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Model for the Estimation of Partial Burst of Ripstop Electro-Conductive Fabrics

John J. Pantoja* (1,2), Jorge Cristancho(2), Jorge Rodriguez(2), Carlos Rivera(2), Francisco Román(2), Felix Vega(1,2), Chaouki Kasmi(1,3), and Fahad AlYafei(1)
(1) Directed Energy Research Centre, Technology Innovation Institute, Abu Dhabi, United Arab Emirates, https://tii.ae
(2) Universidad Nacional de Colombia - Sede Bogotá, Bogotá, Colombia
(3) Faculty of Electrical Engineering, Helmut Schmidt University, Hamburg, Germany

Abstract

This paper presents the analysis of high current impulsive tests performed on electro-conductive fabrics. A ripstop conductive fabric is tested against 5.4 kA and 9.0 kA 8/20 µs lightning currents. An equivalent circuit is used to represent the conductive interwoven yarns and the contact resistance between them. Using the proposed circuit and calculating the Specific Action applied at the woven sections and at the contact points, the change of phase and the loss of material on the conductive layer is described. Results show that the Specific Action can be used to estimate determined effects in materials as function of the excitation current signal.

1 Introduction

Conductive fabrics are components interesting for diverse applications due to their remarkable characteristics such as light weight, high flexibility, impermeability, conductivity, and durability. Some applications include conveying electrical signals, textile-based sensors, electromagnetic interference shielding, and heating textiles [1]. Different tests have been conducted to evaluate the applicability of conductive fabrics as part of a lightning protection systems (LPS) [2, 3]. Particularly, experimental tests reported in [2, 3] show that high intensity impulse currents produce partial melting of the fabric's external conductive layer but the conductive behavior is still maintained at certain levels of current. Therefore, preliminary results suggest that conductive fabrics can be used as part of portable LPS [2].

Electro-conductive properties of textiles have been studied from experimental tests. Anisotropy resistance of woven or knitted was reported in [1] and change of resistance of woven and non-woven fabrics due to lightning-type current tests has been reported in [3]. These kind of tests indicate effects of macroscopic parameters, such as surface roughness [1] or sheet resistance [3], on conductive properties. For some analysis, however, such as melting or burst estimation, parameters to describe particular microscopic details of the fabric structure are required.

Scanning electronic microscope (SEM) micrographs of conductive fabrics obtained after lightning impulse tests show the loss of material due to melting and sublimation of the conductive layer [3]. A key parameter to define the application and limits of materials conducting high current is the energy density.

We propose a different mechanism of analysis which takes into consideration the Specific Action, [4] as an additional parameter. This has been used in the literature in order to determine the resistivity of exploding wires carrying high impulsive currents. Therefore, using Specific Action we'll describe the performance and limits of ripstop conductive fabrics subjected to impulsive currents.

2 Specific Action

The Specific Action is a parameter proposed for the analysis and estimation of the performance of conductors subjected to high intense impulsive currents, such as in the study of exploding wires. Specific Action g is defined as [4]

$$g = \int j(t)^2 dt \tag{1}$$

where j is the current density in the conductive material. In a wire or a conductive sheet, g can be calculated as

$$g = \frac{1}{A^2} \int I(t)^2 dt \tag{2}$$

where I is the impulsive current and A is the initial cross-section area of the conductive material. The specific action is related with the energy density by [4]

$$e = \int \rho dg \tag{3}$$

where ρ is the material resistivity, dg is the differential of the Specific Action.

As the energy density injected rises, the conductor resistance increases due to Joule's effect and due to loss of area as the material melts and vaporizes. The value of the Specific Action determines these phase transitions and is preferred to the energy density in this analysis since it is not dependent on the conductor resistivity, which is a function of the temperature and, as a result, on the energy density [4].

Conductive fabrics integrate different structures and materials to provide specific mechanical and electrical characteristics. In this paper, we consider ripstop woven conductive fabrics shown in Fig. 1. The conductive material in this type of fabric consist of a Nickel-Copper alloy layer deposited over each fiber of the woven yarns. Macroscopically, the resulting structure can be considered as a sandwich of two conducted layers separated by inner polyester fibers.

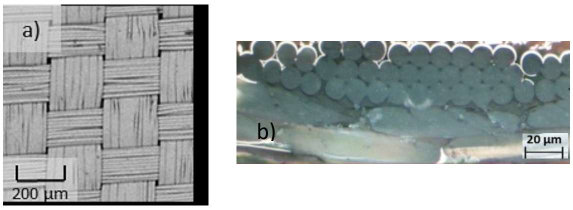


Figure 1. Micrographs of a ripstop woven conductive fabric: a) top view and b) cross-section view (adapted from [3]). Notice in b) the shiny external metallic layer and the polyester yarns in gray.

The Specific Action required for melting beginning and end, vapor beginning, and burst are listed in [4] for different metals. Particularly, the transition points for Copper and Nickel are presented in Table I.

TABLE I. SPECIFIC ACTION OF PHASE TRANSITIONS OF COPPER AND NICKEL [4]

Metal	Specific Action (A^2s/mm^4)			
	Melt Beginning	Melt End	Vapor Beginning	Burst
Copper	80492	94228	124008	173000
Nickel	17233	21156	30173	56007

3 Resistive Model of a Woven Conductive Fabric

In this section, the structure of the conductive fabric is analyzed and a circuit model is proposed. Figure 2a shows a representation of a woven conductive fabric where elemental sections can be identified. Each woven section can be modeled as a resistor. Figure 2b shows an equivalent circuit of a conductive fabric carrying a current i between two edges.

Here, it is assumed that the current is distributed homogeneously through parallel resistive paths and each path includes section resistances, R_s, and contact resistances between two sections, R_c. Based on Fig. 3, one can calculate these resistances as follows

$$R_s = R_p || R_t \tag{4}$$

$$R_c = \frac{\rho \ell_c}{w s_c} \tag{5}$$

where R_p and R_t are, respectively, the resistances of the fibers parallel and transversal to the current flow in a section, ρ is the conductor resistivity, ℓ_c, w, and s_c are, respectively, the length, width, and thickness of an intersection as shown in Figs. 2 and 3. The contact between two sections is modeled as an additional resistance because its thickness can be reduced since it is the junction between fibers of contiguous sections. This resistance particularly is included to represent the current density increase in the contact area between two sections.

Resistances R_p and R_t can be calculated as

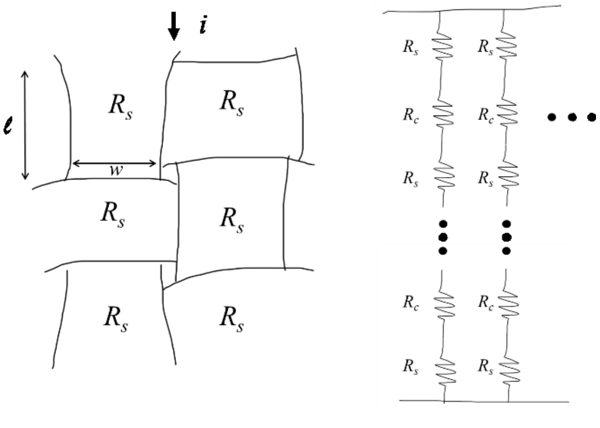
$$R_p = \frac{\rho \ell}{(\pi r^2 - \pi (r-s)^2) n}, \tag{6}$$

$$R_t = \left(\frac{n}{2} R_{tf}\right) || \left(\frac{n}{6} R_{tf}\right) || \left(\frac{n}{3} R_{tf}\right), \tag{7}$$

where ℓ is the length a section, $r = d/2$ is the radius of a fiber, s is the thickness of the conductive layer as shown in Fig. 3, and n is the number of fibers per yarn. R_{tf} is the resistance of an individual fiber transversal to the current flow and can be approximated to

$$R_{tf} \approx \frac{\rho \pi r}{s w} + \frac{\rho r}{s_{cf} w}, \tag{8}$$

where s_{cf} is the contact thickness at the junction of two contiguous fibers. The Skin effect is neglected in this analysis since the penetration depth in Nickel-Copper alloy is higher than the conductive layer thickness for lightning waveforms.



a) b)

Figure 2. a) Diagram and b) equivalent crcuit of a woven conductive fabric.

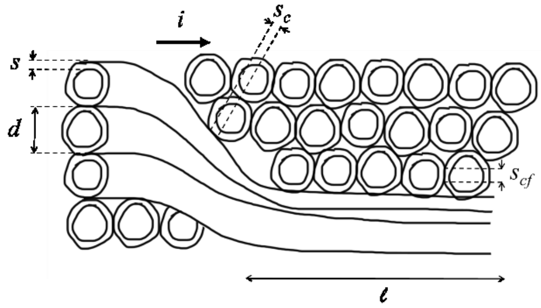


Figure 3. Cross-section diagram of the contact between two sections on a waven conductive fabric.

4 Experimental Tests

4.1 Fabric Samples

Three 10 cm x 10 cm samples of rip-stop conductive fabrics were tested using high-amplitude impulsive current, as described in [3]. The average physical dimensions of the fabrics estimated from micrographs are shown in Table II.

TABLE II. CONDUCTIVE FABRIC AVERAGE DIMENSIONS

Parameter	Variable	Value (µm)
Section length	ℓ	250
Section width	w	250
Section thickness	s	~1.5
Contact length	ℓ_c	~1
Contact thickness between sections	s_c	>0.5
Contact thickness between fibers	s_{cf}	5
Fiber diameter	d	10

The total sample resistance can be calculated using (4) and the equivalent circuit proposed in Fig. 2. R_c can be neglected due to its small value as compared with R_s. The conductive layer of the samples is made of 55/45 Cu-Ni alloy [3], which typically presents an electrical resistivity of 49.5 µΩ·cm at 20 °C. Assuming $\ell = w$, as presented in Table II, and 48 fibers per yarn, the section resistance R_s yields

$$R_s = 0.029\ \Omega. \tag{9}$$

The total resistance for a square sample is equal to the section resistance. This results agrees with the sheet resistance provided by the manufacturer, which is <0.05 Ω for a square sample.

4.2 Impulse Current Tests

Two current impulses with 5.4 kA and 9.0 kA peak amplitude were applied to the samples. Both pulses had 8 µs rise time and 20 µs half duration times. The impulse tests were conducted using the experimental setup shown in Fig. 4. The applied current was measured using a Rogowski coil located at the connection wire between ground and the sample. The induced voltage between the electrodes was measured using a high-voltage probe.

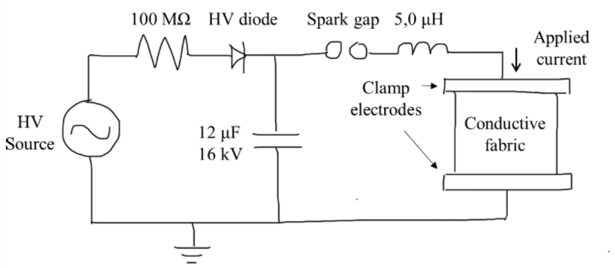


Figure 4. Experimental setup used in the impulse current tests. Adapted from [2, 3].

For the case of the 5.4-kA impulse, no evident change of color was obtained in the samples. The estimated energy delivered was 7.2 J. On the other hand, the 9.0-kA impulse produced a series of brown scratches in the fabric, as shown in Fig. 5. The change of color in the samples suggests that the energy delivered was enough to produce a phase change in the conductive material. The estimated energy delivered was 18.8 J. This energy was calculated considering the first 100 µs of the signals and the average resistance obtained experimentally.

Figure 5 shows that scratches form brown lines perpendicular to the current direction. This can be explained using the proposed equivalent circuit of Fig. 2. The scratch lines perpendicular to the current are presented at locations where the dissipated energy by the contact resistances was enough to burst the conductive layer. From (4-5), it is possible to observe that the per-unit-length contact resistance (i.e. R_c/ℓ_c) is higher than the per-unit-length section resistance (i.e. R_s/ℓ) since the thickness is reduced in the contact area; therefore, higher energy is dissipated in this particular position as Joule effect consequence.

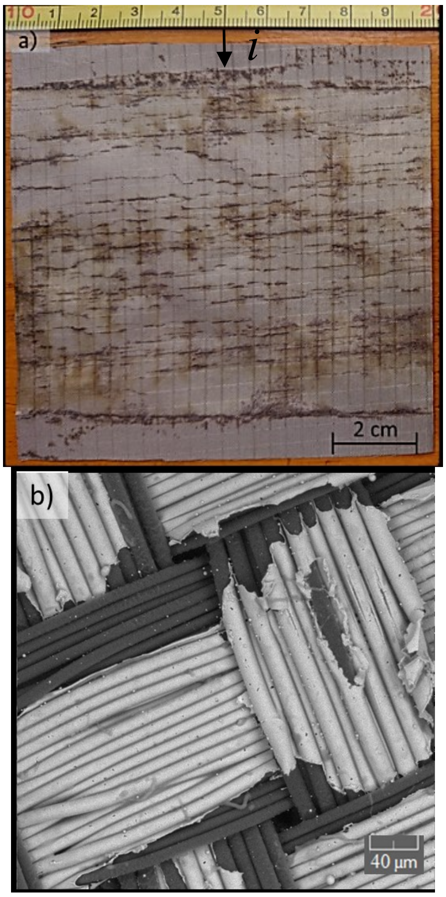


Figure 5. Fabric after a 9.0-kA impulse current: a) photograph of a 10 cm x 10 cm sample and b) micrograph showing the loss of the conductive layer at contact areas. Adapted from [3].

Since the thickness s_c can have variations in each junction, the contact thickness and the contact resistance can be modeled as random variables. As a consequence, scratches parallel to the current flow are produced at random distances.

Table III presents the Specific Action calculated using Equation (2) for the tested samples. To analyze these results, we compare the calculated values of Specific Action with the phase-change limits of Nickel presented in Table I. Nickel is used for comparison since it presents similar thermo-electric properties and dependence of the Specific Action with the temperature as the Cu-Ni alloy. From this analysis one can conclude that only the 9-kA impulse test at the contact points produced a Specific-Action higher than the required one to burst Nickel. The burst Specific Action for Nickel is 56007 A^2s/mm^4 meanwhile the value produced by the 9-kA impulse at the contact points is 74812 A^2s/mm^4, that means that burst should be produced. These results agree with the micrographs presented in Fig. 5, where the loss of the conductive layer particularly at the contact area is shown.

TABLE III. SPECIFIC ACTION APPLIED TO THE CONDUCTIVE LAYER DURING THE IMPULSIVE CURRENT TESTS

Test	Position	Cross-section Area (mm^2)*	Specific Action (A^2s/mm^4)
5.4 kA impulse	Woven section	1.69	378
	Contact área**	0.2	26932
9.0 kA impulse	Woven section	1.69	1050
	Contact area**	0.2	74812

*The cross-section area is calculated considering a 10 cm wide sample.
**Six contact points of 0.5 μm thickness each one were assumed.

5 Conclusions

The Specific Action is used to assess effects of high current impulsive on electro-conductive textiles. The obtained results allow to determine Specific-Action values required to produce phase change in the conductive layers. In addition, a circuit model is proposed to describe the current flow and the highest current densities in woven conductive fabrics. Particularly, results show that scratches, perpendicular to the current presented after high specific action impulses, are due to the reduction of the cross-section area at the contact point between two woven sections.

The Specific Action, as opposed to the current density or the energy, is a parameter independent of the resistivity value that is not constant in a high current impulsive test due to the heating and the phase change. As a consequence, using this parameter simplifies the analysis to determine the required values of excitations to produce specific effects in the materials. Although in the presented analysis the Nickel's melt and burst specific actions are used to compare the conductive-layer phase change, work is in progress to determine the values for the Copper-Nickel alloy used in the conductive fabrics. The procedure proposed here can be applied to determine and assess the limits of other types of conductive fabrics and different excitation waveforms.

6 References

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