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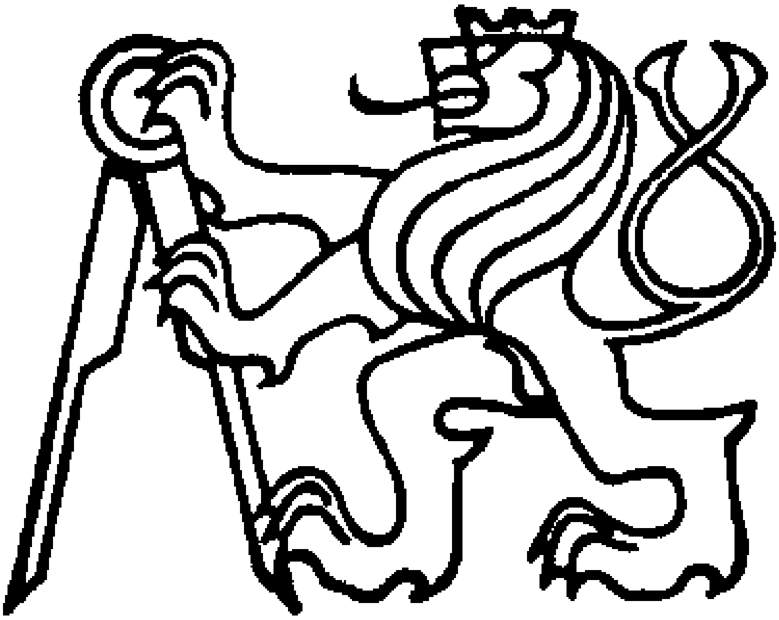

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Telecommunication Engineering

Ing. Bc. Marek Neruda

MODELLING OF ELECTRICAL RESISTIVITY FOR ELECTRICALLY CONDUCTIVE TEXTILE MATERIALS

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1. CURRENT SITUATION OF THE STUDIED PROBLEM

Modelling the electrical property of conductive fabrics for knitted fabric sensors is described in [1]. Electrical model of 1×1 rib conductive knitted fabrics is proposed based on Kirchhoff's voltage law and electric circulation theories. It however describes only the relationship between resistance of 1×1 rib fabric knitted with stainless steel fibres and its extension. It does not include electrical resistivity modelling, woven fabrics consideration or fibres manufactured from conductive and non conductive fibres. The rest of the papers describe electrical resistivity parameter only as an input parameter for modelling for example textile antennas, textile sensors or textile transmission lines.

A textile antenna is often designed in the simulation software, optimized and fabricated. The simulation software often uses the numerical methods such as Method of Moment (MoM), Finite Element Method (FEM) and Finite Difference Time Domain (FDTD). Basic parameters of antennas such as gain, radiation pattern, input impedance, etc. are then compared by simulation and measurement results. Paper [2] describes the comparison of measurement and modelling results of two experimental monopole antennas which were produced from a conductive textile radiating element and a metallic conductor. Modelling and measurement of input impedance for two different thicknesses of the sample, i.e. physical and effective one, is presented in [3]. Authors compare resistance for different layered impedance boundaries, which is a parameter of HFSS (High Frequency Structure Simulator) software used to model multiple thin layers in a structure as one impedance surface. Electrical conductivity of thread is modelled by HFSS software and measured in [4]. A comprehensive study of the high frequency properties of the electro-textiles for wearable antenna applications is carried out in [5]. Paper [6] presents a design procedure for a textile planar inverted-F antenna (PIFA) and evaluates its efficiency. Read range of sewed RFID (Radio Frequency Identification) tag with dipole antenna is discussed in [7]. Patch type UHF RFID antenna is designed and different electro-textile ground planes are investigated in [8].

Numerous other papers have been published about the design, fabrication and applications of textile antennas [9 - 16]. However, the papers usually present antenna design, simulations and measurement of specific antenna parameters, not the modelling of the electrical resistivity or conductivity. It is often only the input parameter for simulations. The chapter about the electrical surface resistivity of the conductive fabrics is described in the survey [17]. The surface resistivity is discussed as quantification of electrical behaviour of fabrics as planar materials. Authors mention used standards and test methods of surface resistivity, the choice of the conductive fabric for the patch and the ground planes and they also discuss the influence of fabric structure to antenna parameters.

Many papers also design the conductive textile structure as a sensor. The paper [18] presents a design of flexible resistive pressure sensor woven from electrical conductive fibres in parallel connection. The paper [19] introduces textile pressure sensor design consisting of textile sensor array and the measurement electronics. The sensor is formed by three-layer structure forming a variable capacitor. Electrical model of stretch sensor is described in [20]. Authors employ Delta-Y transform for calculation of anti-ladder topology of stretch sensor.

Textile transmission lines are investigated in the [21]. Authors discuss material properties, impedance characterization, time domain reflectometry (TDR) measurement and frequency characterization. Electrical performance of textile transmission lines is also discussed in [22]. Authors consider textile geometry, transmission line configuration, impedance measurement and find out among others a good signal transmission for a 100MHz clock signal. The paper [23] reports the electrical conduction properties of an antistatic 2/1 twill fabric with 10% of a conductive fibre. Authors use rectangular electrodes to measure specimen resistance between them and calculate resistivity. Modelling of metalized textiles for shielding purposes introduces [24]. Modelling is based on developed software by authors that can calculate shielding efficiency of metalized textiles.

Patent databases of Industrial Property Office of Czech Republic [24], ESPACENET database of European Patent Office [25] or U.S. database of USPTO [26] contain many patents or utility models which describe methods for fabric or yarn production, fabric modelling by finite element analysis or by optical analysis. Modelling of electrical resistivity misses in these databases.

Standards [27 - 32] focus on materials characterized by volume resistivity in the range of $1.0 – 1.0x10^{11}$ Ω·cm and surface resistivity in the range of $1.0x10^{3}$ - $1.0x10^{12}$ Ω/square. It represents moderately conductive, static dissipative and insulating materials. Most of standards present measurement method of specimen resistance and calculation of electrical resistivity, surface or volume resistivity, by multiplication of measured resistance and coefficient which corresponds to electrode arrangement. Circular electrodes, i.e. concentric ring arrangement, are preferred to rectangular shape of electrode because circular electrodes do not have to consider specific orientation of specimen and electrodes, which has to be taken into account by rectangular electrodes, and inhomogeneity of planar textile material. The measurement principle however provokes to take advantage of it for modelling purposes.

It is currently not known that the modelling of electrical resistivity for electrically conductive planar textile materials is being solved for woven fabrics. However, modelling of the electrical property of 1×1 rib fabrics was published for knitted fabrics describing the tendency of resistance change of 1×1 rib knitted fabrics under uni-direction extension. Modelling of electrical resistivity of woven fabrics is however very important for the needs of material engineering in the field of electrically conductive planar textile materials.

2. AIMS OF THE DOCTORAL THESIS

Present electrically conductive textile materials can be used in many applications such as textile antennas, sensor, transmission lines or ESD applications. However, electrical resistivity or its reciprocal value electrical conductivity is an input parameter for material property determination, papers usually describe design of real sample, simulations and measurement of specific parameters, not the modelling of the electrical resistivity or conductivity.

However many papers describe improvement of electrically conductive textile materials in the form of real samples, modelling the electrical property of conductive fabrics for knitted fabric sensors is described in [1] and, as previously mentioned, it does not include electrical resistivity modelling, woven fabrics consideration or fibres manufactured from conductive and non conductive fibres. It is focused on relationship between resistance of 1×1 rib fabric knitted with stainless steel fibres and its extension.

Modelling of electrical resistivity moreover misses in the Patent databases of Industrial Property Office of Czech Republic, ESPACENET database of European Patent Office or U.S. database of USPTO and also in standards [27 - 32] which focuses on measurement methods.

The motivation and aims of this thesis is to achieve applicable model for electrical resistivity determination of electrically conductive planar textile materials. The main objectives of the thesis are:

- To analyse the issue of electrical resistivity determination
- To propose a model describing electrically conductive planar textile materials
- To verify possible simplifications of the model considering real electrically conductive textile material
- To propose a generally applicable model for electrical resistivity determination
- To verify designed generally applicable model for electrical resistivity determination

3. WORKING METHODS

Fulfilment of the aims of the thesis is achieved by sequential use of several research methods. Observation without interference, experiment, i.e. observation in specific laboratory conditions and measurement are referred to be empirical methods. However, they are in a large measure used in Kolb`s experimental cycle [33, 34], which gives into context logical methods deduction and induction, Fig. 1.

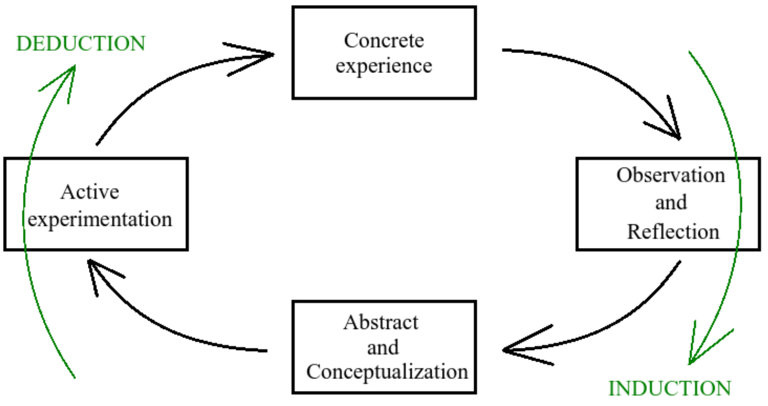

Fig. 1 Kolb`s experimental cycle [33, 34].

Explanation of Concrete experience is obvious, i.e. for example experience with measurement method, reading results, process production etc. Observation and Reflection is process of thought about the experience. Abstract and Conceptualization represents a process of draw conclusions from the experience, generalization and concept proposal. Active experimentation is a process of concept verification.

It is obvious Kolb`s experimental cycle can be used in spiral. An example of this is a process of measurement method improvement, programming, modelling, etc.

The use of induction method leads to considering only limited amount of information because the research is based on concrete experience. Therefore the researcher is aware of limited amount of models and theories.

The risk of using deduction method can be seen in applying already verified procedures at all costs which can lead to failure of analysing new or interesting stimuli.

Modelling of resistivity uses several software environments and laws of electric circuits, i.e. circuit equations which include Kirchhoff's circuit laws, Loop Current Method, calculation of resistors in series and parallel and Delta Star and Star Delta Transformation. Electric circuits are simulated in a GNOME application for schematic capture and simulation of electronic circuits called Oregano [35], which is licensed under the terms of the GNU GPL (GNU's Not Unix) (General Public License) [36]. Numerical computation and programming are executed in high-level language and interactive environment MATLAB®, product of The MathWorks, Inc. [37]. Visualization is performed in Excel [38].

Weakness of modelling is excessive simplification of the model which can lead to incorrect conclusions. Therefore it is recommended to verify modelling method by appropriate measurement method, if exists.

Measurement setup consists on self-made apparatus, Voltcraft® LCR 4080 LCR Multimeter and cables. Weakness of the measurement method can be seen in wrong choice of measurement device and cables, ignorance of all aspects of used measurement method and for example results interpretation.

4. RESULTS

Analysis of electrical resistivity determination

Standardized test method focus on measurement procedure of moderately conductive, static dissipative and insulating materials by circular electrode setting in the form of concentric ring. Rectangular shape of electrodes is also considered, it however requires specific orientation regarding to orientation of specimen, i.e. electrodes are parallel to the yarn in the fabric length and also in the fabric width. The advantage of circular electrodes is seen in independence from weft and warp directions and inhomogeneity of planar textile material.

Electrical resistivity is also determined by its definition published not only in standards. Derivation of electrical resistivity, surface or volume resistivity, is based on Ohm`s law in differential form for concentric circular electrodes and concentric ring electrodes.

Surface and volume resistivity is calculated for rectangular shape of electrodes as:

$$\mathrm{\rho_S} = \frac{\frac{U}{L}}{\frac{\mathrm{I}_S}{W}} = \frac{U}{\mathrm{I}_S} \cdot \frac{W}{L} = R_S \cdot \frac{W}{L}\,[\Omega/square] \tag{1}$$

$$\mathrm{\rho_V} = \frac{U}{\mathrm{I}_V} \cdot \frac{A_c}{l} = R_V \cdot \frac{A_c}{l}\ [\Omega \cdot \mathrm{cm}] \tag{2}$$

where ρ_S indicates surface resistivity, U represents DC voltage, I_S specifies surface current, L is distance between electrodes, W denotes width of electrodes, R_s indicated surface resistance, ρ_V indicates volume resistivity, I_V specifies volume current, A_c represents cross-sectional area of specimen dimensions, l denotes distance between electrodes and R_V indicated volume resistance.

Surface and volume resistivity is calculated for concentric ring electrodes as:

$$\rho_S = R_S \cdot \frac{2\pi}{\ln\frac{r2}{r1}} = R_S \cdot k[\Omega/square] \tag{3}$$

$$\rho_V = R_V \cdot \frac{\mathrm{\pi D1}^2}{4\mathrm{t}_h}[\Omega \cdot cm] \tag{4}$$

where r_1 specifies outer radius of the centre electrode and r_2 represents inner radius of the outer ring electrode, k represents geometric coefficient of electrodes, D_1 is a diameter of inner electrode, t_h is the distance between electrodes.

Proposal of a model describing electrically conductive planar textile materials

The concept of model assumes several assumptions:

- Conductive woven fabric with plain wave can be seen as a grid of resistors
- Transition resistance of interlacing points is much lower than measured resistance, so it can be neglected
- Modelled textile material can be seen as it is compound from homogenous yarn
- Input parameter of the model is resistance value of resistor *R*` (*R*1 in figures) which is the same for all resistors *R*` (R1)
- Points with the same potential can be connected or disconnected as necessary

As a consequence, it is possible to see electrical conductive planar textile material with plain weave as a grid of resistors, Fig. 2.

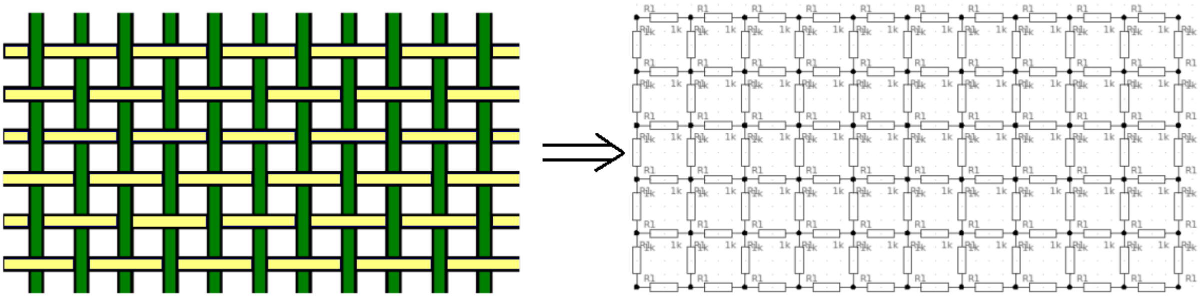

Fig. 2 Equivalent circuit diagram of used textile material.

Moreover, points with the same potential can be connected or disconnected as necessary. Considering measurement procedure [27], power supply can be connected to shorter sides of electrically conductive textile model and the same voltage drop in the nodes which are at the same "distance" from the connected power supply occurs. Then the model is simplified as shown in Fig. 3.

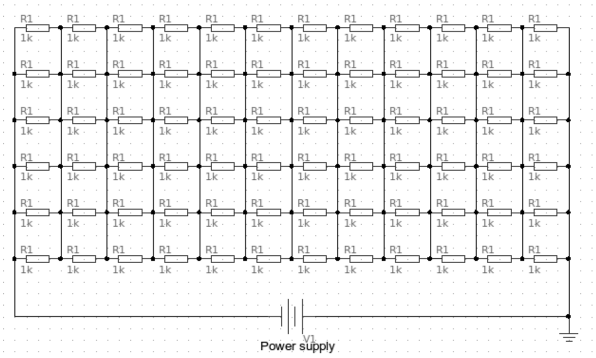

Fig. 3 Simplified electrical circuit by eliminating resistors.

Verification of possible simplifications of the model considering real electrically conductive textile material

Resultant resistance of simplified electrical circuit depicted in Fig. 3 can be calculated from series-parallel connection of resistors as:

$$\mathrm{R} = \ {}_{1}^{12}\frac{R`}{6} = \frac{12R`}{6} = 2\mathrm{R}`[\Omega] \qquad (5)$$

where *R* represents resultant resistance and *R'* specifies resistance value of modelled resistor *R1* depicted in Fig. 3.

If a common formula is derived, resultant resistance is described as:

$$\mathrm{R} = \ {}_{v=1}^{u}\frac{R`}{s}, v, u, s \in \{N\}[\Omega] \qquad (6)$$

where *v*, *u* is number of squares in "horizontal" direction, *s* represents number of squares in "vertical" direction.

Equipotential lines can be also verified by software. It is possible to use for example software called Oregano, GNOME application, for verifying points with the same potential [35]. It is capable to place voltage probes into the individual points of electric circuit and show voltage values in these points. Fig. 4 depicts results for the points with different potential and Fig. 5 shows points with the same potential.

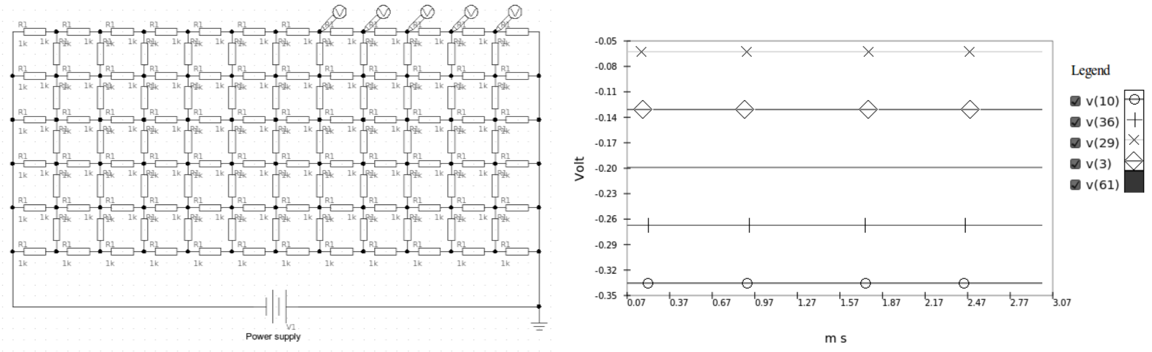

Fig. 4 Voltage values for the points with different potential.

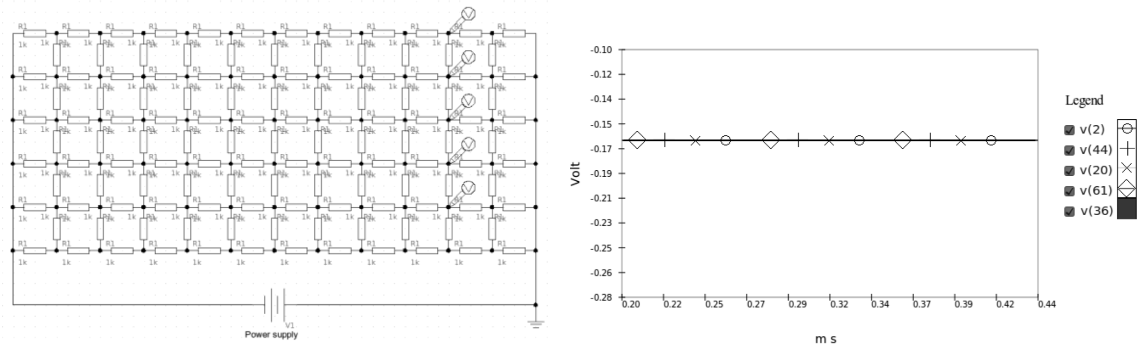

Fig. 5 Voltage values for the points with the same potential.

Moreover, simplifications of the presented model can be verified by inspection of real planar textile specimen No. 60, which is characterized by the sett of 25 threads/cm in warp and 20 threads/cm in weft, dimensions of 30x100 mm, composition of 30% SilveRstat, 30% Shieldex and 40% PES (Polyester) and fineness of 35.5 tex. Verification of (2) requires knowledge of parameters u, s and R'. Number of threads u and s can be calculated as:

$$s = 20 \cdot 3 = 60\ [-] \tag{7}$$

$$u = 25 \cdot 10 = 250\ [-] \tag{8}$$

Value of modelled resistance R' is obtained from:

$$\mathrm{R}' = \frac{R_l \cdot l_{R'}}{l_R}\ [\Omega] \tag{9}$$

$$\mathrm{l}_{R'} = \frac{W - s \cdot d_Y}{s}\ [mm] \tag{10}$$

where R_l is measured resistance of fibre with length l_R and $l_{R'}$ is the length of R', W represents width of measured sample, s defines number of threads in weft and d_Y is measured diameter.

Diameter measurement of fibre is obtained by micrometre measurement and by microscopic examination. Resistance R of real specimen is measured by rectangular shape of electrodes, which corresponds to (2), as well as resistance of fibre with length $l_{\mathrm{R}} = 100$ mm. Measurement results are depicted in Tab. I. Tab. II shows parameters for resistor R' and length $l_{\mathrm{R'}}$ determination.

TABLE I. MEASUREMENT RESULTS OF THE FIBRE

Measurement parameter	***Value***
Average diameter of fibre d_Y [mm]	0.210
Measured resistance of fibre with length $l_R = 100\ mm$ R_l [Ω]	335
Measured resistance R [Ω]	3.952

TABLE II. PARAMETERS FOR LENGTH OF R' AND R' CALCULATION

Measurement parameter	***Value***
Number of threads in weft *s* [-]	60
Width of measured specimen *W* [mm]	30
Specimen length L [mm]	100
Systematic error of Voltcraft LRC 4080 Multimeter measurement [Ω]	0.027

$$\mathrm{l}_{R'} = \frac{W-s\cdot d_Y}{s} = \frac{30-60\cdot 0.210}{60} = 0.290\ [mm] \tag{11}$$

$$\mathrm{R}' = \frac{R_l\cdot l_{R'}}{l_R} = \frac{335-0.027\ \cdot 0.290}{100} = 0.971\ [\Omega] \tag{12}$$

The formula, which is the modelling results, can be now calculated as:

$$\mathrm{R} = {}^{u}_{v=1}\frac{R`}{s} = {}^{250}_{v=1}\frac{R`}{60} = \frac{250\cdot R`}{60} = 4.166\cdot 0.971 = 4.045\ [\Omega] \tag{13}$$

Measurement results for rectangular measurement setting show average value 3.952 Ω for No. 60. The difference of modelling and measurement results is $\mathrm{dif}_{\mathrm{model,\ measurement}}$ = 0.093 Ω.

Accuracy of modelling method is much higher than the error of measuring method which is on principal caused by a type of measured specimen, i.e. electrically conductive planar textile material.

The measurement results verify the validity of presented assumptions.

Proposal of a generally applicable model for electrical resistivity determination

The limitation of used rectangular model is seen in considering specific orientation of specimen and rectangular electrodes, i.e. electrodes are parallel to the yarn in the fabric length and also in the fabric width. So, only two directions are taken into account. This limitation is overcome by using concentric ring probe, Fig. 6.

Equations (1) – (4) can be used for electrical resistivity modelling because the equations consist of multiplication of resistance, which can be modelled, and a constant, which corresponds to specific specimen and electrode arrangement. Verification of modelling principle is therefore necessary to perform for only for example surface resistivity.

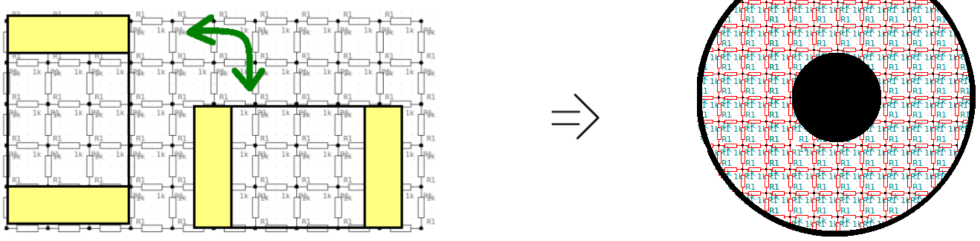

Fig. 6 Overcoming of limitation of electrical resistivity determination by rectangular shape of electrodes.

Location of equipotential lines and points is firstly performed for square shape of concentric electrodes. Resistance is calculated and assumption of location of equipotential points is verified by calculation (delta-star transform, series-parallel connection of resistors) and software as well. As a consequence equation for resistance determination for square concentric probes is expressed as:

$$\mathrm{R} = \frac{R`}{8} + \frac{1}{4}\cdot\ {}^{m1-2}_{n=5}\frac{R`}{n-1} +\ R^*_{n-2} + \frac{R`}{4\ n-3}\quad ,n\in\ 5, m1), r, m1\ are\ odd, R^*_5 = \frac{R`}{8} + \frac{R`}{8}\quad \frac{R`}{8} \tag{14}$$

where *R* is calculated resistance, *R'* specifies modelled resistor and R^*_{n-2} denotes value of calculated resistance for *n*-2, *n* is number of resistors between opposite sides of the square.

Subsequently, points with the same potential are identified for concentric ring electrodes, Fig. 7. It is found that it is possible to divide the model into four quadrants and calculate only one quadrant because four quadrants represent four parallel connected resistors. Moreover, it is also possible to divide this one quadrant to an half for the same resistance values or warp and weft. Procedure of resistance determination is programmed in MATLAB. Input parameters are determined as dimensions of inner and outer electrode, value of modelled resistor *R'* and sett *d*. The resistor network corresponding to R_x is transformed to matrix *A*, which is also limited by inner electrode. Impedance matrix *Z* is obtained by Method of loop currents and determinant is calculated. The sub-matrix Z_s of matrix *Z* omits first row and column which represents the loop including power supply. The determinant ratio of the matrix *Z* and Z_s is than equalled to resistance R_x. Resultant resistance *R* is calculated as four parallel connected resistors R_x.

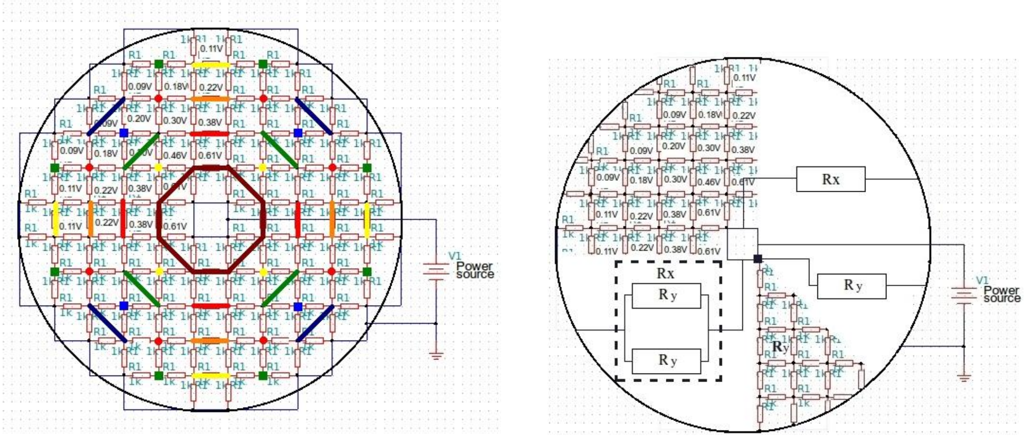

Fig. 7 Identification of the points with the same potential and model simplification.

Verification of designed generally applicable model for electrical resistivity determination

Model validity can be verified by changing one of the input parameters and simultaneously monitoring resultant resistivity. The value of resultant resistivity has to be the same for all cases and all electrode setting including rectangular shapes of electrode. The cases can be described as:

- Resistivity for rectangular shapes of electrodes and circular electrodes are comparable for different values of resistance of the yarn for the length 0.1 m, i.e. different values of *R'*
- Calculated resistivity from resistance modelling for different dimensions of circular electrodes is comparable with resistivity obtained by resistivity modelling for rectangular shapes of electrodes
- Resistivity for rectangular shapes of electrodes and circular electrodes are comparable for different setts

Results for resistivity modelling for different yarns

Resistivity modelling for different values of resistance of the yarn for the length 0.1 m considers input parameters are constant, i.e. dimensions of inner electrode r1 = d1/2, outer electrode r2 = d2/2 and sett d, Tab III.

TABLE III. MODEL INPUT PARAMETERS FOR DIFFERENT YARNS

Input parameters	***Value***
Sett d [threads/cm]	20
Diameter of inner electrode d_1 [mm]	30.84
Diameter of outer electrode d_2 [mm]	57.15
Resistance of the yarn for the length 0.1 m [Ω]	500 - 8300
Calculated resistance of the modelled resistor R' [Ω]	1.5 – 24.9

Results depicted in Fig. 8 show that increasing value of resistance yarn of the length l = 0.1 m leads to increasing value of resultant resistance. Resultant resistance is calculated from the modelled resistor R’ which is calculated from the resistance of yarn and therefore the dependence is increasing. The slope of a curve depends on the value of electrical resistivity of used yarn. The results also verify determinant calculation of impedance matrix.

The results for surface resistivity calculation are depicted in Fig. 9. The curve is the same but shifted due to multiplication geometric coefficient of electrodes.

Fig. 10 shows comparison of electrical resistivity values for concentric ring probes and rectangular shapes of electrodes. Only surface resistivity is compared because the surface and volume resistivity value is only multiple of the modelled resistance. Surface resistivity for rectangular shapes of electrodes is calculated with respect to (1) and (6) for square shape of electrodes, which is a special case of rectangular shape. It is numerically calculated as:

$$\mathrm{\rho_S} = \mathrm{R}_S \cdot \frac{W}{L} = \quad {}_{n=1}^{m1} \frac{R`}{s} \cdot \frac{W}{L} = R` \frac{60}{60} \cdot \frac{30}{30} = R` \tag{15}$$

Fig. 10 shows two linear curves with different slope of a curve. It can be however calculated for specific values. Considering Ryarn = 8300 Ω, ρS, square = 24.9 Ω/square and ρS, circular = 89.11 Ω/square. The slope of a curve is than calculated as the ratio of these values and the correction coefficient kc = 3.58. The validity of this correction factor can be verified by a change of input parameter and comparison of surface resistivity results. The result of applied correction factor is depicted in Fig. 11.

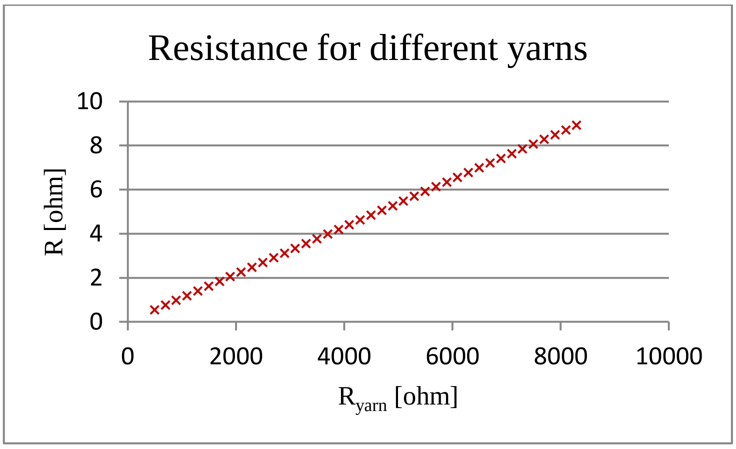

Fig. 8 Resistivity for different resistance values of yarn of the length l = 0.1 m.

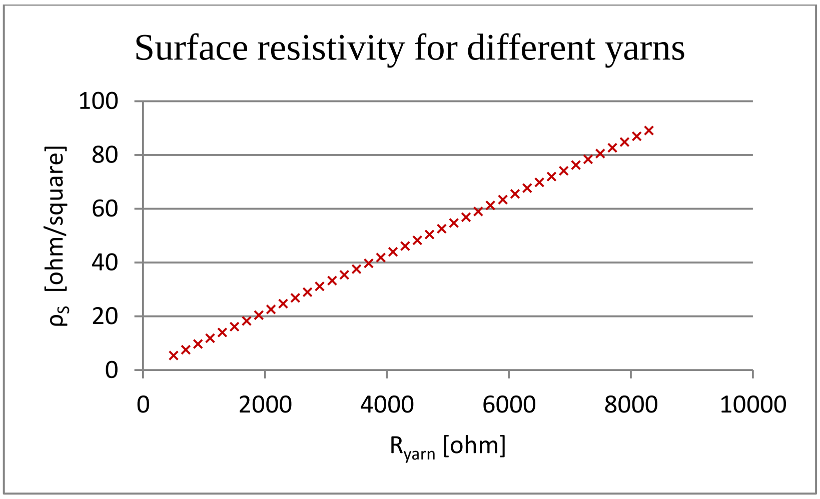

Fig. 9 Resistivity for different resistance values of yarn of the length l = 0.1 m.

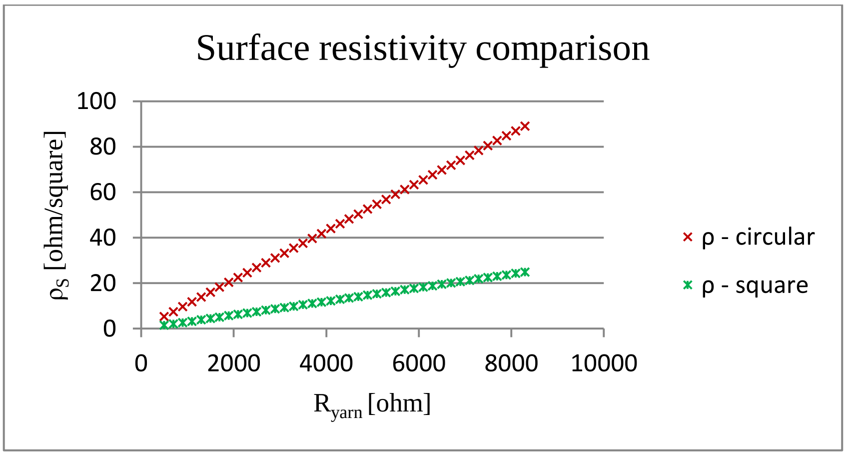

Fig. 10 Comparison of surface resistivity values for square and concentric ring electrodes.

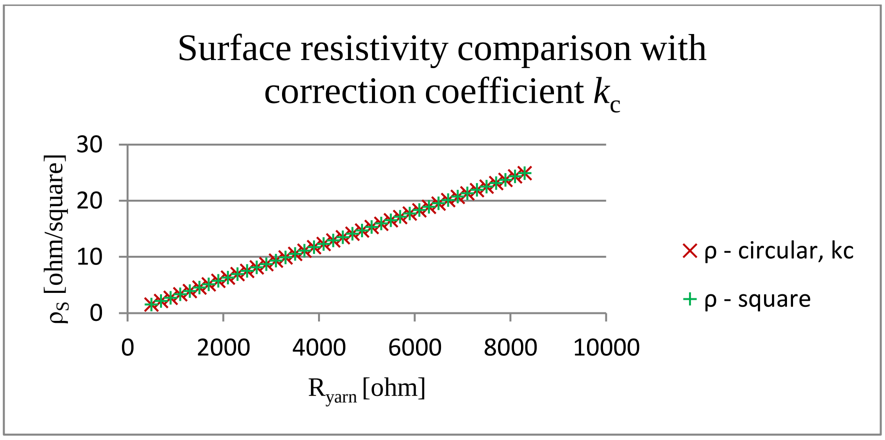

Fig. 11 Comparison of surface resistivity values for square and concentric ring electrodes considering correction coefficient k_c.

Results for surface resistivity modelling for different dimensions of electrodes and setts

The validity of correction factor k_c = 3.58 is further shown for the case of different dimensions of circular electrodes and for different setts. Results for surface resistivity comparison are depicted in Fig. 12 and Fig. 13. Fig. 12 shows the same curve tendencies from the sett d_2 = 40 mm. Differences for smaller setts are caused by small difference of diameter of inner and outer electrode, i.e. small specimen is taken into account and it causes inaccuracies. Both curves are almost constant because electrode arrangement is changed, not the specimen. Different values of resistors which are limited by circular electrodes at the margin are also calculated for different diameters of outer electrodes. This fact results in fluctuation of the curve. Fig. 13 depicts surface resistivity decreases with an increasing value of the sett which is obvious from (9) and (10). Fluctuations in curve smoothness can be caused by resistor calculation in the margins of electrodes.

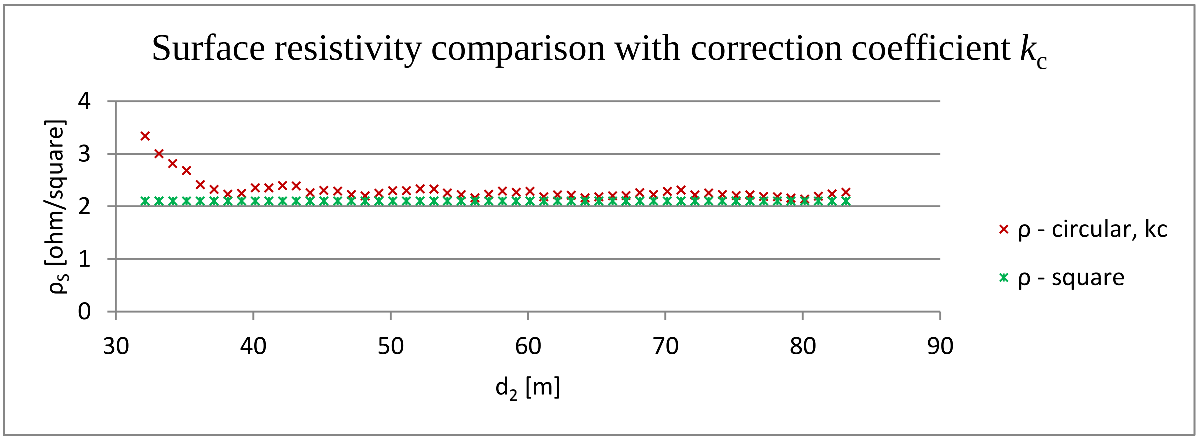

Fig. 12 Comparison of surface resistivity values for square and concentric ring electrodes considering correction coefficient k_c.

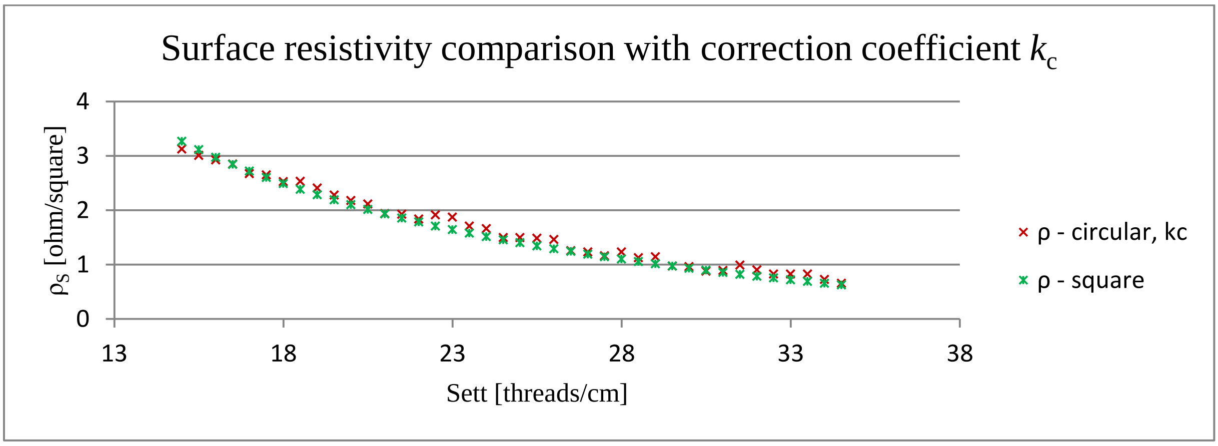

Fig. 13 Comparison of surface resistivity values for square and concentric ring electrodes considering correction coefficient kc.

Results for surface resistivity modelling considering different yarns in warp and weft

Moreover, it is possible to modify this model and consider different values of resistor R' in warp and weft. It is possible to obtain similar graphs as previously shown for different dimensions of electrodes, different setts and different values of yarn. These results are shown and discussed in the thesis. An example is shown in Fig. 14. Surface resistivity decreases with increasing value of sett due to smaller value of modelled resistor R_W' and R_P' for increasing sett. Influence of margins leads to fluctuation of the curve smoothness.

The comparison with the model for rectangular shapes of electrodes misses because the model for rectangular shapes of electrodes considers only two directions of the warp and weft yarns. It is however possible to verify it by substitution of different values of R_W and R_P with the same values, i.e. $R_W = R_P$, which corresponds to previously presented results. Fig. 15 – Fig. 17 show the same values of surface resistivity for both cases and therefore it verifies the validity of the modified model.

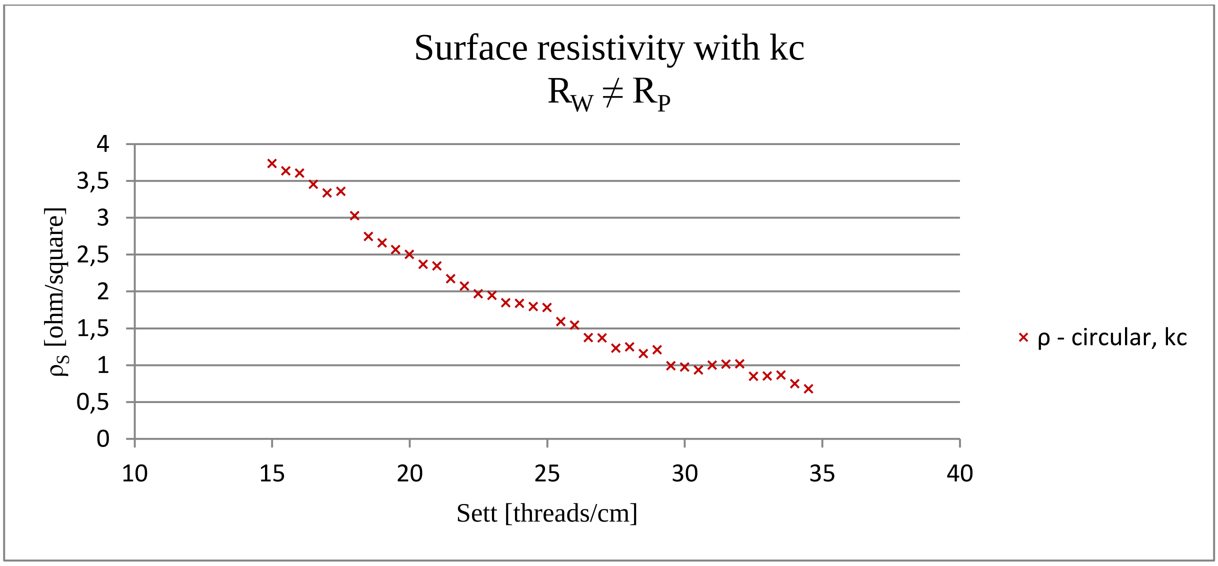

Fig. 14 Surface resistivity values for circular electrodes considering correction coefficient k_c (R_W = 1100 Ω and R_P = 700 Ω).

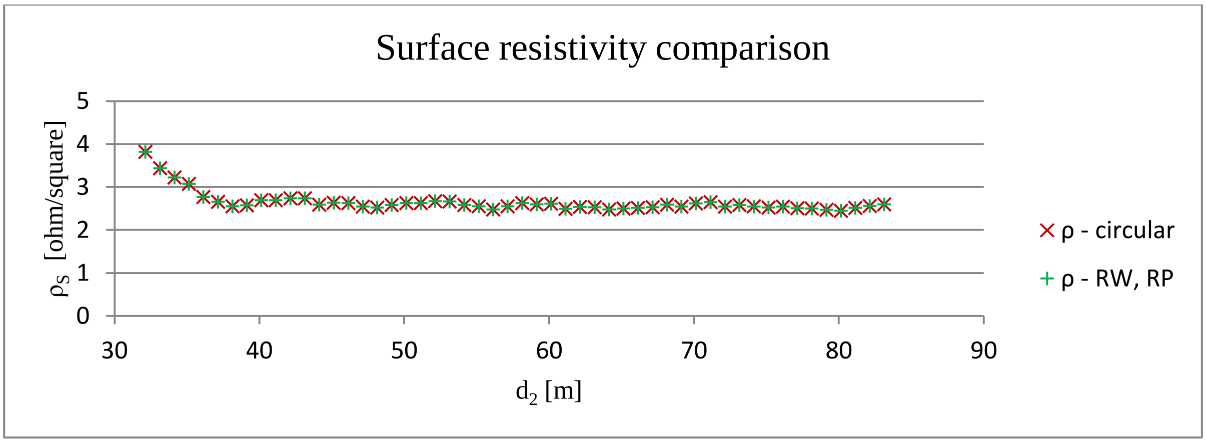

Fig. 15 Comparison of surface resistivity values for concentric ring electrodes considering model with and without differentiation of resistance values of warp and weft yarns (R_W = R_P = 700 Ω).

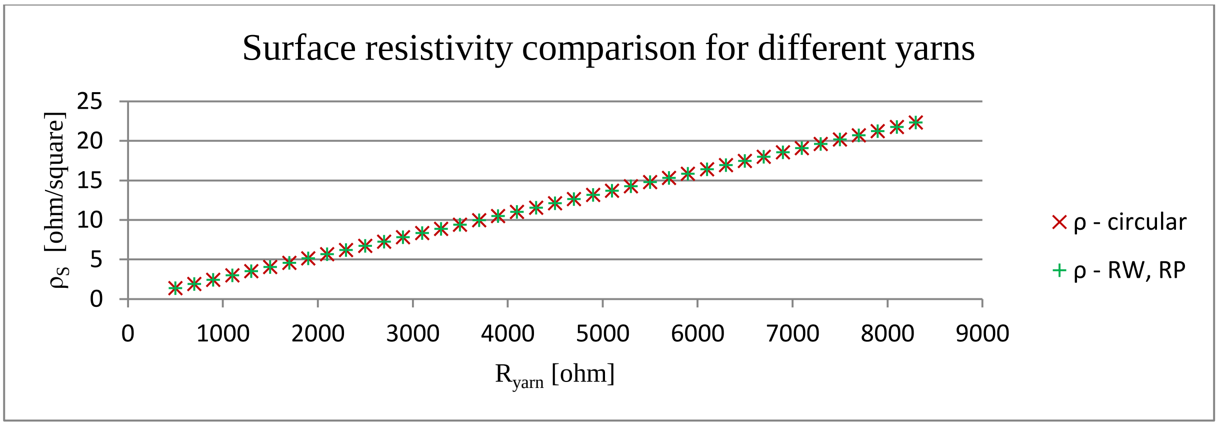

Fig. 16 Comparison of surface resistivity values for concentric ring electrodes considering model with and without differentiation of resistance values of warp and weft yarns (R_W = R_P = R_{yarn}).

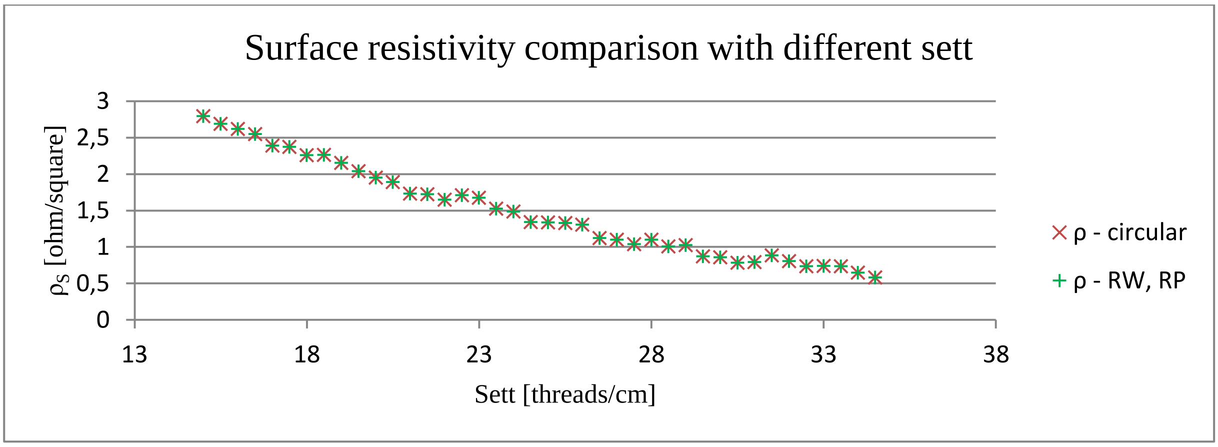

Fig. 17 Comparison of surface resistivity values for concentric ring electrodes considering model with and without differentiation of resistance values of warp and weft yarns ($R_W = R_P$).

From the above it follows that the sub-goals and the main aim of this Doctoral thesis have been met.

5. CONCLUSION

Results from the modelling of electrical resistivity of electrically conductive textile materials can be profitably used during material engineering of new electrically conductive textile materials, which can be used for example for realization of textile antennas, textile transmission lines or textile shielding covers. Modelling and measurement results showed it is possible to see electrically conductive planar textile material with plain weave as a structure compound of a grid of resistors. Moreover, this structure of resistor network can be modified to meet circular electrode arrangement of standardized measurement methods. Electrical resistivity is than calculated as multiplication of the resultant resistance of this resistor network and geometric coefficient of electrodes, which depends on arrangement and dimensions of electrodes.

The proposal of generally applicable model for electrical resistivity determination for concentric ring probes can be further extended for different number of warp and weft sett. It can be achieved by addition zero rows or columns into matrix A, so the determinant can be calculated as well as resultant resistance.

The proposal of a generally applicable model for electrical resistivity determination can be also extended for determination of electrical resistivity of the yarn.

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Proportion of co-authorship of doctoral student for individual publications is equal.

Responses and reviews are not known.

SUMMARY

This doctoral thesis deals with modelling of electrical resistivity for electrically conductive planar textiles materials, which belong to the group of so-called smart textiles. These new materials find their place not only in the field of telecommunication technology. The ability of these materials to conduct electrical current allows the emergence of new applications such as textile antennas, shielding textile coverings (e.g. for shielding contactless cards or mobile signals), textile conductors (conductor in the form of textile strips), ESD applications, etc.

The main goal of this work is to find and derive a procedure for modelling of electrical resistivity for electrically conductive planar textiles materials. This parameter is now determined by standardized test methods for the measurement of specific textile specimens. The designed process of modelling of electrical resistivity for electrically conductive planar textile materials in the future will allow material engineering in this area. The input parameter of the present procedure of electrical resistivity modelling is the resistivity of yarn.

Modelling of electrical resistivity for electrically conductive planar textile material is derived from the definition of electrical resistivity and standardized test methods for measuring the electrical resistance of a particular specimen of the electrically conductive planar textile materials. Electrical resistivity is independent of the arrangement of the electrodes.

The described procedure is based on assumptions to simplify the model for which is shown not to affect the results of the model, on the procedures of circuit analysis and standardized test methods.

The result of the thesis is a derivation of a general model for determining the electrical resistivity of electrically conductive textile materials with plain weave, which is a prerequisite for materials engineering in the field of electrically conductive planar textile materials.

RESUMÉ

Disertační práce se zabývá modelováním elektricky vodivých plošných textilních materiálů, které patří do skupiny takzvaných smart textiles. Tyto nové materiály nalézají své uplatnění nejen v oboru telekomunikační technika. Schopnost těchto materiálů vést elektrický proud umožňuje vznik nových aplikací, jako jsou textilní antény, textilní stínící kryty (např. pro stínění bezkontaktních karet či mobilního signálu), textilní vodiče (vodiče v podobě textilních proužků), ESD aplikace, apod.

Hlavním cílem předkládané práce je nalézt a odvodit postup pro modelování měrného elektrického odporu elektricky vodivých plošných textilních materiálů. Tento parametr se dnes určuje pomocí standardizovaných zkušebních metod měření konkrétních textilních vzorků. Vytvořený postup modelování měrného elektrického odporu elektricky vodivých plošných textilních materiálů tak v budoucnu umožní materiálové inženýrství v této oblasti. Vstupním parametrem předkládaného postupu modelování měrného elektrického odporu je měrný elektrický odpor příze.

Modelování měrného elektrického odporu elektricky vodivých plošných textilních materiálů je odvozeno z definice měrného elektrického odporu a pomocí standardizovaných zkušebních metod měření elektrického odporu konkrétního vzorku plošných textilních materiálů. Měrný elektrický odpor je nezávislí na uspořádání měřicích elektrod.

Popsaný postup modelování měrného elektrického odporu elektricky vodivých plošných textilních materiálů je založen na předpokladech pro zjednodušení modelu, u nichž je ukázáno, že neovlivňují výsledky modelu, na postupech obvodové analýzy a na metodách vycházejících ze standardizovaných zkušebních metod.

Výsledkem disertační práce je odvození obecného modelu pro stanovení elektrického měrného odporu elektricky vodivých plošných textilních materiálů s plátnovou vazbou, což je předpokladem pro možnost materiálového inženýrství v oblasti elektricky vodivých plošných textilních materiálů.