The Sensitivity of the Input Impedance Parameters of Track Circuits to Changes in the Parameters of the Track

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Abstract. *This paper deals with the sensitivity of the input impedance of an open track circuit in the event that the parameters of the track are changed. Weather conditions and the state of pollution are the most common reasons for parameter changes. The results were obtained from the measured values of the parameters R (resistance), G (conductance), L (inductance), and C (capacitance) of a rail superstructure depending on the frequency. Measurements were performed on a railway siding in Orlova. The results are used to design a predictor of occupancy of a track section. In particular, we were interested in the frequencies of 75 and 275 Hz for this purpose. Many parameter values of track substructures have already been solved in different works in literature. At first, we had planned to use the parameter values from these sources when we designed the predictor. Deviations between them, however, are large and often differ by three orders of magnitude (see Tab. 8). From this perspective, this article presents data that have been updated using modern measurement devices and computer technology. And above all, it shows a transmission (cascade) matrix used to determine the parameters.*

Keywords

Impedance, parameter estimation, railway safety, sensitivity analysis.

1. Introduction

In this article, the results of measuring the parameters of rail traction - the resistance of the track circuit, the conductance between the rails, and the inductance and the capacitance of the track circuit - are described. The sensitivity of the input impedance of the track circuit is calculated after changing the parameters of the track. These parameters were investigated to design the predictor, which detects the occupancy of the rail traction. This article does not provide a new method of measurement. The modified Ohm impedance measurement method was used in the measurement. However, elaboration of the results must provide parameter values in a form which can be directly used in a laboratory simulation of track circuits. This simulator was assembled from type two-ports (parameters G, R, L, C) and it was used to verify the device characteristics to predict the occupancy of the track circuit. Thus, cascade coefficients were used for evaluating traction parameters, as well as for elaboration of the measured values in the simulator. Therefore, it is possible to immediately correct potential deficiencies of the simulator.

All these parameters were calculated as specific parameters, which means they were recalculated to the unit length (km) of the tracks.

The following approach was chosen to determine the primary parameters:

- Measurement of the input impedance of an open circuit and input impedance of a section of a railway line terminated with a short circuit.
- Calculation of cascade coefficients.

- Calculation of impedance and admittance of two-ports of type Π, T and Γ.
- Calculation of the primary two-port parameters and their conversion to the unit length.

Measurements were performed in the Orlova locality in the rail yard of a private firm, AWT. The section of the measured track did not have any track crossings or track branches and had only a slight radius of curvature of the track. The railway yard was very dirty from coal dust, loam and clay, dry fallen leaves, twigs, and so on. The weather was rainy. It was raining slightly when the measurements were taken, and had been raining for a long time beforehand. The length of the track section was 540 m.

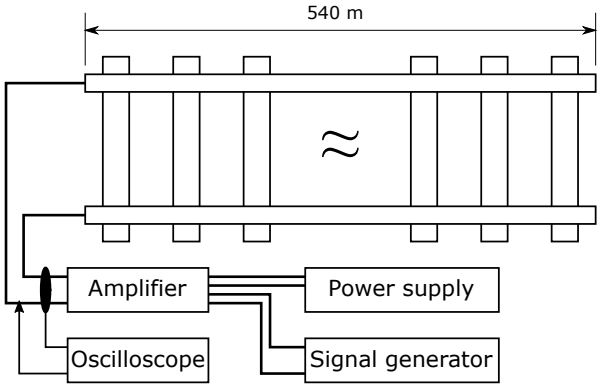

Fig. 1: Connection diagram.

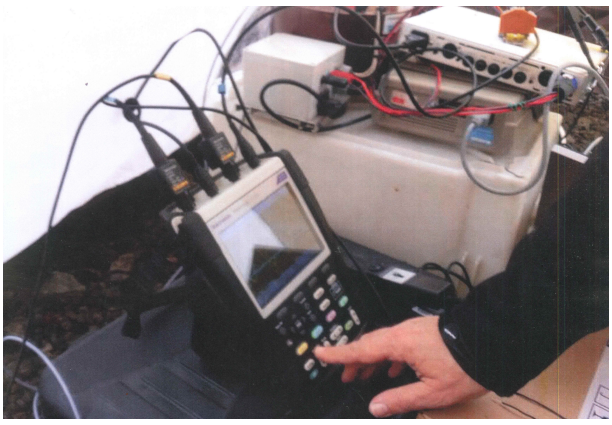

Fig. 2: View of the workplace arrangement.

Examples of display of the measured waveforms on the oscilloscope:

At lower frequencies, the current leads the voltage on empty track (see Fig. 3).

The voltage leads the current at higher frequencies and therefore the track circuit has an inductive character. Figure 4 shows an example of waveforms for a track that was shunted to 524 m away from the measuring site.

The track circuit in Fig. 4 certainly has an inductive character.

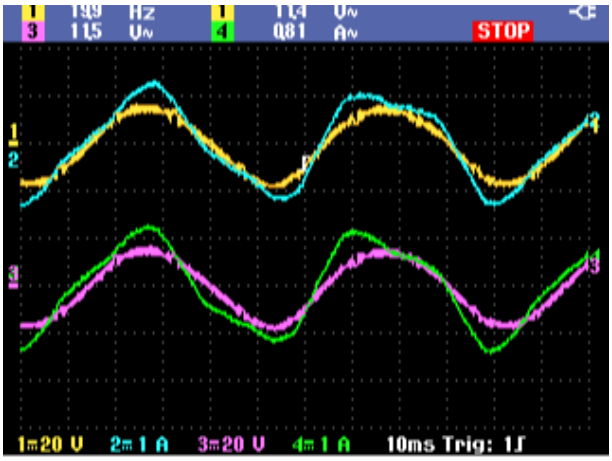

Fig. 3: Voltage and current courses for the frequency of 19.9 Hz.

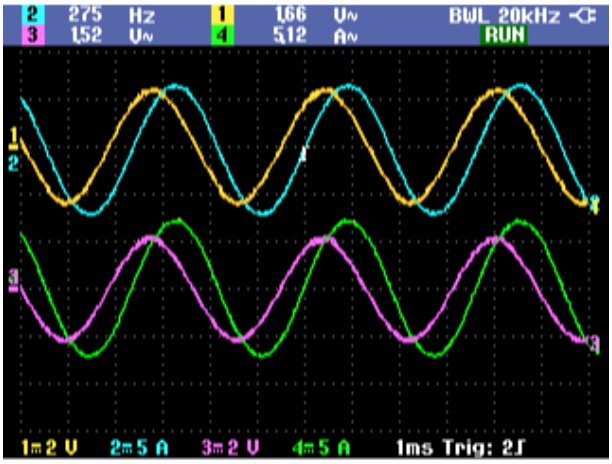

Fig. 4: Voltage and current waveforms for the frequency of 275 Hz.

A device for prediction of occupancy of the track circuit must be regularly calibrated during operation when weather conditions are changing. Calibration will be done on unoccupied track circuits. In an open circuit of the traction, mostly capacity and conductivity of the substructures may be varied. Therefore, we are

Tab. 1: Assignment of oscilloscope channels to the measured quantities.

No.	Quantity	Function
CH1	U1	Voltage at the amplifier output
CH2	'I1	The output current from an amplifier
CH3	U2	Voltage between the rails at the measuring location
CH4	'I2	Current to rails

Tab. 2: Module and phase of impedance of open traction circuit and short traction circuit.

Impedance open circuit			Impedance short circuit		
f_524m (Hz)	Zop_524m (Ω)	Fi0_524m (rad)	f_524m (Hz)	Zsh_524m (Ω)	Fik_524m (rad)
19.89	14.47	-0.26	19.43	0.44	0.36
50.26	13.44	-0.14	49.74	0.67	0.76
74.76	13.25	-0.1	75.86	0.85	0.83
100.51	13.8	-0.09	100.23	1.1	0.89
123.57	12.99	-0.06	125.32	1.18	0.93
149.86	12.94	-0.09	150.59	1.34	0.99
173.21	12.84	-0.06	174.85	1.49	0.99
202.7	12.72	-0.07	199.82	1.64	1.1
250.73	12.66	-0.08	248.55	1.9	1.4
274.19	12.62	-0.05	275.29	2.4	1.8
302.48	12.27	-0.01	303.74	2.2	1.6
491.28	11.93	0.05	500.87	3.24	1.11
1009.77	11.93	0.13	1032.62	5.81	1.17

interested in finding out how the parameters change as the weather changes, and which parameter of the device will be the most responsive one. This parameter will be determining during the calibration of the instrument.

2. Open and Short Circuit Impedance

Measurements were performed for the frequency range from 20 to 5000 Hz. The length of the measured section of rail traction was 540 m. The courses were obtained in the form of graphs (Fig. 3 and Fig. 4) and in table form. The obtained curves expressed in tabular form contained a large amount of noise and in order to use them, they had to be approximated by a sine wave function - (Fig. 5).

The measured values were the magnitude Z and the phase φ of the input impedance at the beginning of the track circuits. Measurements were performed under the open circuit Z_{op} and short circuit Z_{sh}. It is clear from Tab. 2 that the frequency at which the impedances are measured in the open and short circuits are not completely identical. Therefore, three kinds of interpolation by polynomials were performed for both curves: cubic spline interpolation, B-spline interpolation, and polynomial regression.

$$\begin{aligned} vsc &:= cspline(vx, vy), \\ vsb &:= bspline(vx, vy, u, 2), \\ vsr &:= regress(vx, vy, 3). \end{aligned} \tag{1}$$

From these polynomials, impedance values have been assigned to the same integer frequencies (see Tab. 3).

Impedance components were converted to the form of complex numbers using a simple Eq. (2):

$$\underline{Z} = Ze^{j\varphi} = Z(\cos\varphi + \mathrm{j}\sin\varphi). \tag{2}$$

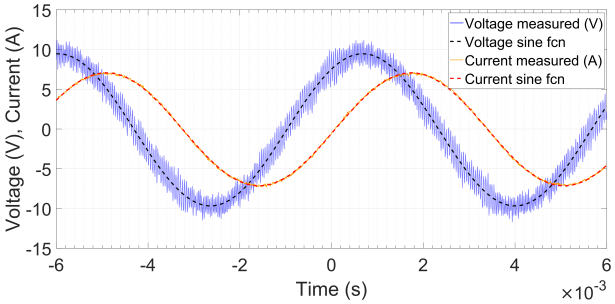

Fig. 5: Example of interleaving of the actual course of state variables by the sine function.

Tab. 3: Impedance of the open circuit and the short circuit.

Freq.	$\underline{Z}_{op}$ (Ω)	$\underline{Z}_{sh}$ (Ω)
20	13.99-3.73j	0.42+0.16j
50	13.3-1.95j	0.48+0.46j
75	13.18-1.4j	0.57+0.64j
100	13.02-1.28j	0.63+0.79j
125	12.98-0.8j	0.7+0.96j
150	12.89-1.2j	0.73+1.13j
175	12.82-0.87j	0.82+1.25j
200	12.7-0.9j	0.87+1.4j
250	12.61-1.09j	0.95+1.65j
275	12.54-0.39j	0.96+1.81j
300	12.27-0.15j	1.07+1.93j
500	11.91+0.7j	1.43+2.91j
1000	11.83+1.61j	2.25+5.36j
3000	12.01+0.46j	6.8+11.54j
5000	11.99+7.79j	11.31+14.38j

3. Calculation of the Cascade Coefficients

Matrix of cascade coefficients:

$$\underline{A} = \begin{vmatrix} \sqrt{\frac{\underline{Z}_{op}}{\underline{Z}_{op}-\underline{Z}_{sh}}} & \underline{Z}_{sh}\sqrt{\frac{\underline{Z}_{op}}{\underline{Z}_{op}-\underline{Z}_{1k}}} \\ \frac{1}{\sqrt{\underline{Z}_{op}(\underline{Z}_{op}-\underline{Z}_{sh})}} & \sqrt{\frac{\underline{Z}_{op}}{\underline{Z}_{op}-\underline{Z}_{sh}}} \end{vmatrix}. \tag{3}$$

Primarily we are interested in the frequency of 75 Hz with the wavelength of 1154701 m, and secondarily, the frequency of 275 Hz with the wavelength of 314918.3 m. Consequently, the 524 m segment of the railway can be considered as an elementary line section - for example as a two-port of type T or Π with a matrix of cascade coefficients according to Tab. 4.

Coefficient A12 was negative for frequencies above 1000 Hz. Also, the determinant of the matrix coefficients from this frequency was not equal to zero. Therefore, these values were not used again. The frequencies of 75 and 275 Hz interest us most.

Cascade coefficients were also calculated from the secondary circuit parameters:

$$\underline{Z_0} = \sqrt{\underline{Z_{10}}\,\underline{Z_{1k}}}, \tag{4}$$

$$\tanh(\underline{g_0}) = \sqrt{\frac{\underline{Z_{1k}}}{\underline{Z_{10}}}} \Rightarrow \underline{g_0} = \frac{1}{2}\ln\left(\frac{1+\sqrt{\frac{\underline{Z_{1k}}}{\underline{Z_{10}}}}}{1-\sqrt{\frac{\underline{Z_{1k}}}{\underline{Z_{10}}}}}\right). \tag{5}$$

From these secondary parameters, the following equation is valid:

$$\underline{A_{22}} = \underline{A_{11}} = \frac{e^{\underline{g_0}} + e^{-\underline{g_0}}}{2} = \cosh(\underline{g_0}), \tag{6}$$

$$\underline{A_{12}} = \underline{Z_0}\sinh(\underline{g_0}). \tag{7}$$

Tab. 4: Cascade coefficients.

Freq.	$\underline{A_{11}}$	$\underline{A_{12}}$	$\underline{A_{21}}$
20	1.013+0.009j	0.424+0.166j	0.067+0.019j
50	1.014+0.020j	0.478+0.477j	0.074+0.012j
75	1.018+0.028j	0.563+0.667j	0.076+0.010j
100	1.020+0.034j	0.615+0.827j	0.077+0.010j
125	1.020+0.041j	0.676+1.011j	0.078+0.008j
150	1.021+0.049j	0.690+1.190j	0.078+0.011j
175	1.025+0.055j	0.772+1.327j	0.079+0.010j
200	1.026+0.062j	0.805+1.490j	0.080+0.011j
250	1.025+0.074j	0.851+1.762j	0.080+0.013j
275	1.028+0.081j	0.841+1.939j	0.082+0.009j
300	1.034+0.089j	0.935+2.091j	0.084+0.008j
500	1.046+0.140j	1.088+3.245j	0.088+0.007j
1000	1.043+0.271j	0.894+6.198j	0.089+0.011j
3000	0.826+0.547j	-0.694+13.252j	0.070+0.043j
5000	0.766+1.253j	-9.357+25.195j	0.093+0.044j

4. Calculation of Parameters of Two-port

The measured part of traction was replaced by a two-port of type Π. This two-port can be described as a matrix Eq. (8):

$$\underline{A} = \begin{vmatrix} 1+\underline{YZ} & \underline{Z} \\ \underline{YZ}+\underline{Y^2Z} & 1+\underline{YZ} \end{vmatrix}. \tag{8}$$

Thus

$$\underline{Z} = \underline{A_{12}}, \tag{9}$$

$$\underline{Y} = \frac{\underline{A_{11}}-1}{\underline{Z}}. \tag{10}$$

From the matrix Eq. (8), we have calculated the parameters of the two-port (see Tab. 5 and Tab. 6). The parameter values R, G, L, and C were converted to a unit length of 1 km.

Tab. 5: Parameters of two-port.

Freq.	$\underline{\mathbf{Z}}(\Omega)$	$\underline{\mathbf{Y}}$(S)
20	0.453+0.149j	0.032+0.016j
50	0.575+0.493j	0.037+0.004j
75	0.565+0.665j	0.038+0.003j
100	0.653+0.812j	0.038+0.005j
125	0.660+1.014j	0.039+0.001j
150	0.721+1.188j	0.039+0.001j
175	0.841+1.286j	0.038+0.010j
200	0.798+1.519j	0.040+0.001j
250	0.897+1.763j	0.039+0.007j
275	0.860+1.941j	0.040+0.001j
300	0.926+2.114j	0.040+0.002j
500	1.079+3.233j	0.041+0.003j
1000	0.839+6.020j	0.043+0.004j

Tab. 6: The resulting values for the parameters R, G, L, and C of the type Π two-port.

Freq.	$\mathbf{R}\cdot\mathbf{km}^{-1}$	$\mathbf{G}\cdot\mathbf{km}^{-1}$	$\mathbf{L}\cdot\mathbf{km}^{-1}$	$\mathbf{C}\cdot\mathbf{km}^{-1}$
20	0.839	0.118	0.0022	0.000458
50	1.6	0.139	0.0029	0.0000468
75	1.5	0.141	0.00261	0.0000258
100	1.21	0.142	0.00239	0.0000304
125	1.22	0.144	0.00239	0.00000352
150	1.34	0.145	0.00234	0.00000348
175	1.56	0.14	0.00217	0.0000361
200	1.48	0.147	0.00224	0.00000342
250	1.66	0.146	0.00209	0.0000158
275	1.59	0.149	0.00206	0.00000324
300	1.72	0.15	0.00208	0.00000328
500	2,00	0.154	0.0019	0.00000315
1000	1.55	0.158	0.00176	0.00000212

Tab. 7: The resulting values for the parameters R, G, L, and C converted to a unit length of 1 km.

Freq.	$\mathbf{R}\cdot\mathbf{km}^{-1}$	$\mathbf{G}\cdot\mathbf{km}^{-1}$	$\mathbf{L}\cdot\mathbf{km}^{-1}$	$\mathbf{C}\cdot\mathbf{km}^{-1}$
20	0.839	0.117	0.0022	$3.08\cdot10^{-4}$
50	1.6	0.12	0.0029	$9.03\cdot10^{-5}$
75	1.5	0.14	0.00261	$3.68\cdot10^{-5}$
100	1.21	0.14	0.00239	$3.43\cdot10^{-5}$
125	1.22	0.144	0.00239	$1.27\cdot10^{-5}$
150	1.34	0.142	0.00234	$2.07\cdot10^{-5}$
175	1.56	0.144	0.00217	$1.94\cdot10^{-5}$
200	1.48	0.145	0.00224	$1.03\cdot10^{-5}$
250	1.69	0.144	0.00209	$1.35\cdot10^{-5}$
275	1.56	0.151	0.00206	$6.46\cdot10^{-6}$
300	1.72	0.153	0.00208	$3.83\cdot10^{-6}$
500	2.2	0.16	0.0019	$3.58\cdot10^{-7}$
1000	1.62	0.169	0.00176	$-2.63\cdot10^{-7}$

Graphs of the dependence of these parameters on the frequency are shown in Fig. 6, Fig. 7, Fig. 8 and Fig. 9.

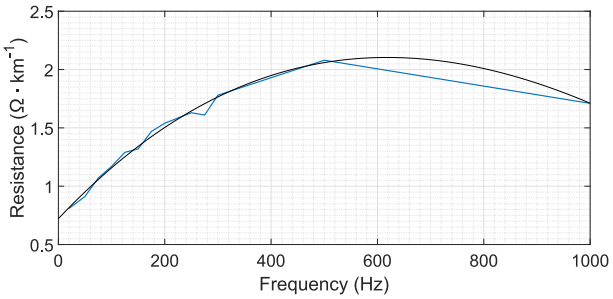

Fig. 6: Specific resistance as a function of frequency.

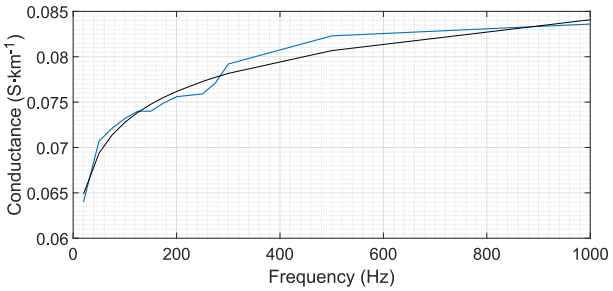

Fig. 7: Specific conductance as a function of frequency.

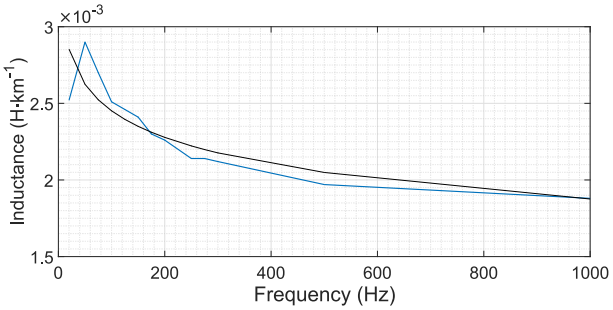

Fig. 8: Specific inductance as a function of frequency.

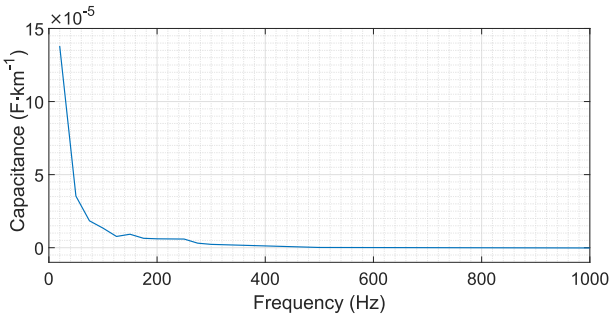

Fig. 9: Specific capacitance as a function of frequency.

5. Calculation of the Sensitivity of the Input Impedance to Changes of Parameters

The parameters of traction circuits change with the weather. First, we determined the sensitivity of the input impedance of the open circuit when changing the individual parameters. Thus we found which parameter affected the function of the predictor predominantly, and vice versa, which one can possibly be neglected. The assessed frequency was 275 Hz. Thus, we used these values:

Tab. 8: Used values of R, G, L and C.

$\mathbf{R \cdot km^{-1}}$	$\mathbf{G \cdot km^{-1}}$	$\mathbf{L \cdot km^{-1}}$	$\mathbf{C \cdot km^{-1}}$
1.56	$1.51 \cdot 10^{-1}$	$2.06 \cdot 10^{-3}$	$6.46 \cdot 10^{-6}$

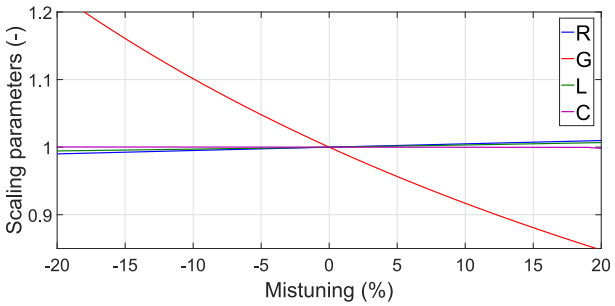

Fig. 10: Dependence of changes of normed real component of impedance in the open circuit on the percentage change of each parameter.

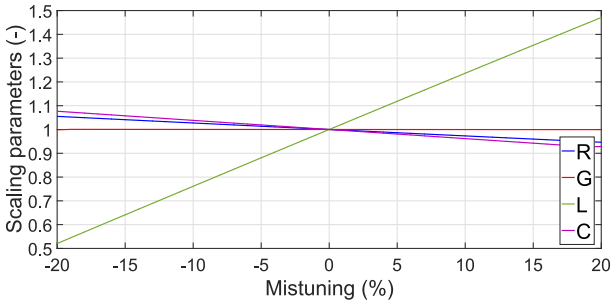

Fig. 11: Dependence of changes of the normed imaginary component of impedance in the open circuit on the percentage change of each parameter.

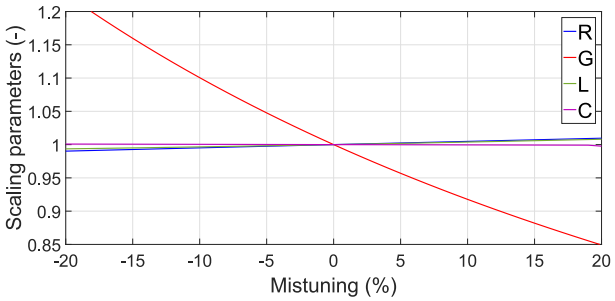

Fig. 12: Dependence of changes of normed magnitude of impedance in the open circuit on the percentage change of each parameter.

These parameters were gradually mistuning about 20 % in both the positive and the negative values while the values of the other parameters remained constant.

6. Conclusion

The measurements that are described herein are intended for the design of a predictor that searches the occupancy of the track circuit. This predictor needs to react to weather changes and changes of other conditions of traction. Therefore, repeated measurements must be carried out, especially in the open circuit condition. When measuring under open circuit conditions, it is necessary to evaluate the particular ratio of effective values of voltages and currents and thus to evaluate the magnitude of the impedance. Itis most sensitive to changes of conductance G. Conductance G and capacitance C change the most with the weather conditions. Thus is enough, if only the change of the conductivity G is respected during calibration. Other parameters remain constant.

Finally, we compared the calculated values with those from various works in literature for the frequency of 275 Hz.

Tab. 9: Comparison of our results with those of other papers.

$\mathbf{R \cdot km^{-1}}$ **(Ω)**	$\mathbf{G \cdot km^{-1}}$ **(S)**	$\mathbf{L \cdot km^{-1}}$ **(H)**	$\mathbf{C \cdot km^{-1}}$ **(F)**	**Ref.**
0.55	2.25	$1.55 \cdot 10^{-3}$	$0.25 \cdot 10^{-6}$	[2]
1.1	$1.04 \cdot 10^{-3}$	-	$0.9 \cdot 10^{-6}$	[4]
0.18	$18 \cdot 10^{-3}$	$12.7 \cdot 10^{-3}$	$7 \cdot 10^{-6}$	[5]
0.004	-	$1.45 \cdot 10^{-3}$	-	[8]
1.56	$1.51 \cdot 10^{-1}$	$2.06 \cdot 10^{-3}$	$6.46 \cdot 10^{-6}$	[*]

[*] this paper

However, it is too difficult to compare the values of measurements under different conditions at different shunt resistances conducted in series to the rails when measuring the short circuit and so on. The measuring conditions are not comparable at all.

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