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Some aspects of modelling and design of ESD protective fabrics

***Abstract**. The paper considers an important problem of designing ESD protective fabrics. Accurate models of the fabrics containing a mesh of conductive threads were developed in general-purpose COMSOL Multiphysics® software. Then model simplifications were made and lumped-element circuit models were proposed. The circuit models were used in a numerical method for fitting weft and warp thread parameters to the desired values of surface and vertical resistance of the fabrics.*

***Streszczenie.** W pracy omówiono ważny problem projektowania tkanin antystatycznych. Dokładne modele tkanin zawierających siatkę z nici przewodzących opracowano w oprogramowaniu COMSOL Multiphysics®. Następnie dokonano uproszczeń modelu i zaproponowano modele obwodowe tkanin. Modele te wykorzystano w numerycznej metodzie doboru parametrów nici wątku i osnowy do pożądanych wartości rezystancji powierzchniowej i skrośnej tkanin. (**Wybrane aspekty modelowania i projektowania tkanin antystatycznych**).*

Keywords: anti-static textile, circuit models, electrostatic discharge protection, surface and vertical resistivity.
Słowa kluczowe: materiały antystatyczne, modele obwodowe, ochrona przed wyładowaniami elektrostatycznymi, rezystancja powierzchniowa i skrośna.

Introduction

Static electricity is a set of phenomena associated with the accumulation of electrostatic charges on materials with low electrical conductivity and on conductive objects isolated from the substrate. The creation of electrostatic charge by contacting and separating materials is known as *triboelectric charging*. Electrostatic discharge (ESD) is the result of the transfer of electric charge between bodies of different potentials through physical contact or electrostatic field induction. ESD leads to serious economic losses and can be dangerous to people in areas where substances with low ignition energy values are present due to the risk of fire or explosion. The problem of protecting electronic equipment and systems from ESD energy is present at the stage of production, storage, delivery and use of electronic equipment. It is estimated that average product losses due to ESD range from 8 to 33% [1].

Natural fibres of plant origin (hemp and flax) and artificial cellulose fibres have the lowest charging capacity, while natural fibres of animal origin (wool and natural silk) have a much higher charging capacity. Synthetic fibres and artificial acetate fibres, on the other hand, have incomparably higher charging capacity [2]. Anti-static finishes can be used to reduce static electricity. Chemical auxiliaries used in the production of yarns, knits, fabrics and nonwovens contain anti-static agents. Studies show that about 30-50% of all electronic product faults detected during production are attributed to some sort of operator's clothing [3]. Well designed protective clothing (ESD clothing) worn over the operator's regular clothing avoids the accumulation and retention of these charges.

Depending on the required level of conductivity, geometric, strength and process requirements, there are various methods of achieving electrical conductivity of textiles. Conductive yarn can be obtained by either adding carbon or metals in various forms, such as wires, fibres or particles or using conductive polymers or by coating with conductive substances.

ESD garments are typically made of composite fabrics, where a mesh or strips of conductive threads are present inside a matrix of cotton, polyester or blends of these materials (see Fig. 1). This leads to highly heterogeneous clothing fabrics. As a result, developing test methods to characterize the protective performance of garments and recommendations on the design of these garments is a significant challenge. The electrical conductivity of fabrics plays a crucial role in maintaining the electrified state of an object. It can be expressed by the value of vertical resistance R_v and surface resistance R_S. It has been found that the risk of ESD damage is minimized when the surface resistance of the fabric is within the range of electrostatic dissipative materials (10^4 to 10^{11} Ω) and there are no continuous insulating areas in the garment exceeding a size of about 20 mm x 20 mm [4]. Anti-static material can be conductive ($R_S \leq 10^4$ Ω), static dissipative ($10^4 < R_S \leq 10^{10}$ Ω), or anti-static ($10^{10} < R_S \leq 10^{11}$ Ω) [1]. It should be noted, that in the case of fabrics with a core of conductive fibres, it is not possible to characterize the protective properties of ESD by any resistivity method at all, because the measuring electrode cannot be in galvanic contact with the conductive elements of the fabric.

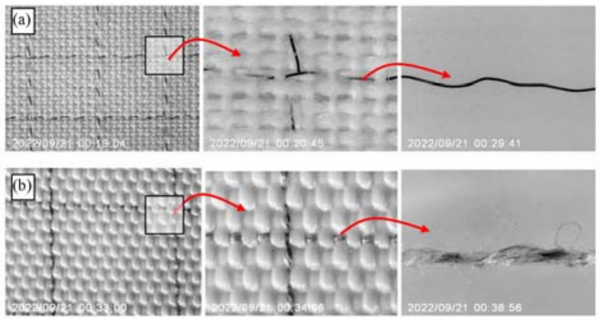

Fig.1. Macroscopic appearance of samples of heterogeneous ESD protective fabrics with (a) 5 mm, and (b) 10 mm conductive grid

The effect of ESD is the subject of intensive research [1]-[15]. Reference [5] proposes the fabrication of conductive knitted fabrics of polypropylene as base material, glass fibres as reinforcement and copper wires as conductive fillers, and investigates the immunity of these fabrics to ESD. Report [6] focuses on the impact of using ESD protective clothing inside a dedicated ESD Protected Area in a manufacturing facility. Reference [6] focuses on the description of the surface conductivity model. The assumption of the existence of equipotential lines was introduced and verified using a simulation program and by calculating the surface resistance of a simple electrical circuit. Reference [7] presents the results of a study on the electrical characteristics of yarn and fabric considering multiple water treatments. Comparative studies for several types of ESD garments with carbon-conducting fibres used in the electronic industry and the characterization of their anti-electrostatic properties are included in Ref. [8]. In Refs. [9-10], a simplified analytical fabric-grounded-object model was developed for estimating the energy stored in the electric field occurring in the space surrounding a charged fabric. The individual chapters in [11] provide a basic understanding of the principles, roles, types and methods of evaluating anti-static and conductive textile materials. Review [12] focuses on various conductive materials and methods used to coat e-textile devices. Reference [13] presents a new approach to assessing the electroconductivity of woven and knitted fabrics based on the determination of electrical resistivity in combination with the analysis of textile surface roughness. Reference [14] describes a bicomponent melt spinning technique for granting anti-static properties to synthetic fibres. The effect of anti-static polyester fibres containing carbon black on the performance of knitted fabrics are subject of studies in [15].

To design protective clothing that meets existing standards for evaluating ESD protective fabrics, it is necessary to develop reliable fabric models. Therefore, the paper focuses on the modelling of plain weave fabrics to determine surface and vertical resistances. Although the reality is very complex, we assume that the conductive threads have a constant cross-section (may be different for warp and weft), and are smooth and characterized by the effective conductivity of the threads (may be different for warp and weft). Initially, 1:1 scale electromagnetic models (EM models) were developed in COMSOL Multiphysics® software [16] to determine both resistances. Subsequent simplifications of these models were made, and the final result was lumped-element circuit models that can be simulated e.g. in LTspice® simulator software [17]. These models were described using two variables, and a numerical method was developed to fit the variables to the required values of surface and vertical resistances. The method has been verified by numerous simulation studies and some laboratory tests.

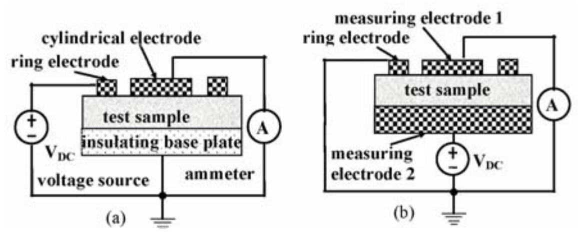

Fig.2. Diagram of the test bench for the determination of surface resistance (a) and vertical resistance (b) according to EN 1149

Electrostatic properties – test methods

EN 1149 is a suite of clothing standards that have been around for several years and was last updated in 2018. EN 1149 is broken down into the following parts: test methods for the measurement of surface resistance (EN 1149-1), test methods for the measurement of vertical resistance (EN 1149-2), test methods for the measurement of charge decay (EN 1149-3), and material performance and design requirements (EN 1149-5). The test methods EN1149-1/-2 measure in various ways the electrical resistance of materials, which corresponds to how resistant materials are to charge build-up. The higher the resistance, the more likely it is that charge will begin to accumulate on the surface or inside the material and pose a hazard in the workplace. These methods are briefly characterized below. The principle of test method 1149 - 1 is that the sample is placed on an insulating plate (see Fig. 2(a)), and an electrode assembly of the dimensions specified in the standard rests on the sample. The stainless steel electrodes consist of a cylindrical electrode and a ring electrode, which are arranged concentrically with respect to each other. A DC voltage is applied to the electrode assembly and the surface resistance of the fabric is measured. The principle of test method 1149 - 2 is that the measuring electrodes are placed on opposite sides of the test sample (see Fig. 2(b)). The diameters of the individual electrodes are given in the standard, and these dimensions were kept in the modelling process. In contrast, the thickness or weight of the electrodes, which do not play a role in modelling the resistance measurement, were not kept.

Modelling of plain weave fabrics in general-purpose multiphysics software

Several software environments are available on the market to model complex physical problems. For this purpose, e.g. Ansys, CST Studio Suite®, and COMSOL Multiphysics® can be used. COMSOL software was utilized in the paper. Electrical Currents module (ECURM) allows the analysis of conductive devices by modelling direct, transient or alternating currents. Under static conditions and at low frequencies, the modelling of electric currents is sufficient to obtain accurate results. Based on the resulting potential field, resistance, conductance and current density, among others, can be calculated [16]. In this way, the unit resistances of the weft and warp threads were determined. The models, parameters and results of example analyses are shown in Fig. 3. Electrical Circuits module (ECIRM) allows the creation of lumped-element circuit models to find currents and voltages in circuits. Electrical circuit models can be combined with distributed field models, and this capability was used to model surface and vertical resistance measurements. To model the selected fabric, we measure the thickness of the fabric and the threads, find the distance between conductive threads, determine the number of weft and warp threads occurring between conductive threads, and determine the geometric model of the weft and warp threads. We build a model corresponding to the specified geometry in ECURM. Next, we select the material and enter the material parameters. The conductive thread model uses the averaged conductivity of the thread, regardless of its physical realization. This makes it possible to make ESD protective fabric from different thread with the same surface and vertical resistances. The prerequisite, however, is to ensure that the threads of the weft and warp are in mutual contact with each other at the same points and that these threads are in contact with the corresponding electrodes at the same points as well. Next, we add measuring electrodes and choose the electrode material and in ECIRM module, we make external connections to obtain the measuring system according to the standard. Finally, we simulate the model, calculate the desired resistance, and determine the current density in each thread. This allows us to determine the current flow paths that are important from the point of view of circuit modelling. A complete model of a plain weave fabric including both conductive threads and base threads (such as polyester) can be used for both stationary and transient (charge decay) tests.

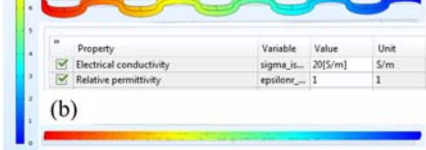

Fig.3. Model and result of the simulation of the unit resistance in COMSOL Multiphysics® software of (a) the weft; (b) the warp

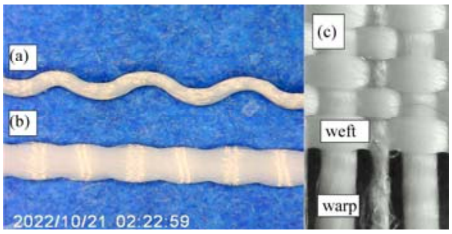

Fig.4. Macroscopic view of the weft thread; (a) side view; (b) top view; (c) piece of fabric with weft and warp threads marked

The methodology described above is general and allows to model of fabrics with a conductive mesh of any mesh size. In the following, we illustrate the modelling process for the fabric shown in Figure 1(b). It is a fabric with a thickness of 0.52 mm, with a conductive mesh size of 10 mm x 10 mm, containing 17 threads of weft and 9 threads of warp between the threads of the conductive mesh. In order to determine the geometric model of threads, they were extruded from the fabric. Based on macroscopic observations (see Fig. 4), the weft and the warp thread geometries shown in Fig. 3 were selected. After placing the measuring electrodes we obtain the model of the measurement system, which for surface resistance is shown in Fig. 5. Since the laboratory measurement has shown that the surface resistance of the fabric had a value of less than 10^4 Ω, a DC supply voltage value of 10 V was assumed in the simulations, according to the standard. In simulations, the following conductivity values were assumed, base thread $\sigma = 10^{-13}$ S/m, and stainless steel $\sigma = 4\cdot 10^6$ S/m. The average conductivity of the conductive thread, σ=20 S/m was determined by means of measurements. Using these parameters, a surface resistance R_s=788 Ω was found. Analysis time on a computer equipped with an Intel Core i7-6700 processor and 64 GB of RAM was 575 s, using 24.06 GB of the physical memory of the computer. Figure 6(a) shows the multi-slice regarding the current density norm. The red colour indicates the highest value of this quantity. Observation of these results allows us to conclude that the current, as expected, flows mainly through the conductive threads of the weft and warp, and therefore, in order to determine the resistance, the base threads can be removed from the model. The results of this approach for determining surface resistance are shown in Fig. 6(b). The resistance value is almost identical to that determined with the full model. Analysis time was 84 s, using 3.81 GB of memory.

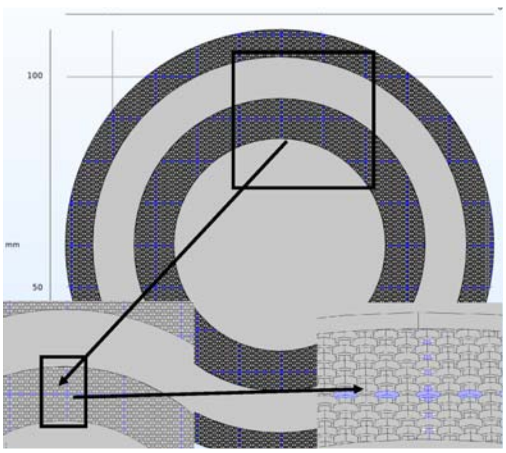

Fig.5. ESD protective fabric and measuring electrodes model to determine surface resistance - model with marked conductive threads and subsequent enlargements of a fragment of this model

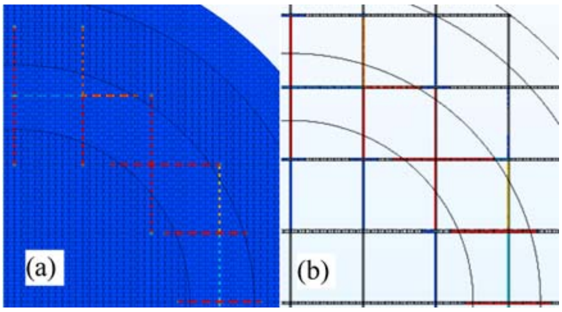

Fig.6. The result of surface resistance determination in COMSOL Multiphysics® – current density norm in A/m^2 - an enlarged part of (a) full model; (b) simplified model

By placing a conductive measuring electrode under the sample and modifying the external part in the ECIRM model according to the standard, we obtain a system that allows the simulation of vertical resistance. After calculations, the value of the resistance R_v = 5.66 Ω was determined, both using the full and the simplified model.

During laboratory tests, the effect of the position of the test sample relative to the measuring electrodes was observed. This influence was investigated by simulation in the case of determining surface resistances. The results indicate differences up to about 5% of the average value.

Lumped-element circuit models

We discuss the circuit modelling process in detail for the case of surface resistance. A model for determining vertical resistance was built in an analogous way. Based on the results of the analysis of the model in COMSOL we select the parts of threads that play an important role and analyze the points of mutual contact between the threads as well as between the threads and conducting electrodes. To built the lumped-element circuit models of fabric we consider the case of symmetry of the structure, which occurs when the point of contact of warp and weft threads is located in the centre of the circles forming the geometry of the corresponding electrodes. We consider only one quadrant of the full mesh. The surface resistance of the sample is then a parallel combination of four identical resistances. To get the correct result, the resistances belonging to the common edge of the rectangle with another quarter of the sample must be multiplied by two. Since, in the considered fabric, warp threads are not in direct contact with the measuring electrodes the resistances of the parts of warp threads taking into account in the model are always equal to unit length resistance (per 1 cm). The situation is different in the case of weft threads, where the resistance of the parts of thread in the model depends on its position relative to the electrodes and must be adjusted accordingly to make the circuit model adequate. Resistor values were selected by analyzing the current geometry of system.

To develop a model, unit warp and weft threads (per 1 cm) having the form shown in Fig. 3, were considered. Assuming the same cross-sectional area of both threads and the same material (the same conductivity), the unit resistances of both threads were determined in COMSOL software, $\overline{R}$ and $\widetilde{R}$ (unstretched thread), respectively. If the threads were straight their unit resistance should be the same. However, since the weft thread model has the form shown in Fig. 3(a), the unit resistance $\widetilde{R}$ is larger. The ratio of these resistances is a constant value for a plain weave fabric with an assumed weft and warp model. We get the following values of warp and weft resistance, $\overline{R}$ = 10074 Ω, and $\widetilde{R}$ = 11856 Ω. The ratio of these resistances equals 0.85. We take the resistance of 1 cm of weft thread (Fig. 3(a), unstretched thread) as a model parameter and denote this resistance by R in the models given below (R = $\widetilde{R}$). Then the coefficient of 0.85 in the warp thread models is related to the conversion of the warp thread length to the straightened weft thread length.

The resistances between the conductive electrodes and the warp threads have small values, and their neglect does not significantly change the resulting surface resistance. The value of these resistances was assumed as $0.0158R$ (by a simplified analysis of the geometry).

In order to make it possible to model fabrics with different conductivities of weft and warp threads, we introduce an additional parameter k into the models. Let k be a ratio of the warp thread unit resistance to the unstretched weft tread unit resistance. So, a factor of $k\ R$ appears for each resistance of the warp thread model. The modelling process described above leads to the lumped-element circuit models shown in Figs. 7 and 8 for the surface and vertical resistance, respectively.

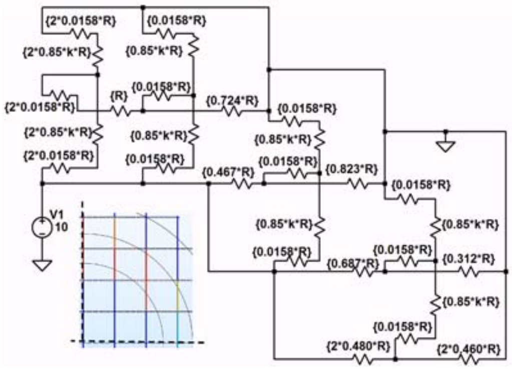

Fig.7. Lumped-element circuit model used to determine R_s

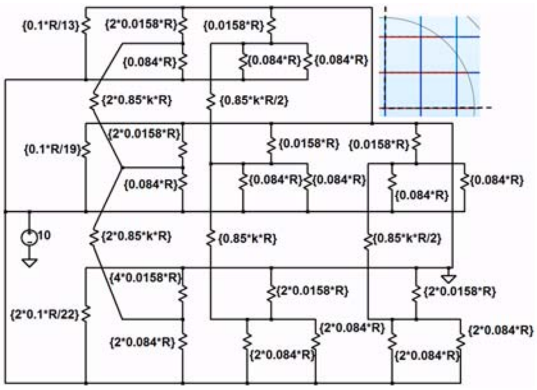

Fig.8. Lumped-element circuit model used to determine R_v

Analysing the circuit shown in Fig. 7 for R = 11856 Ω and k = 1, the resistance of quadrant of the full physical model R_q = 2879 Ω, and the surface resistance of the entire fabric sample equals R_s=R_q/4=720 Ω, were found. The last value is very close to the value determined in COMSOL. Analyzing the circuit shown in Fig. 8 the vertical resistance R_v =5.69 Ω was determined (the value R_v = 5.66 Ω was found in COMSOL).

Fitting the parameters of circuit models to the required values of resistances

The circuit models of the conductive fabric mesh are characterized by two parameters $\widetilde{R}$ – the unit resistance (per 1 cm) of the weft, and k – the ratio of the warp unit resistance to the weft unit resistance. Now, a numerical method to fit these parameters to the desired values of surface resistance and vertical resistance is presented. An algorithm that is a combination of the concept of homotopy and the simplicial method [18] is used. In the general case, the algorithm makes it possible to find many solutions to nonlinear equations that are not given in an explicit analytical form and it does not require the calculation of the derivative. In this paper the algorithm was adapted to determine a single solution to the problem of interest. A sketch of the algorithm for the problem considered in the paper is described below. A detailed explanation of the formation of the initial and the adjacent simplex as well as the determination of the end point of the segment inside the simplex is discussed in Ref. [18].

It is convenient to represent the parameters $\widetilde{R}$ and k as a function of some relative parameters p_1, p_2 according to equations $\widetilde{R} = \widetilde{R}_0 p_1$, $k = k_0 p_2$, where $\widetilde{R}_0$, k_0 are some initial values of the unit weft resistance and the ratio. We present the relative parameters in the vector form $\boldsymbol{p} = [p_1\ p_2]^{\mathrm{T}}$. For fixed values of $\widetilde{R}$ and k, it is possible to determine the actual values of R_s and R_v from circuit models. Let the surface and vertical resistance values for the current parameter values form a vector $\boldsymbol{r} = [r_1\ r_2]^{\mathrm{T}}$, where r_1=R_s, and r_2=R_v. Each of the elements depends on the values of the relative parameters p_1, p_2, i.e. $r_i = f_i(p_1, p_2)$. We can therefore write down $\boldsymbol{r} = \boldsymbol{f}(\boldsymbol{p})$, where $\boldsymbol{r} = [r_1\ r_2]^{\mathrm{T}}$, and $\boldsymbol{f}(\boldsymbol{p}) = [f_1(\boldsymbol{p})\ f_2(\boldsymbol{p})]^{\mathrm{T}}$ is a nonlinear function. Let the desired values of surface and vertical resistance form a vector $\bar{\boldsymbol{r}} = [\bar{r}_1\ \bar{r}_2]^{\mathrm{T}}$. Thus, the nonlinear equation we want to solve takes the form

$$\boldsymbol{f}(\boldsymbol{p}) = \bar{\boldsymbol{r}}\ . \tag{1}$$

To determine the solution to this equation we will use the concept of homotopy. Assume that the parameters $\widetilde{R}$ and k have their initial values $\widetilde{R}_0$, k_0. Hence, the vector $\boldsymbol{p} = [p_1\ p_2]^{\mathrm{T}}$ takes the form $\boldsymbol{p}^0 = [1\ 1]^{\mathrm{T}}$. We substitute these parameters and analyze the circuit circuits, finding the vector $\boldsymbol{r} = \boldsymbol{r}^0$. Thus, $\boldsymbol{f}(\boldsymbol{p}^0) = \boldsymbol{r}^0$ holds. For equation (1), we create the Newton homotopy equation in the form

$$\boldsymbol{f}(\boldsymbol{p}) - \boldsymbol{r}^0 - p_3(\bar{\boldsymbol{r}} - \boldsymbol{r}^0) = \boldsymbol{0}\ , \tag{2}$$

where p_3 is a homotopy parameter. For p_3=0 the equation (2) reduces to the equation $\boldsymbol{f}(\boldsymbol{p}^0) = \boldsymbol{r}^0$ having the known solution $\boldsymbol{p}^0$, whereas for p_3=1 it becomes the original equation (1). For each value of p_3, the corresponding solution is calculated taking into account the previous solution. As a result, a homotopy path is traced, and the intersection of the path with the p_3=1 plane is a solution to the test equation. We use the simplicial algorithm to trace the homotopy path and to determine the solution. (the explanation of the method is given in Ref. [18]). After determining the parameters $\widetilde{R}$ and k, we can calculate $\overline{R}$, and then, taking into account the cross-sectional area of the threads and the length of the weft thread after straightening, the conductivities $\widetilde{\sigma}$ and $\overline{\sigma}$ of the weft and warp threads, respectively. The numerical method was implemented in the DELPHI environment.

Results and discussion

Under laboratory conditions, resistance values were determined using a Tera-Ohm-Meter 6206 from Eltex. Resistances below $10^5\,\Omega$ were determined by measuring the current through an ammeter (in the lab a METRAHIT M249A) connected in series with the sample of fabric placed in electrode system. During the determination of the vertical resistance for samples with a small value of surface resistance, there may be an overload of the voltage source caused by the flow of a large current. The measurement then may be unreliable. In this case, a sample with measuring electrodes and a 100 Ω auxiliary resistor in series was connected to a power supply and calculate the resistance from Ohm's law. In accordance with the standard, five conditioned circular samples were cut to measure their resistances. For the fabric shown in Fig. 1(b), R_s=781.4 Ω, and R_v=5.57 Ω were obtained close to the value found in the COMSOL environment.

In order to validate the correctness of the proposed method the values of R_s = 720 Ω and R_v = 5.69 Ω obtained at the circuit modelling stage were taken as $\boldsymbol{\bar{r}}$. The following results $\tilde{R}$ =11850 Ω, k = 1.003, $\bar{R}$ = 10103 Ω, $\tilde{\sigma}$ = 20.01 S/m, and $\bar{\sigma}$ = 19.94 S/m, were obtained. They are very close to the values assumed at the modelling stage. Next, we consider six cases of plain weave fabrics, with the values of surface and vertical resistances assumed a priori. The results are summarized in Tables 1 and 2. We verify the results by determining the surface and vertical resistances in COMSOL software, R_s^C and R_v^C, respectively.

Table 1. Results of the process of numerical fitting of weft and warp thread parameters to the required surface and vertical resistances

No.	R_S [Ω]	R_V [Ω]	$\tilde{R}$ [Ω]	k	$\bar{R}$ [Ω]
1	$5 \cdot 10^3$	100	$2.08 \cdot 10^5$	0.1836	32503
2	$2 \cdot 10^4$	500	$1.04 \cdot 10^6$	0.1318	116658
3	$2 \cdot 10^4$	1000	$2.08 \cdot 10^6$	0.0475	84097
4	$3 \cdot 10^5$	2400	$4.99 \cdot 10^6$	0.9726	$4.13 \cdot 10^6$
5	$3 \cdot 10^5$	10000	$2.08 \cdot 10^7$	0.0871	$1.54 \cdot 10^6$
6	$2 \cdot 10^6$	15750	$3.28 \cdot 10^7$	1.0122	$2.82 \cdot 10^6$

Table 2. Results of the process of numerical fitting of weft and warp thread parameters to the required surface and vertical resistances

No.	$\tilde{\sigma}$ [S/m]	$\bar{\sigma}$ [S/m]	R_s^C [Ω]	R_v^C [Ω]
1	1.1389	6.1982	5288	93.4
2	0.2278	1.7269	20788	464
3	0.1139	2.3956	19665	920
4	0.0474	0.0487	314620	2259
5	0.0114	0.1306	317870	9243
6	0.0072	0.0071	2000000	14808

Relative errors, related to the values obtained in the COMSOL environment, do not exceed on average 3.6% for surface resistance and 7.4% for vertical resistance.

Conclusion

The methodology for the design of ESD protective fabrics containing a mesh of conductive threads was proposed. The methodology can be generalized to fabrics with different weave and thread geometry, except fabrics containing conductive threads with a conductive core. Based on the results of the analysis of models made in the COMSOL environment, the lumped-element circuit models was developed. The application of these models in the gradient-free numerical method makes it possible to fit the parameters of conductive threads to the required values of surface and vertical resistance of ESD protective fabrics. Effectiveness of the proposed models and method was confirmed by simulation and laboratory tests. The proposed models can be elaborated for any ESD protective fabric that uses a conductive mesh with a known mesh size. The use of circuit models allows us to carry out the design process by the method proposed in a much shorter time than in the case of using COMSOL. Circuit models can be made more accurate by taking into account some secondary resistances. Further research work will be carried out to incorporate the EN-1149-3 standard into the design process. The standard allows the testing of any ESD-protective fabric, including those fabrics in which the conductive thread contains only a conductive core.

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