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Modelling of Surface and Bulk Resistance for Wearable Textile Antenna Design

Abstract. *Antennas and other high frequency structure design influence also textile industry in the form of smart textile applications. One of them calls wearable antennas. Proper design of these antennas includes also modelling based on knowledge of textile material parameters of its functional surface, substrate and structure. Paper focuses on modelling of textile structure with electrically conductive fibres and its verification by optic and DC surface and bulk resistance measurement methods.*

Streszczenie. *W artykule przedstawiono zagadnienie tworzenia anten zintegrowanych z odzieżą. Skupiono się na modelowaniu struktury tkaniny, w zależności od rodzaju materiału i jego struktury, zawierającej przewodzące włókna. Dokonano analizy materiału, w oparciu o rezystancję objętościową, powierzchniową i optyczną. (**Projektowanie anten zintegrowanych z tkaniną - modelowanie rezystancji powierzchniowej i objętościowej)**.*

Keywords: Bulk resistance; conductive fibres; surface resistance; textile modelling.
Słowa kluczowe: rezystancja objętościowa, włókna przewodzące, rezystancja powierzchniowa, modelowania tekstyliów.

Introduction

Modern textile materials are used in many technical applications. One of the perspective branches is so-called Smart textile, which is capable to keep electrical current flow or to operate as electrical sensors. Special group of Smart textile materials is called wearable antenna, which is characterized by electrical conductive textile structure designed for substrate or it is functional material designated for a production of planar antenna structures. These antenna structures are designed as a part of clothing, or they can be applicable directly on the human body [1]. Though the most of synthetic materials in the sheet shape can be used for these applications, textile structures provide many advantages [2].

Modelling of antennas and other high frequency structures requires knowledge of basic material parameters of used substrates and functional surfaces. One of the fundamental parameters is electrical conductivity σ, which is generally derived from electrical resistivity ρ and as a consequence from sheet resistance R_S [3] in the case of metal coating. The most of conductive textile materials are composed from non-conductive material, e.g. based on polyesters, and subsequently the woven fabric is electrochemically coated with the aid of electroplating practice procedures.

If the textile material is electrochemically coated, sheet resistance [Ω/□] is a parameter describing a measure of resistance of constant thin film. It is proportional to $1/(t{\cdot}\sigma)$. Parameter t is a thickness of metal layer, which is coated on the surface of originally non-conductive textile material. The used metal is characterized by conductivity σ. As a consequence it is possible to measure the conductivity by DC methods [4]. The results of these measurements are often used also for high frequency applications. It leads to certain inaccuracies, but accuracy of measurement is sufficient for many models [5].

If textile materials are woven from electrical conductive fibres, it is completely different condition. Sheet resistance cannot be considered as a parameter based on upper layer of textile and its thickness. Considering a conductivity of used fibres in whole cross section and capacity, it is important to reason bulk conductivity, not the surface one, during measurement by DC methods. This rule has to be fulfilled also in the case of high frequency applications even though skin effect predominates and the whole cross section is not used.

Conductivity σ is reciprocal value of resistivity, i.e. $1/\rho$. Many standards describe methods for surface and bulk resistivity measurement via surface resistance measurement. Basic principle of surface resistance measurement is based on putting down specific define electrodes on the textile surface [6 – 9]. The electrodes can be circular formed by cylindrical and ring electrodes or square electrodes of defined dimensions [6 – 10]. If the electrodes are put down on the textile surface, it assumes all currents flow between electrodes along the surface and do not penetrates into the bulk of the material [6]. Meter provides constant voltage and current is measured between two electrodes. Resistance and resistivity are then calculated with respect to electrode dimensions. Conductivity is reciprocal value of resistivity. Some more advanced techniques for surface resistance measurement are developed to ensure currents do not penetrate into the bulk of material [7 – 10]. Standards use underlying electrode and different circuit. They also describe bulk resistance measurement.

Standards [7, 9 and 10] are especially designed for application for protection from electrostatic discharge (ESD). Standard [8] focuses on insulating materials. As a consequence, the standards are limited for lower values of resistance. Common measurement assumes material resistance above 10^6 Ω at 100 VDC test voltage. Resistance values under 10^5 Ω require 10 VDC test voltage. It prevents from sample destruction. The lowest limit is not clearly specified. Standard [7] mentions that readings of instrument shall be at least 10^3 Ω and considering resistance lower than 10^4 Ω, resistance of the probe(s) should be taken into account. Manufactures produce probes, which follow these standards [11 – 13]. They present the range of measurable resistivity or resistance starts at 10^3 Ω. The reason can be seen in probe resistance 10^2 Ω [13]. However, textile materials designed for wearable antennas production reach the values about units of Ω.

As a consequence, these circular electrodes cannot be used for surface and bulk resistance measurement of textile materials from electrical conductive fibres. However, it is possible to simulate it with respect to physical laws and design a meter. Structure of textile materials composed form conductive fibres can be seen as grid of resistors. The advantage of this point of view rests in using circuit analysis. Therefore it is possible to model material parameter σ and also measure by DC methods.

Paper focuses on modelling of textile materials from electrical point of view, modelling of circular probes measurement and DC measurement of surface and bulk resistance.

Resistance Modelling of Grid of Resistors

The textile material can be seen from electrical point of view as an electrical circuit composed from connected resistors and battery. Battery represents electrode poles and resistors correspond to structure of fibres. Fibres form regular shapes in textile material. Considering ideal case the shapes are seen as squares. Then every side of the square represents resistor R′ (marked R1 in figures), Fig. 1. The both poles of battery are connected to shorter sides of textile, i.e. to common nodes of outer resistors of equivalent circuit diagram. The poles of battery were chosen with respect to basic setup for measurement [4]. Calculation of this electrical circuit can be solved by Kirchhoff's circuit laws or by simplifications of equipotential lines or points. These points are significant, because the points with the same potential can be connected or disconnected as necessary. Then the value of resistor between these equipotential points is equal to zero and it can be eliminated. Following this presumption, the electrical circuit is simplified and resultant resistance is calculated from series-parallel connection of resistors, Fig. 2. It can be calculated as:

$$R = \sum_{1}^{12} \frac{R'}{6} = \frac{12R'}{6} = 2R' \tag{1}$$

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

$$R = \sum_{n=1}^{r} \frac{R'}{s}, n, r, s \in \{N\} \tag{2}$$

where: n, r – number of squares in "horizontal" direction, s – number of squares in "vertical" direction.

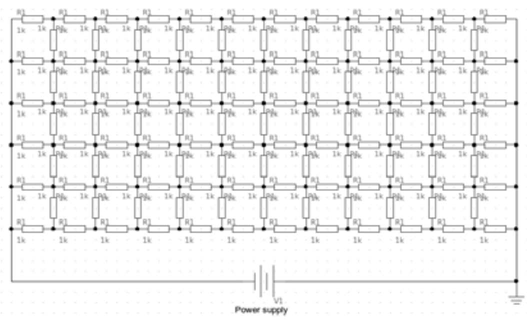

Fig. 1. Equivalent circuit diagram of used textile material

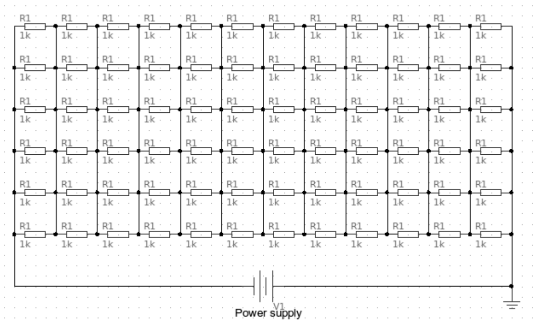

Fig. 2. Simplified equivalent electrical circuit with eliminated resistors placed between two points of the same potential

Verification of Equipotential Points Validity

It is possible to use for example software called Oregano, GNOME application, for verifying points with the same potential [14]. Fig. 3 depicts voltage probes, which are placed in five points of different potential. Results are shown in Fig. 4. Different results are naturally obtained by placing voltage probes into the points with the same potential, Fig. 5. Results depicted in Fig. 6 show only one value of voltage for all five measurement points. As a consequence voltage drop between individual resistors is equals to zero, and therefore the resistors can be eliminated. The presumption is thus confirmed and (2) is valid.

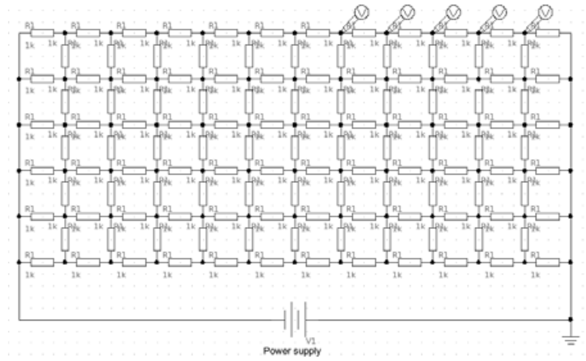

Fig. 3. Voltage probes placed in the points with different potential

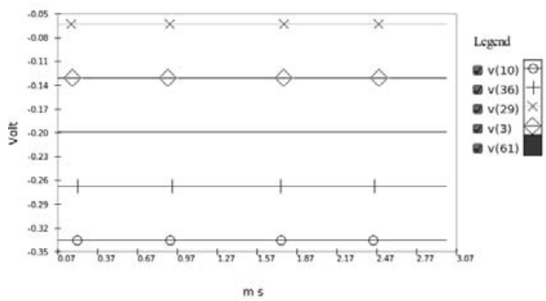

Fig. 4. Voltage probes placed in the points with different potential

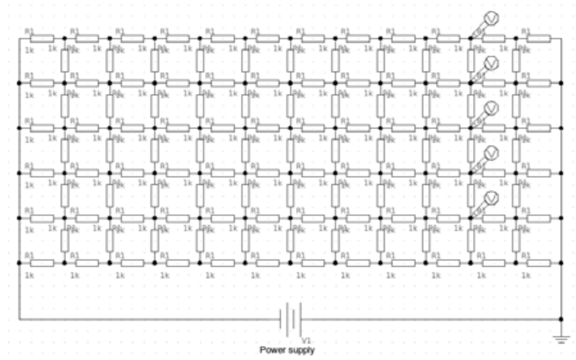

Fig. 5. Voltage probes placed in the points with the same potential

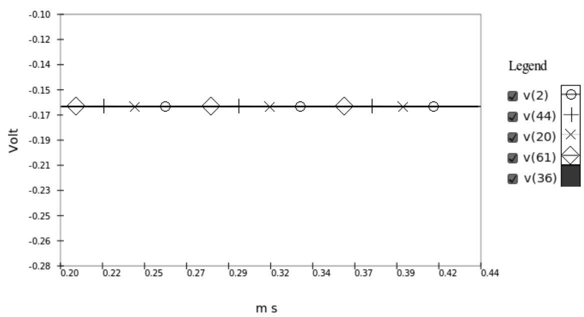

Fig. 6. Voltage probes placed in the points with the same potential

Modelling of Circle Segment of Grid of Resistors

Textile materials can be also modelled with respect to measurement standards. Standards [7 – 10] define test method for measurement surface resistivity. Measurement principle is based on surface resistance measurement by exactly defined cylindrical electrodes and ohmmeter, Fig. 7 and Fig. 8 [7]. Resultant surface resistivity is calculated as:

$$(3)\quad \rho = R \cdot k \left[\Omega\right]$$

where: ρ – surface resistivity, R – surface resistance, k – geometrical coefficient of electrode.

Parameter *k* is expressed as:

$$(4)\quad k = \frac{2\pi}{ln\left(\frac{r_2}{r_1}\right)}$$

where: k – geometrical coefficient of electrode, r_2 – inner radius of outer (ring) electrode in mm, r_1 – radius of inner (cylindrical) electrode in mm.

Measurement settings shows, the surface resistance is measured between cylindrical electrode, the inner one, and ring electrode, the outer one, Fig. 7 and Fig. 8.

Considering the idea of grid of resistors, cylindrical shapes of segment of grid of resistors can be also modelled. Model does not include transition resistance between electrodes or probe resistance and therefore it can be also used for low resistance values. Modelling principle is depicted in Fig. 9. Reference point is defined as centre of grid of resistors and of one square, which is formed by four resistors. The reference point can be also defined as centre of the grid in one of the connections of resistors. These connections are called nodes. Fig. 9 is then replaced by another scheme, but the calculation of resultant resistance follows the same physical and electrical principles.

Simplified scheme of measurement with the aid of circular electrodes put the cylindrical electrode into one square, which encloses reference point. The ring electrode represents cylindrical segment of grid of resistors, continuous cylindrical line in Fig. 9. If electrical current flows from cylindrical towards ring electrode, equipotential curves can be also found, dotted lines in Fig. 9.

The validity is also confirmed by electrical circuit model, where electrodes are replaced by DC power source, Fig. 10. Results show the places with the same potential, i.e. equipotential curves, Fig. 11. If a resistor is located between two points with the same potential, it can be eliminated, black marked resistors in Fig. 9.

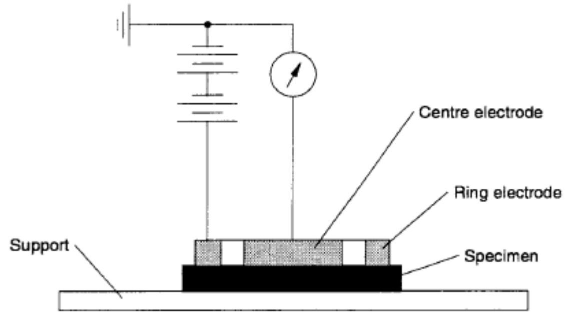

Fig. 7. Surface resistance measurement connection [7]

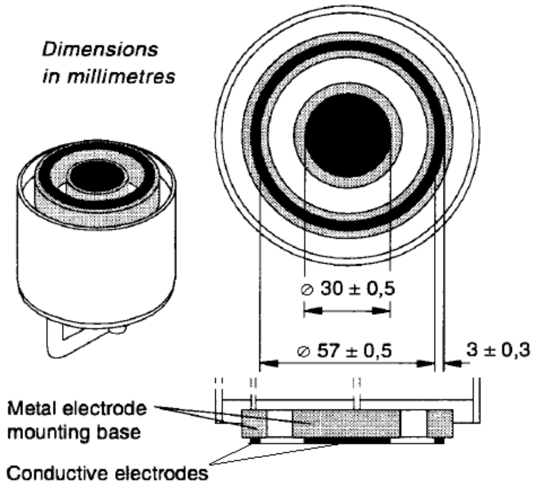

Fig. 8. Surface resistance measurement electrode assembly [7]

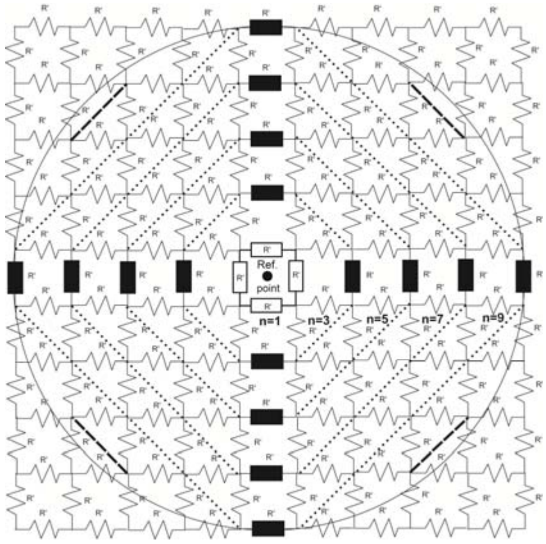

Fig. 9. Modelling of circle segment of grid of resistors

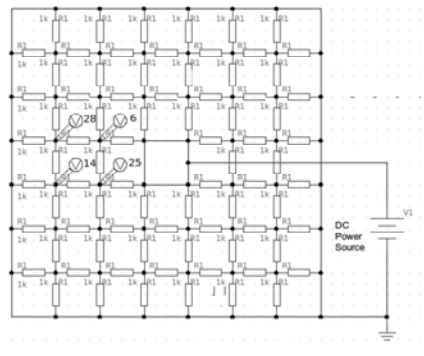

Fig. 10. Modelling of circle segment of grid of resistors

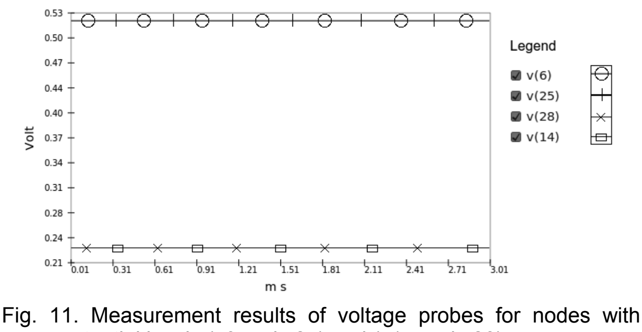

Fig. 11. Measurement results of voltage probes for nodes with same potential levels (v6 and v25) and (v14 and v28)

If equipotential curves, eliminated resistors and the scheme in Fig. 9 are considered ($n=9$), resultant resistance is formed by series-parallel connection of resistors as:

$$(5)\quad R=\frac{R'}{8}+\frac{R'}{16}+\frac{R'}{24}+\frac{R'}{32}=\frac{1}{4}\cdot\sum_{n=3}^{r}\frac{R'}{n-1}, n\in(3,r), r\, is\, odd$$

where: R – resultant resistance, R' – resistance of fibre length of one square, n – number of squares.

The (5) calculates only resistors, which are placed between dotted line in Fig. 9 and reference point. The rest of the resistors are located between the equipotential curve, which is the closest one to circle (represented by ring electrode) and circle. These resistors are depicted by dash line in Fig. 9.

It is possible to calculate general formula for these resistors, but it requires finding mathematical relationship between individual series of resistors for different number of squares n. Considering $n=9$, $n=11$ and $n=13$, the series are equalled to:

$$(6)\quad R=\frac{R'}{8}+\frac{R'}{16}+\frac{R'}{24}+\frac{R'}{32}+\frac{R'}{8}, n=9$$

$$(7)\quad R=\frac{R'}{8}+\frac{R'}{16}+\frac{R'}{24}+\frac{R'}{32}+\frac{R'}{40}+\frac{R'}{24}, n=11$$

$$(8)\quad R=\frac{R'}{8}+\frac{R'}{16}+\frac{R'}{24}+\frac{R'}{32}+\frac{R'}{40}+\frac{R'}{48}+\frac{R'}{24}+\frac{R'}{32}, n=13$$

Textile samples can reach about number of squares $n=250$. If the dependence for series of resistors is found, resultant formula can be calculated. Recent research shows, it can be calculated by easier way. It is possible to use e.g. software Matlab. Fig. 12 depicts basic principle of Matlab program.

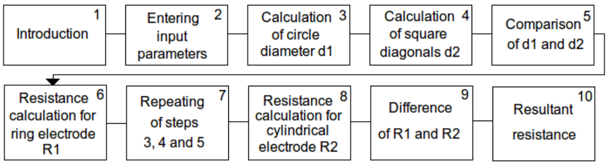

Fig. 12. Program basic principle

Introduction includes identification of program. Entering input parameters asks for entering of warp texture value. The program limits for the same values of warp and weft, i.e. model is based on square grid, not the rectangular one. Number of squares is calculated with respect to real electrode dimensions. Circle diameter d_1 is obtained for all odd number of squares n. Parameter n is always odd because of symetry of the model and electrodes as well. Diameter d_1 is distance between reference point and nodes, which are placed horizontally or vertically from reference point of the square model (9). Calculation of square diagonals d_2 is obtained similarly (10), Fig. 13. Edge size n_s is equaled to 1, beacause its value is irrelevant for model calcualtion. Values of d_2, which are lower than d_1 are then recorded. It corresponds to resistors, which are chosen from the grid of resistors by ring electrode dimensions. Resistance R_1 is calculated as sum of series-parallel resistors. Parallel resistors are connected between adjacent equipotential curves. These resistors are summed in series (6), (7) and (8). Values d_1, d_2 and its difference are then calculated again for dimensions of cylindrical electrode, step 7 in Fig. 12. Resistance R_2 is calculated similarly as R_1. These resistances are deducted and the result is resistance between two electrodes, ring and cylindrical one.

$$(9)\quad d_1^2=\left(\frac{n-1}{2}\right)^2\cdot n_s^2+\frac{n-1}{2}\cdot n_s^2+\frac{n_s^2}{2}$$

where: d_1 – circle diameter, n – number of squares in horizontal direction, n_s – edge size.

$$(10)\quad d_2^2=d_1^2+\frac{n_s^2}{2}+\left((i-1)\cdot n_s+\frac{n_s}{2}\right)^2$$

where: i – row index for program purpose.

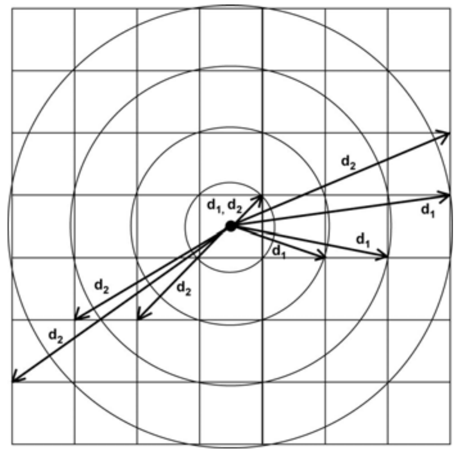

Fig. 13. Circle diameter d_1 and square diagonals d_2 determination

Bulk and Surface Resistance Measurement Procedure

Simplified equivalent electric circuit represents model of real textile material. Comparison of the model and real characteristics is also possible to perform by measurement method. Manufactured circular electrodes cannot be used because of measurement range limitation. However, it is possible to use rectangular electrodes of defined dimensions [6, 7]. Resultant resistance of specific textile material requires calculation of r and s parameters according to (2) for square model. Measurement sample No. 60 is characterized by 25 n/cm warp texture and 20 n/cm weft, where n is number of threads. Sample No. 60 is manufactured from 30% SilveRstat, 30% Shieldex and 40% PES (Polyester). Considering the sample of dimensions 100 x 30 mm, number of threads is calculated as:

$$(10)\quad r'=10\cdot 25=250\,[n]$$

$$(11)\quad s'=3\cdot 20=60\,[n]$$

As a consequence r and s parameters are equalled to:

$$(12)\quad r=r'-1=250-1=249\,[n]$$

$$(13)\quad s=s'-1=60-1=59\,[n]$$

Resultant resistance is then equals to:

$$(14)\qquad R=\sum_{n=1}^{r}\frac{R'}{s}=\sum_{n=1}^{249}\frac{R'}{59}=\frac{249R'}{59}=4,22\cdot R'$$

Resistance R' of fibre length of one square is obtained from diameter measurement of specific fibre and calculation. It is possible to use basic measurement instruments for approximation of diameter, such as micrometer. Exact value is measured by known methods of textile industry, e.g. microscopic examination or it can be calculated from density and fineness [15].

If the micrometer is used, the fibre length diameter equals to $d=0.21\ mm$. This value is consequently verified by microscopic examination. Fibre sample is put and enlarged under the microscope, Fig. 14. Diameter is then measured in different places of the fibre and average value is calculated. Some of the measurement places are depicted in Fig. 15. The average value is also specified by sample standard deviation, which corresponds to measurement of random sample of diameter, Table 1.

Fig. 14. Fibre detail of sample No. 60 under microscope

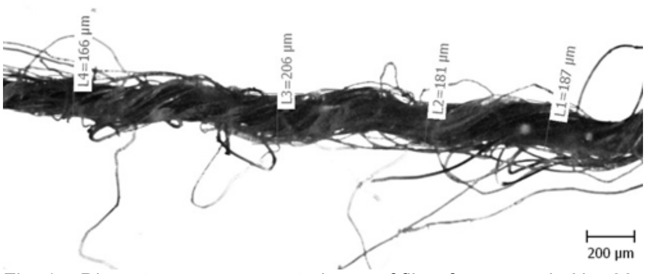

Fig. 15. Diameter measurement places of fibre from sample No. 60

Table 1. Measurement results of fibre diameter

Diameter measurement [μm]	232	208	217	149	219	224	249
	185	215	221	227	206	232	226
	224	217	261	196	221	199	209
	206	242	228	214	174	189	138
	172	176	183	161	186	219	189
	188	204	181	170	174	173	151
	183	195	195	183	235	202	227
Average [μm]	201.5306						
Sample standard deviation [μm]	26.91197						

The results of diameter measurement by microscope examination confirm micrometer measurement. Average value of diameter got by microscope is $d=0.20\ mm$ and sample standard deviation is equalled to $s^*=0.026\ mm$. It includes the measurement value obtained by micrometer.

Resistance value R' is subsequently calculated as:

$$(15)\quad l_{R'} = \frac{W - s' \cdot d}{s} = \frac{30 - 60 \cdot 0.21}{59} = 0.29\ mm$$

where: $l_{R'}$ – length of R', s – number of resistors in weft, s' – number of threads in weft, d – measured diameter, W – width of measured sample.

$$(16)\quad R' = \frac{R_l \cdot l_{R'}}{l_R} = \frac{(334.83 - 0.07) \cdot 0.29}{100} = 0.97\,\Omega$$

where R_l – measured resistance of fibre with length l_R.

$$(17)\quad R = 4.22 \cdot R' = 4.22 \cdot 0.97 = 4.09\,\Omega$$

Resultant resistance of square model calculated from mathematical model with respect to measured fibre diameter is equalled to $R=4.09\ \Omega$. Measurement diagram for modelling verification is depicted in Fig. 16. The gauging fixture is used for resistance measurement of three textile samples. Resistance is measured by RLCG bridge ESCORT ELC-3133A with the systematic error $se=0.07\ \Omega$, which is caused by resistance of cables and connectors.

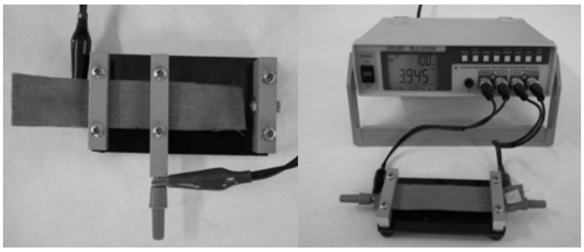

Fig. 16. Resistance measurement diagram (left) and square setting of electrodes (right)

Measurement is not possible to perform by DC power source at high voltage, usually 100 VDC because resistance is lower than $10^3\ \Omega$. If 100 V is used and resistance is very low, current is very high. It can cause overheating and destruction of the sample.

Three textile samples are measured in three different positions for two electrode setting, square and rectangular. Square setting measures a sample of dimensions 30x30 mm between electrodes. Rectangular one is 100 mm long, width is also 30 mm, Fig. 16. Textile samples are in addition measured with and without insulation material, i.e. paper, which is placed between electrodes. Fibre resistance R_l is also obtained for different positions of fibre, which is used for all textile samples production. Measurement is performed at 56.8% humidity and 22.9 °C.

Table 2. Measurement results

Measurement setting	Measurement of Bulk Resistance		
	No. 60, R [Ω]	*No. 62, R [Ω]*	*No. 64, R [Ω]*
Square, without insulator	1.295 1.473 1.315 avg: 1.361	1.309 1.294 1.235 avg: 1.279	1.269 1.160 1.172 avg: 1.200
Rectangular, without insulator	3.946 3.934 3.977 avg: 3.952	3.834 3.950 3.968 avg: 3.917	3.668 3.671 3.678 avg: 3.672
Square, with insulator	1.358 1.280 1.329 avg: 1.322	1.293 1.249 1.213 avg: 1.252	1.194 1.160 1.197 avg: 1.184
Rectangular, with insulator	3.933 3.984 3.953 avg: 3.957	3.850 3.890 3.977 avg: 3.906	3.644 3.695 3.670 avg: 3.670
		R_l [Ω]	*l=100 mm*
One fibre	331 342 348	379 320 395	307 313 277 358 282 366
		avg: 348.33	

Validation of Results Evaluation

If the insulator is not used, sample is placed between two rectangular electrodes. It corresponds to bulk resistance measurement. If the insulator is used, only one electrode contacts the sample, which corresponds to surface resistance measurement.

Considering sample No. 60, equation (17) gives the bulk resistance result of model $R=4.09$ Ω for rectangular setting of electrodes. Measurement results for the same setting and sample are almost the same, e.g. $R=3.952$ Ω for rectangular settings without insulator. It confirms the described model is valid. Inaccuracy is caused by measurement method for diameter determination, fibre length measurement and by pressure of sample fixation. Considering fibre diameter $d=0.22\ mm$, $R=4.02$ Ω. Considering $d=0.18\ mm$, $R=4.49$ Ω. Both values are in the range of sample standard deviation. Recommended values for pressure fixation are in the range 140 – 170 kPa [8].

However, the influence of fixation is minimal because results for rectangular setting are about 3.3 multiple of square setting, which is equalled to ratio of their length. For example: No. 64 without insulator, $R_{square}=1.200$ Ω, $R_{rectangular}=1.200 \cdot 3.3=3.96$ Ω, $R'_{rectangular}=3.672$ Ω. The difference is about 0.3 Ω. Second reason is resistance takes the same values for measurement with and without insulator. It shows very important conclusion. Surface resistance is equalled to bulk resistance for low resistance values (about units of Ω), i.e. for conductive materials.

Circular model counts number of series-parallel resistors. Resistance of fibre length of one square (one resisor) is equalled to $R=0.97$ Ω. Considering for example diameter of ring electrode is $r_1=110\ mm$, $r_2=55\ mm$ of cylindrical electrode. Correction factor is calculated from (2), $k=9.1$. Resultant surface resistivity according to (3) is equalled to $R=1.13$ Ω. Surface resistivity is defined as resistance between opposite edges of a square of the material [10]. Measurement settings square, without insulator gives the results about $R=1.25$ Ω. The difference of circular model is given by different value of sample weft and warp and by elimination of parts of fibres, which correspond to circle – grid of squares approximation.

Conclusion

The paper describes modelling of textile material from electrical point of view. The structure of fibres is replaced by series-parallel connection of resistors. Equivalent electrical circuit is simplified and resultant resistance is calculated for two different models, square and circular one. The square model is verified by proposed measurement with the aid of RLCG Bridge. Bulk resistivity is measured for two different electrode setting and with and without insulator. Measurement inaccuracy is also discussed. Results show the square model is valid, proposed gauging fixture is suitable for measurement and different length of textile sample does not affect resultant bulk resistance. Measurement with and without insulator proves surface resistance is equalled to bulk resistance for low resistance values. Circular model shows model of surface resistivity can be also used even it calculates bulk resistance. It is valid for high conductive textile materials.

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