisture, pressure, grain size and compaction.

The so called “step potential” or “step voltage” calculated at a distance span of a person walking step, i.e. commonly 1 m, is the earth potential rise mainly due to the ground currents and the earth resistivity. If the contact points are both feet and they are close together, the step voltage can be negligible. Conversely, at an appreciable distance span, even more close to the lightning strike point, the step voltage could have fatal consequences. Fig. 1 represents, in an out of scale drawing, the earth potential rise close to the lightning striking point, due to the lightning current. The magnitude of *Us* across a person is indicated by circles in three situations: lying down on the ground in supine position, walking close to the strike point and walking outside of a safe approach limit. The ground potential is higher closer to the strike point and increases with the distance between contact points.

E. *Energy tolerable by a human body*

In the 1950s, using power frequency currents in electrocution experiments on animals, Dalziel concludes that 50 watt·second of energy is a safe tolerable limit while others works suggest that ventricular fibrillation can occur when a human body absorbs energy in the range from 10 to 50 Joules [22]. In lightning transient conditions, 20 J is assumed as a safe-limit of energy tolerable by a human body [21].

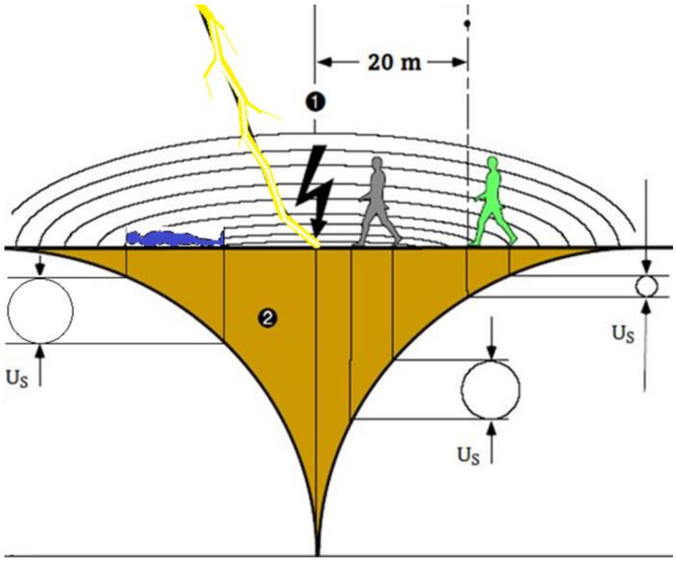


Fig. 1. When a lightning strikes a point of the ground (1) the earth potential rises (2) due to the lightning currents. The circles represent the magnitude of the *Us* potentials across a person in three situations: lying on the ground in supine position, walking close to the strike point and walking outside a safe approach limit. The image is out of scale. Source: adapted from Freynik W., 2000 - zu den Gefahren der Elektrizität.

A protection measure to keep the step voltages due to lightning currents as low as possible is the surface equipotentialization [21], [23].

III. Methodology

To assess the potential rise on a conductive fabric due to lightning impulse currents, tests were performed at the High Voltage Teaching Laboratory of the Electrical and Electronic Department of the *Universidad Nacional de Colombia – Sede Bogotá*. The conductive fabric potential rise was measured at different points for different lightning impulse current amplitudes.

A. Conductive fabric samples

Rip-Stop type conductive fabric samples of 2,25 m by 1,40 m, with yarns of polyester core coated with a metallic layer are used as object under test. Table I summarizes the main characteristics of these conductive fabric samples.

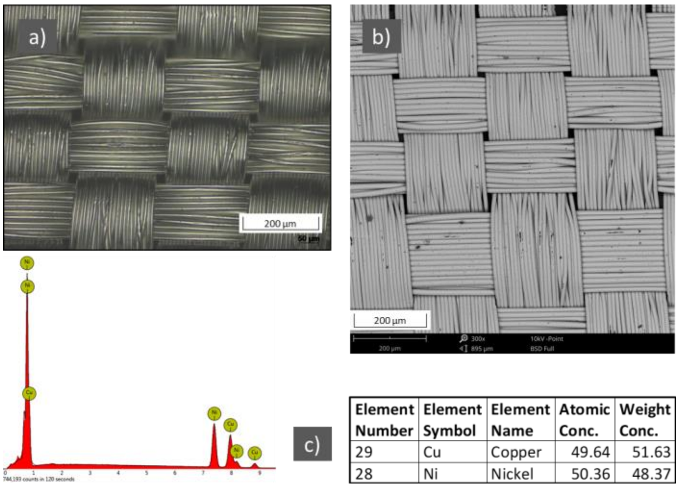
TABLE I. CHARACTERISTICS OF THE RIP-STOP CONDUCTIVE FABRIC

Item	unit	value
Weight	g/m^2	90±10
Thickness	mm	0,10±0,01
sheet resistance	Ω/□ [(a)] or Ω/sq	≤ 0,05
material coating	type	Ni-Cu

a. Ω/□ (ohms per square) is commonly used for the sheet resistance of a conductive surface

To characterize the morphology and elemental composition of the conductive textile, Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) with Energy Dispersive Spectrometry (EDS) analyses were performed. OM analyses of the fabric surface were obtained in a ZEISS Axio microscope. SEM analyses were carried out in a SEM-EDS Phenom XL operating at a voltage of 15 keV.

By OM and by SEM were done observations of a section of the conductive fabric used. Fig. 2a) shows an OM micrograph and Fig. 2b) by SEM. Using SEM-EDS was possible obtain the elemental composition spectrum of the surface fabric (Fig. 2c) showing the nickel and copper weight concentration of the outer conductive layer.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
29	Cu	Copper	49.64	51.63
28	Ni	Nickel	50.36	48.37

Fig. 2. Micrographs by OM (a) and SEM (b) of the tested fabric with the EDS spectrum (c) of the observation area showing the semi-quantitative composition of the main elements of the fabric surface.

B. Contact points for voltage measurement

Since conductive fabrics could be used as a conductive mesh to equipotentialize and protect a person lying on it, the pressure points as contact places and distances of a human being in the supine position (face up) were used to measure the potential rise while a lightning impulse current flow through it. It was considered a 1,86 m height person to obtain the distance between the contact points of the body model. As it is shown in Fig. 3, the distances between the four main contact points: head, scapula, coccyx and heel are used as distance spans over the conductive fabric to measure the potential rise referred to head-to-heel (HH), head-to-coccyx at buttock area (HC) and head-to-scapula at shoulder area on the back (HS).

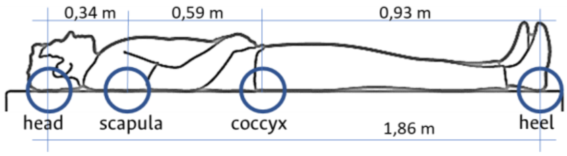


Fig. 3. Contact points (of pressure) at supine position for measurements of difference of conductive fabric potential rise. Source: adapted from https://www.dimensions.guide/.

C. High current generator setup

Since there are not standards or recommendations to perform impulsive current tests over conductive fabrics, the measurement of potentials are made following the recommendations of IEEE Std 81-2012 “Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System” [24]. This guide proposes the measurement procedure of step voltages (section 9.3) through electrodes separate away 1 m, the span average of a human step. For this research, instead 1 m span, the measurement distances shown in Fig. 3 are used.

To obtain the conductive fabric potential rise, the 8 kA peak impulse current generator (ICG) schematically shown in Fig. 4 was constructed. The 12 µF capacitor was implemented using individual 6 µF high voltage capacitors. A Rogowski coil and a high voltage probe were used to measure current and voltage respectively. Those signals were leaded and registered in an Agilent DSO6104A oscilloscope. Additionally, the 2,25 m x 1,40 m conductive fabric was extended on an acrylic sheet which was placed over a conductive plate. Other details of this experimental set-up are also shown in the same Fig. 4.

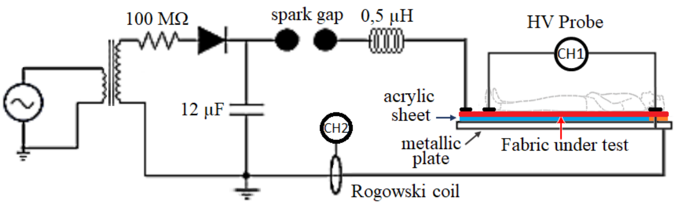


Fig. 4. Schematic setup of the Impulse Current Generator bench used for measurements of voltage due to impulsive currents over the conductive fabric.

Three or four lightning impulse current tests were performed at each pair points distance. For each test an untested conductive fabric sample was used.

D. Energy calculation

For the estimation of the energy of each applied current pulse a total resistance of the human body of 1 kΩ was assumed, according to IEEE Std 80-2013, section 7.1 “Resistance of the human body” [25]. The following expressions were used to evaluate the energy of each pair points:

$$P = V_e I = V_e \frac{V_e}{R} = \frac{V_e^2}{R} \quad (2)$$

$$E = \int_{t0}^{t1} P(t)dt = \frac{1}{R}\int_{t0}^{t1} V_e^2(t)dt \quad (3)$$

where P is the power, Ve the measured voltage between electrodes, R the resistance of human body, E the energy, and t the time.

IV. Results

In Table II are summarized the results of the rip-stop conductive fabrics potential rise across the three electrode locations HH, HC and HS.

TABLE II. RESULTS FROM THE EXPERIMENTAL TESTS

Pair Points	Electrodes distance [m]	Vc Charge voltage [kV]	Ip peak current [kA]	Vp peak volt. Electrodes [V]
HH	1,86	3,70	7,63	320,0
	1,86	3,80	8,32	353,7
	1,86	3,80	8,30	357,5
	1,86	3,80	8,30	356,2
HC	0,93	3,80	8,30	207,5
	0,93	3,86	8,30	208,7
	0,93	3,86	8,30	218,8
HS	0,34	3,86	8,30	162,5
	0,34	3,88	8,34	182,5
	0,34	3,87	8,34	175,0
	0,34	3,88	8,34	193,8

In Figs. 5, 6, and 7 are shown representative signatures of measured voltage and current for HH, HC and HS. In Fig. 8 are presented the conductive fabric potential rise difference between the voltage signatures measured at the three electrode locations HH, HC, and HS.

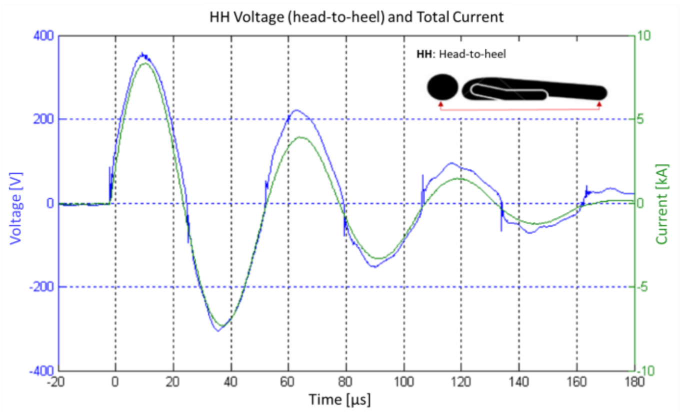


Fig. 5. Difference of potential Head-to-Heel HH, of a 1,86 m span.

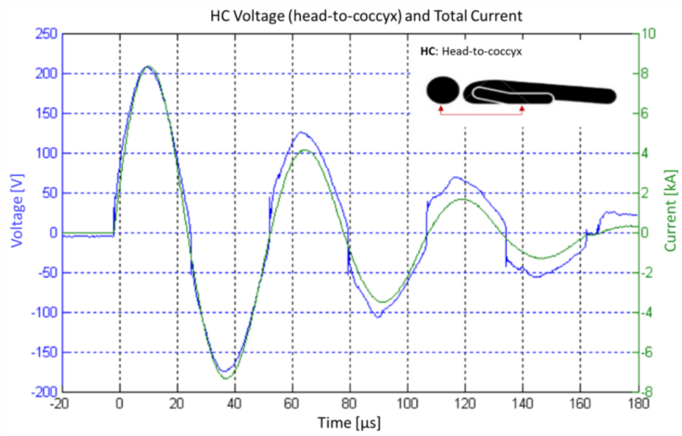


Fig. 6. Difference of potential Head-to-Coccyx HC, of a 0,93 m span.

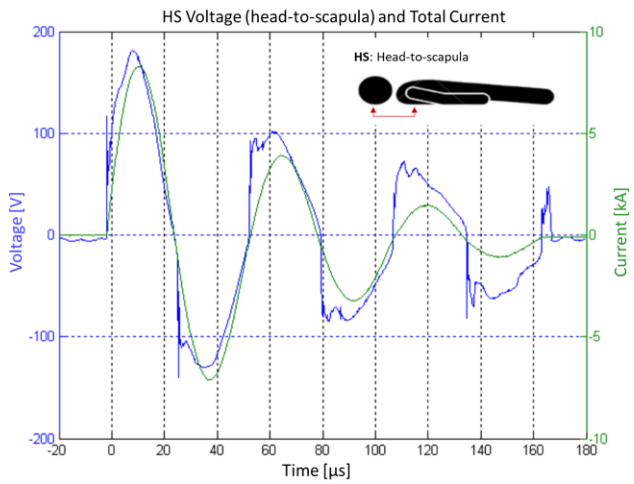


Fig. 7. Difference of potential Head-to-Scapula HS, of a 0,34 m span.

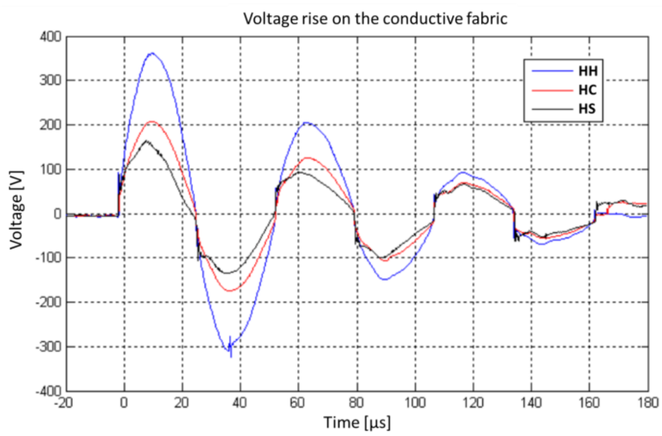


Fig. 8. Difference of potential at three set of tests. The potential peak average of each set was HHp=346.6 V, HCp=211,7 V and HSp=178,45 V.

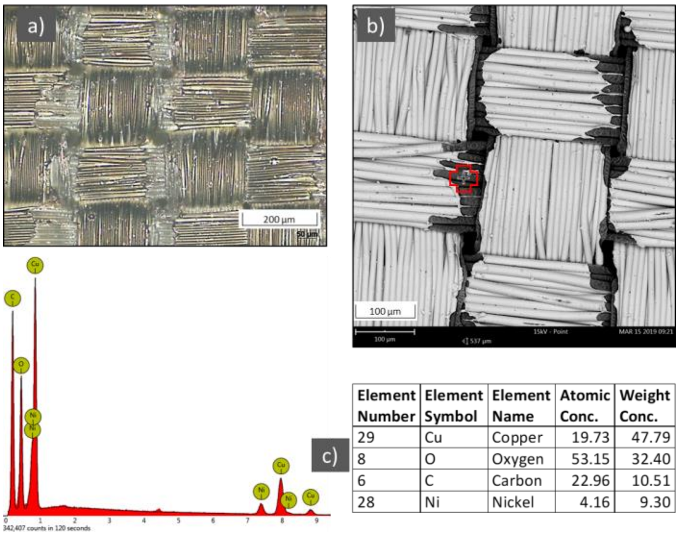
The conductive fabric resistance value is calculated by using the Ohm’s law and the first peak value of both the voltage and current signatures presented in Table II. The average calculated resistance of all the fabric samples tested is 0,030 Ω. However, as the distance between electrodes is different for each pair points, the resistance changes. If only the HH 8 kA test is considered, an average resistance of 0,043 Ω is obtained. On the other hand, the energy calculation is performed by using the entire voltage signal, the body model resistance of 1k Ω and (3). In Table III are presented both, the calculated average resistance of the fabrics and the energy on body for the three electrode locations HH, HC and HS.

TABLE III. CALCULATED FABRIC RESISTANCE AND ENERGY OVER THE BODY AT EACH PAIR POINTS

Pair points	Fabric Resistance [mΩ]	Energy over body[b] [mJ]
HH	42,58	4,25
HC	25,50	1,55
HS	21,42	1,13

b. The energy dissipated was calculated considering the impedance of the human body as 1 kΩ.

After the lightning impulse current tests, some marks and color changes on the conductive fabrics surface were observed. Optical microscopy (OM) and Scanning Electron Microscopy (SEM) revealed a marked pattern in the conductive superficial layer, as it is shown in Figs. 9a) and 9b). The Energy Dispersive Spectrometry (EDS) discloses the chemical elements composition of the surface point of observation as shown in Fig. 9c). The EDS reveals the presence of copper, oxygen, carbon and nickel in the weight concentrations presented in the table of Fig. 9c). Ni and Cu are associated to the outer conductive layer of the yarns, while C and O are associated to the inner polyester fibers.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
29	Cu	Copper	19.73	47.79
8	O	Oxygen	53.15	32.40
6	C	Carbon	22.96	10.51
28	Ni	Nickel	4.16	9.30

Fig. 9. Optical microscopy OM (a) and Scanning Electron Microscopy SEM (b) Micrographs of the tested fabric, and the Energy Dispersive Spectrometry EDS (c) of the observation point (cross mark in (b)) showing the local elemental composition of the fabric after the lightning impulse current test.

V. DISCUSSION

The observation of both the applied lightning impulse current and the measured impulse voltage shown in Figs. 5 to 8, reveals that both signatures are in phase and that the voltage signature is proportional to the current one. These two observations clearly indicate a resistive behavior of the conductive fabric.

For the used E-textile, the EDS analyses reveals the presence of a conductive layer of nickel (Ni) and copper (Cu) in a weight concentration relation of about 52/48. After performing the electrical lightning impulse current experiment, the morphology of the conductive layer changed altering the conductive fabric surface as presented in Fig. 9a) and 9b). Moreover, EDS analyses have shown some variation of the elemental composition of the conductive layer.

The measurements (Table II) and calculations (Table III), suggest that despite of the fact that the estimated energy for Head-to-Heel case is the highest of the three considered situations. The value of this energy dissipated by the body of 4,25 mJ is much lesser than the human body tolerable energy level (< 0,1% of 20 J). Energies of the order of 20 J could produce tachycardia, that could lead to fibrillation and even to death, if the person does not receive adequate medical assistance. The other two situations Head-to-Coccyx and Head-to-Scapula have much lesser energy levels, of 1,55 mJ and 1,13 mJ respectively.

The conductive fabric electrical resistance variation for the three electrode positions HH, HC and HS is summarized in Table III. It can be observed the effect of the electrode position in the sheet resistance, which according to Table I is less than 0,05 Ω/□ (ohms by square), for a square of the conductive fabric (both sides equal).

On the other hand, the first peak observed in Fig. 5 for the HH potential gives a resistance of 0,043 Ω, while the second positive peak gives a resistance of 0,059 Ω. This suggest that the electrical parameters of the conductive fabric change during the test procedure. Moreover, after successive current impulses, it is observed a progressive deformation in all the voltage signatures, indicating a change in the linear behavior of the resistance. This evidences that the electrical current paths over the fabric could change during the test and they could depend on the applied energy. This observation has been shown in previous work [7] and in unpublished experimental work for small squared samples of 10 x 10 cm.

Under the test conditions with a lightning impulse current peak of about 8 kA, the measured peak value of the potential differences at the three electrode positions HH, HC and HS ranges between 162,5 V and 357,5 V. These results give energy values lower than 0,1% of the consider safe limit of 20 J. For human safety it is also important to consider other aspects not considered in this work such as the ionization, formation of ground surface arcs, barotrauma, temperature rises among others. Despite the need for further research, the results suggest that the tested rip-stop conductive fabric could protect the life of a person lying over it, against lightning ground currents.

VI. Conclusion

The voltage response to lightning impulsive currents of a model of the human body lying on face-up position over a rip-stop type conductive fabric is presented. The voltage measured at pressure points across the 1 kΩ human body model such as Head-to-Heel, Head-to-Coccyx or Head-to-Scapula is interpreted as the conductive fabric potential rise. Optical Microscopy (OM)) and Scanning Electron Microscopy with Energy Dispersive Spectrometry (SEM-EDS) revealed important changes in the morphology and variation of the chemical element composition on the tested conductive fabric surface. Since under the tested conditions, the potential rise over the fabric that could produce hazardous energy levels on the body model remains below the maximum safe energy value of 20 J, the use of the conductive fabric tested can reduce the risk for the life of a person against ground lightning currents.

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References

[1] IEC/TR 62713, *Safety procedures for reduction of risk outside a structure*, vol. IEC/TR 62713:2013. 2013.

[2] M. A. Cooper and R. L. Holle, *Reducing Lightning Injuries Worldwide*. Springer International Publishing, 2019.

[3] A. E. Carte, R. B. Anderson, and M. A. Cooper, “A large group of children struck by lightning,” *Ann. Emerg. Med.*, vol. 39, no. 6, pp. 665–670, Jun. 2002.

[4] J. Cristancho C., H. Suárez, Y. Urbano, and F. Román, “Fatal livestock lightning accident in Colombia,” in *2017 International Symposium on Lightning Protection (XIV SIPDA)*, 2017, pp. 295–298.

[5] C. Cruz, E. Rentería, and F. Román, “Statistics of the Colombian National Army lightning accidents,” in *2013 International Symposium on Lightning Protection (XII SIPDA)*, 2013, pp. 324–328.

[6] A. S. Dickson, “Assessing the dangers of lightning to livestock, a case study of a lightning event resulting in the deaths of 22 cattle,” in *2014 International Conference on Lightning Protection (ICLP)*, 2014, pp. 146–151.

[7] J. A. Cristancho C., J. E. Rodriguez M., C. A. Rivera G., F. Roman, and J. J. Pantoja, “High Current Tests over Conductive Fabrics,” in *2018 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, 2018, pp. 428–432.

[8] D. De Rossi, “Electronic textiles: a logical step. - PubMed - NCBI.” [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/17471270. [Accessed: 28-May-2019].

[9] A. Harlin, P. Nousiainen, A. Puolakka, J. Pelto, and J. Sarlin, “Development of polyester and polyamide conductive fibre,” *J. Mater. Sci.*, vol. 40, no. 20, pp. 5365–5371, Oct. 2005.

[10] W. C. Smith, *Smart Textile Coatings and Laminates*. Woodhead Publishing, 2010.

[11] P. T. Hammond, “Form and Function in Multilayer Assembly: New Applications at the Nanoscale,” *Adv. Mater.*, vol. 16, no. 15, pp. 1271–1293, 2004.

[12] L. L. Hench and J. K. West, “The sol-gel process,” *Chem. Rev.*, vol. 90, no. 1, pp. 33–72, Jan. 1990.

[13] V. S. Smentkowski, “Trends in sputtering,” *Prog. Surf. Sci.*, vol. 64, no. 1, pp. 1–58, May 2000.

[14] A. Matthews, “Plasma-based physical vapor deposition surface engineering processes,” *J. Vac. Sci. Technol. A*, vol. 21, no. 5, pp. S224–S231, Sep. 2003.

[15] J. A. Cristancho C., J. J. Pantoja, C. A. Rivera, and F. Roman, “Analysis of two nonfatal lightning accidents in Colombia,” *Electr. Power Syst. Res.*, vol. 153, pp. 159–169, Dec. 2017.

[16] NASA Earth Observatory, “Global Lightning Activity,” 2015. [Online]. Available: http://earthobservatory.nasa.gov/IOTD/view.php?id=85600. [Accessed: 14-Apr-2016].

[17] NASA/MSFC, “Lightning Imaging Sensor - LIS Map, January 1998 - February 2013.” [Online]. Available: https://lightning.nsstc.nasa.gov/data/query/mission.png. [Accessed: 31-May-2017].

[18] Vaisala, “GLD360 v2.0 stroke density map - 20 km grid - Vaisala.” [Online]. Available: http://www.vaisala.com/VaisalaImages/Lightning/GLD_20km_avg_2012-2016_world_map.png. [Accessed: 30-May-2017].

[19] R. I. Albrecht, S. J. Goodman, D. E. Buechler, R. J. Blakeslee, and H. J. Christian, “Where Are the Lightning Hotspots on Earth?,” *Bull. Am. Meteorol. Soc.*, vol. 97, no. 11, pp. 2051–2068, Feb. 2016.

[20] C. Gomes, “Lightning Related Human Risks and Risk Management,” *Am. J. Manag. Sci. Eng.*, vol. 2, pp. 65–79, Jan. 2017.

[21] Christian. Bouquegneau, “External lightning protection system,” in *Lightning Protection*, V. Cooray, Ed. London, UK: The Institution of Engineering and Technology, 2010.

[22] F. Hanaffi, W. H. Siew, and I. Timoshkin, “Step voltages in a ground-grid arising from lightning current,” in *2015 Asia-Pacific International Conference on Lightning*, Aichi, 2015.

[23] IEC 62305-3, *Protection against lightning - Part 3: Physical damage to structures and life hazard*, vol. IEC 62305-3:2010. 2010, p. 313.

[24] “IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System,” *IEEE Std 81-2012 Revis. IEEE Std 81-1983*, pp. 1–86, Dec. 2012.

[25] IEEE Std 80-2013, *IEEE Guide for Safety in AC Substation Grounding*. 2015, pp. 1–226.