

## PROCEDURE FOR THE MEASUREMENT OF THE ELECTRICAL PARAMETERS OF RAILWAY TRACTION LINES

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**Abstract** - Measurements of the electrical parameters of a traction line were performed over the 0-200 kHz frequency range on a line section purposely prepared at La Spezia (Italy). The electrical parameters are determined by an indirect approach: only the terminal variables (voltages and currents and hence impedance and admittance) may be measured and the per-unit-length electrical parameters are determined using a Multiconductor Transmission Line model of the test track section; the parameters of the model are adjusted so that the calculated terminal variables match the measurement results. There is a general accordance with model previsions, within common variations of the most critical properties, e.g. ground and ballast characteristics and rails permeability; the results are very accurate in the frequency range 50 Hz - 50 kHz.

**Keywords:** Electric variables measurement, Rail transportation power systems

### 1. INTRODUCTION

The design of an entire new railway traction system or the introduction of new vehicles or signalling devices require the assessment of the Electromagnetic Compatibility (EMC) of the whole system and the evaluation of the interference between subsystems and components, also by means of numerical models. Several calculation methods may be found in the literature, based on circuit approach and Multiconductor Transmission Line (MTL) approach both in the frequency domain and in the time domain [1-3].

All the methods presented above cannot be implemented without a deep knowledge of the line electrical parameters. Some parameters may be determined with great accuracy, using well known and established formulae [4-6]. Other critical parameters (e.g. the electrical characteristics of the soil and the conductance between the rails and the earth itself) may be determined only experimentally [7,8]; moreover, they may change with time, temperature and other weather conditions. Other parameters cannot be measured directly and in this work it is proposed to estimate them from the measurement of accessible variables data (indirect method). The proposed procedure is described and validated on the basis of the results of a measurement campaign.

### 2. THE MEASUREMENT SITE AND TEST SETUP

The line section used for the measurements is a secondary single track line used for recovery of trains, approximately  $L=140$  m long, with standard dc electrification. Fig. 1 shows the cross section of the line under test. The line is in normal conditions. The rails are insulated from the sleepers by rubber sheets in average conditions and the ballast looks deeply sunk in the ground.

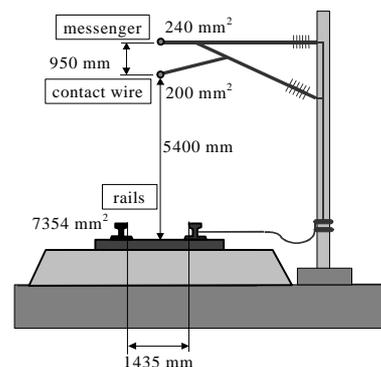


Fig. 1 Cross section of the line under test

Several operations were done to prepare the line for the measurements: electrical insulation of the conductors at both ends; disconnection of all the transversal connections to masts; connections of the instruments by Litz wires; use of dropper clamps (for connection to the overhead conductors) and of "rail shaped" clamps (for connection to rails through).

The measurement configurations were designed to test specific electrical parameters of the traction line with adequate accuracy (signal to noise ratio).

*Configuration 1:* conductors left open on the left side, overhead conductors and rails in parallel (Fig. 2a). The test is conceived to measure the loop capacitance (capacitance between the overhead and the rails), that is responsible for the main resonance of the traction loop impedance.

*Configuration 2:* conductors short circuited on the left side, overhead conductors and rails connected in parallel (Fig. 2b). The test is conceived to measure the traction loop impedance, which is the most important parameter in the simplified single conductor model of the traction line.

*Configuration 3:* rails open on the left side, overhead not connected (Fig. 2c). The test is conceived in order to obtain information on the rail-to-rail capacitance and conductance and also on the earth dielectric constant.

*Configuration 4:* rails short circuited on the left side, overhead not connected (Fig. 2d). The test is conceived to measure the rail-to-rail resistance and inductance. The earth dielectric constant is large enough to produce a resonance, which falls within the investigated frequency range.

*Configuration 5:* conductors open on the left side, overhead conductors in parallel and one rail disconnected (Fig. 2e). The test is conceived to get additional data on the loop capacitance (capacitance between overhead and rails).

*Configuration 6:* conductors short circuited on the left side, overhead conductors in parallel and one rail disconnected (Fig. 2f). The test is conceived to get additional data on the traction loop impedance.

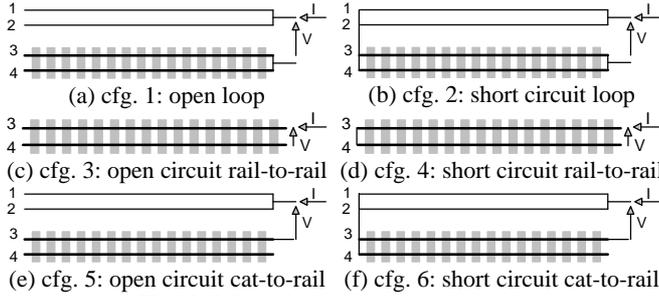


Fig. 2: Measurement configurations

(1 suspension wire, 2 contact wire, 3 rail 1, 4 rail 2)

The railway traction system under test is quite extended and so it is exposed to external electromagnetic interference, such as HF (High Frequency) radio transmitters and LW (Long Wave) and MW (Medium Wave) broadcast transmitters, all above a hundred kHz. In either loop or open circuit configurations it happens that either the signal voltage or current reach small values, influencing the measurement accuracy (depending on the sensitivity of the measuring equipment) and the signal-to-noise ratio.

The electrical parameters of the line are not measured directly. The adopted procedure (see the flowchart in Fig. 3) is as follows:

- 1) the model is assigned with initialisation values;
- 2) the terminal impedance or admittance measured at line terminals is compared with the terminal impedance or admittance resulting as model output;
- 3) the model parameters are adjusted, if necessary, to make the measured and calculated terminal impedance or admittance match.

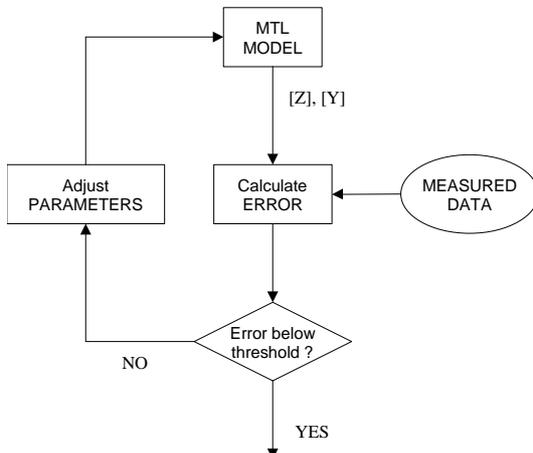


Fig. 3: The proposed procedure

To accelerate the convergence of the proposed procedures, the electrical parameters are assigned average standard values derived from experience and from other published data [1,5,6,7,8].

### 3. REFERENCE MODEL

The line section is modelled using the distributed MTL structure [1]: there are no longitudinal discontinuities and two terminal networks, characterised by the connection matrices  $\mathbf{Z}_S$  on the source (right) side (where the measurements are performed) and  $\mathbf{Z}_L$  on the far end (left) side. The model includes four conductors: suspension wire, contact wire, rail 1 and rail 2; the common conductor for all conductors is the “perfect ground”. The system is characterised by a coupled set of 8 first order partial differential equations:

$$\begin{aligned} \frac{\partial}{\partial z} \mathbf{V}(z,t) &= -\mathbf{R}\mathbf{I}(z,t) - \mathbf{L} \frac{\partial}{\partial t} \mathbf{I}(z,t) \\ \frac{\partial}{\partial z} \mathbf{I}(z,t) &= -\mathbf{G}\mathbf{V}(z,t) - \mathbf{C} \frac{\partial}{\partial t} \mathbf{V}(z,t) \end{aligned} \quad (1)$$

where  $\mathbf{V}$  is a  $4 \times 1$  column vector, containing the 4 line voltages with respect to the reference conductor;  $\mathbf{I}$  is a  $4 \times 1$  column vector containing the 4 line currents;  $\mathbf{R}$ ,  $\mathbf{L}$ ,  $\mathbf{G}$  and  $\mathbf{C}$  denote the per-unit-length parameter matrices of size  $4 \times 4$ .

The solution of the phasor MTL equations for a line of length  $L$  can be written in the chain parameter form as:

$$\begin{bmatrix} \mathbf{V}(L) \\ \mathbf{I}(L) \end{bmatrix} = \begin{bmatrix} \Phi_{11}(L) & \Phi_{12}(L) \\ \Phi_{21}(L) & \Phi_{22}(L) \end{bmatrix} \begin{bmatrix} \mathbf{V}(0) \\ \mathbf{I}(0) \end{bmatrix} \quad (2)$$

where  $\mathbf{V}(0)$ ,  $\mathbf{I}(0)$  are the current at the line near end;  $\mathbf{V}(L)$ ,  $\mathbf{I}(L)$  are the current at the line far end;  $\Phi_{ij}$  are the chain parameters sub-matrices.

The  $\Phi_{ij}$  are related to the line electrical parameters by:

$$\Phi_{11} = \cosh(\sqrt{\mathbf{Z}\mathbf{Y}}L) \quad (3a)$$

$$\Phi_{12} = -\mathbf{Z}_c \sinh(\sqrt{\mathbf{Y}\mathbf{Z}}L) \quad (3b)$$

$$\Phi_{21} = -\mathbf{Z}_c^{-1} \sinh(\sqrt{\mathbf{Z}\mathbf{Y}}L) \quad (3c)$$

$$\Phi_{22} = \cosh(\sqrt{\mathbf{Y}\mathbf{Z}}L) \quad (3d)$$

The constant  $\mathbf{Z}_C$  is the characteristic impedance matrix defined as

$$\mathbf{Z}_C = \mathbf{Y}^{-1} \sqrt{\mathbf{Y}\mathbf{Z}} \quad (4)$$

where

$$\mathbf{Z} = \mathbf{R} + j\omega\mathbf{L} \quad \mathbf{Y} = \mathbf{G} + j\omega\mathbf{C} \quad (5)$$

The phasor MTL equations are solved adding 8 additional constraints, provided by the terminal conditions, derived from the terminal networks using the generalised mixed representation (Kirchhoff voltage and current laws):

$$\begin{aligned} \mathbf{Y}_S \mathbf{V}(0) + \mathbf{Z}_S \mathbf{I}(0) &= \mathbf{P}_S \\ \mathbf{Y}_L \mathbf{V}(L) + \mathbf{Z}_L \mathbf{I}(L) &= 0 \end{aligned} \quad (6)$$

where  $\mathbf{Y}_S$ ,  $\mathbf{Y}_L$ ,  $\mathbf{Z}_S$  and  $\mathbf{Z}_L$  are the result of the branch elements and any controlled sources in the terminal networks;  $\mathbf{P}_S$  is the voltage and current excitation source.

An equivalent formulation of the MTL problem (as defined by (2)) is given in terms of the admittance parameters [6]:

$$\begin{aligned} \mathbf{I}(0) &= \mathbf{Y}_P \mathbf{V}(0) + \mathbf{Y}_M \mathbf{V}(L) \\ -\mathbf{I}(L) &= \mathbf{Y}_M \mathbf{V}(0) + \mathbf{Y}_P \mathbf{V}(L) \end{aligned} \quad (7)$$

where  $\mathbf{Y}_P$  and  $\mathbf{Y}_M$  are the self and mutual admittance parameters matrices respectively. These matrices are a function of the chain parameter matrix

$$\begin{aligned} \mathbf{Y}_P &= \Phi_{12}^{-1}(-L) \cdot \Phi_{11}(-L) = \Phi_{22}(-L) \cdot \Phi_{12}^{-1}(-L) \\ \mathbf{Y}_M &= \Phi_{12}^{-1}(-L) \end{aligned} \quad (8)$$

The final system composed of (7) and (8) is solved directly using matrix inversion algorithm.

#### 4. MEASUREMENT RESULTS AND COMPARISON WITH CALCULATIONS

The procedure proposed in the previous section is executed and it is stopped when the correspondence between calculated results and measured data is satisfactory, that is:

- the most significant elements of the  $[\mathbf{Z}]$  and  $[\mathbf{Y}]$  matrices are in agreement within 20%; the elements used for the comparison are those with physical meaning;
- the resonance frequency, where it is detectable from the measured data, is in agreement with the calculated one within 20%.

For some unknown electrical parameters (such as the electrical resistivity of soil and the magnetic permeability of rails) average values and an adequate interval of confidence are adopted. The values are reported in Table I. It is very difficult to determine an exact value of the dielectric constant of soil by calculation, since different layers in the soil with different dielectric constant values should be accounted for. A unique value of the dielectric constant of the soil is used for the sensitivity analysis.

TABLE I. Model parameters (with intervals)

	Messenger	Contact wire	Rail 1	Rail 2
Height above ground plane [m]	6.10	5.00	0.20	0.20
Distance from horiz. ref. [m]	1.50	1.50	0.75	2.25
Cross section [mm <sup>2</sup> ]	120	200	7354	7354
Resistivity [ $\mu\Omega\text{m}$ ]	0.0177	0.0177	0.225	0.225
Permeability [relative]	1	1	20 $\div$ 50	20 $\div$ 50
Temperature [°C]	55			
Earth resistivity [ $\Omega\text{m}$ ]	50 $\div$ 500			
Earth relative dielectric constant (low water %)	$\approx 4000/\sqrt{f}$			

The graphs shown in Fig. 4 through 10 report in black dots the results of the measurements, properly processed for comparison with the calculation results: the grey bands are the results of the sensitivity analysis; the solid curves inside the band are obtained with average values of the parameters. Table II (omitted) reports the input data used in the model.

#### 4.1. Discussion of the inductance values

The measured values (Fig. 4) fit very well the average curve of the simulated values; the irregular curve shape at low frequency is due to both a change in rails magnetic properties and external disturbances coming from the supply grid at 50 Hz. The two profiles measured for the left and the right rail separately are almost similar (Fig. 5) and they are very close to the curve obtained for the two rails connected in parallel (see Fig. 2) in the intermediate frequency range.

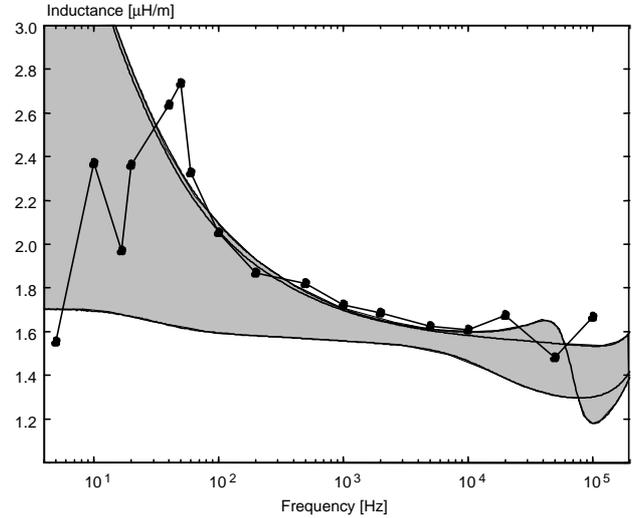


Fig. 4: Cfg. 2, measurement of overhead-rails inductance

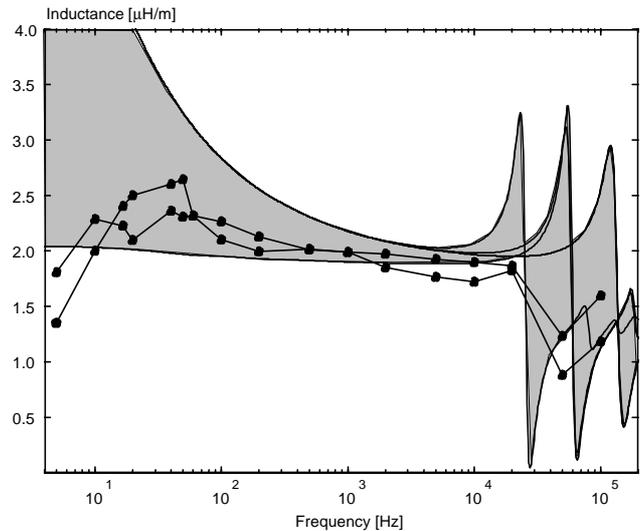


Fig. 5: Cfg. 6, measurement of overhead-rail inductance

#### 4.2. Discussion of the resistance values

The overhead-rails resistance (Fig. 6) is very close to the average curve derived from the sensitivity analysis.

On the contrary, the measured values shown in Fig. 7 are very different at low frequency for the two rails and stay on the two limit curves determined by the sensitivity analysis. This is due to the resistance of the connections, which is comparable with the dc and low frequency resistance of the rails and couldn't be eliminated from the measured data.

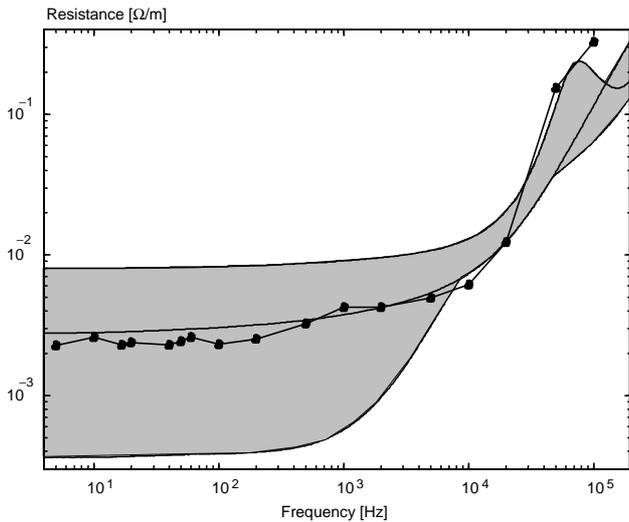


Fig. 6: Cfg. 2, measurement of overhead-rails resistance

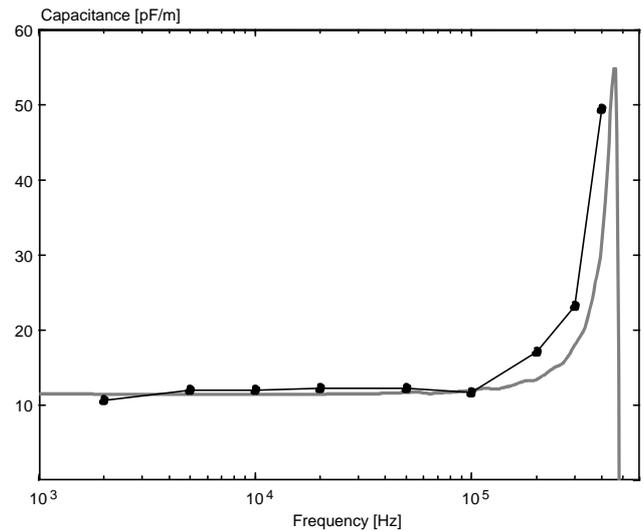


Fig. 8: Cfg. 5, measurement of overhead-rail capacitance

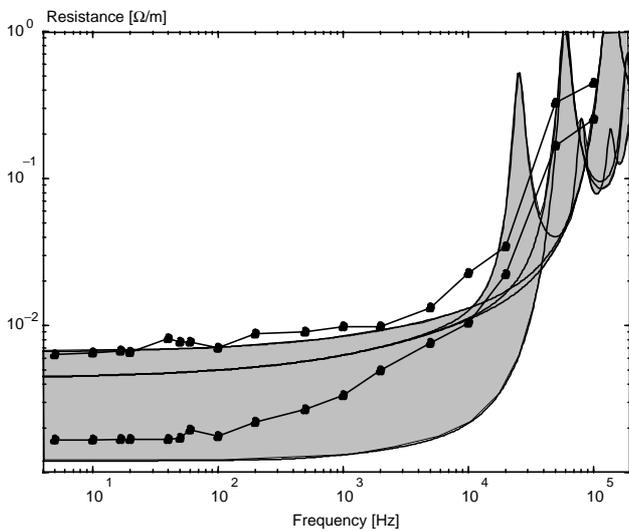


Fig. 7: Cfg. 6, measurement of overhead-rail resistance

The results shown in Fig. 6 and Fig. 7 are in good agreement since the lower resistance of either rail in Fig. 7 corresponds to the measured total overhead-rails resistance.

However, the contribution of the resistance of the contacts and measuring cables cannot be avoided in the lower part of the frequency range.

#### 4.3. Discussion of the capacitance values

The measured data (see Fig. 8) fit very well the calculated values even near the resonance of the test circuit. The calculation of the capacitance for air conductors (overhead conductor) is well established [1], since the behaviour of rails, ballast and soil may be assumed to be that of a perfect ground.

The measured values of the rail-to-rail capacitance (reported in Fig. 9) are all inside the band determined by the sensitivity analysis.

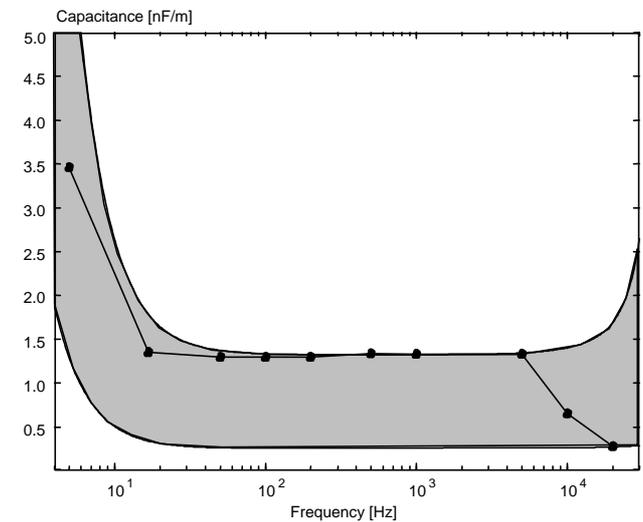


Fig. 9: Cfg. 3, measurement of rail-rail capacitance

#### 4.4. Discussion of the conductance values

The match between the calculated and measured rail-rail conductance values is very close (Fig. 11) over the entire frequency range.

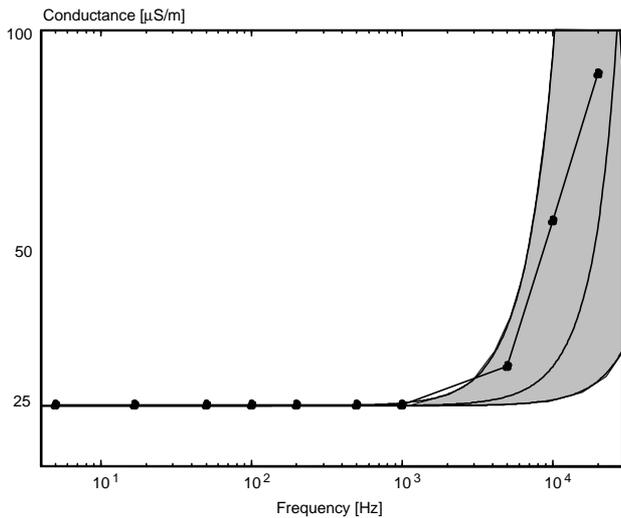


Fig. 11: Cfg. 3, measurement of rail-rail capacitance

The measured values of the rail-rail conductance are compatible with the intervals for rail-earth conductance indicated by CCITT [1] for insulated rail in good conditions ( $2 \cdot 10^{-5} - 5 \cdot 10^{-5}$  S/m).

## 5. CONCLUSIONS

A procedure for the measurement of the electrical parameters of a traction line has been presented based on an indirect method, that is on the results of both the measurements performed on terminal variables and a numerical model of the line under test. The procedure is validated using the results of the measurement campaign performed in La Spezia (IT) on 1999 and other published data. The accuracy of the method is very high especially in the 50 Hz – 50 kHz frequency range, where it is most important to perform the electrical analysis of a traction line.

This procedure may be extended to other electrical traction systems and different electrical systems, where the electrical parameters cannot be determined a priori, cannot be accessed directly for measurement and may be highly variable from site to site.

Future development consists of further analysis of the method for error evaluation and of the improvement of the rules adopted for parameters adjustment. In the present implementation the parameters are adjusted manually by the user at each iteration.

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