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Experimental validation of the electric network model of the Italian 2x25 kV 50 Hz railway

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***Abstract* – The preliminary activity of validation of an integrated electromagnetic railway simulator is presented, with particular attention to the verification of the experimental data used as a validation reference and to the quantification of the model quality. Visual comparison between simulated and experimental results is not quantitative, is subjective, but captures features that deserve to be adequately quantified for the validation process to be repeatable and objective.**

I. INTRODUCTION

Numeric models are widely used in all fields of physics and engineering, when experiments on the real system are expensive or even impossible, when the influence of some parameters is of interest and is not under operator's control, when extreme conditions or worst cases are to be tested, but are not physically feasible, repeatable or even beyond system capability. A working example of a large complex electrical system is a railway traction system [1][2], that features also strict requirements for safety and its demonstration through simulation [3]. A railway is a very large network with "unpractical" power distribution, with trains lying on the running rails below overhead conductors, from which they collect power through pantographs. The return current flows back to the Electric Substations (ESS) through the return circuit. The power distribution scheme of the present case is 2x25 kV 50 Hz.

A numeric simulation model of a railway system is a complex electrical network ruled by known equations (namely Kirchhoff equations and voltage-current equations of components), with system elements that might be modeled in different ways with different degrees of accuracy and completeness, and a general variability of parameters depending on temperature, location, operating point, production tolerances, to cite a few. This variability affects also the real system that is going to be used for the validation, so that the real system used as a reference is far from representing the "real value". Rather, its behavior is evaluated only approximately, capturing one or some configurations and parameter values [6]. It is the experimenter's responsibility to judge on the reliability of data, based on a list of checks on the measurement setup and on the results for plausibility, consistency, repeatability. The same is required to the simulation model, that is validated by evaluating the plausibility of its output with respect to the expected "natural" system behavior, with the help of a sensitivity analysis to parameters and inputs variations, and then the accuracy of its output with respect to measured results. This is however a comparison between two quantities (or sets of quantities) for which only a confidence interval may be given, provided that the extension of the interval may be only estimated using a limited number of measurements and of simulation runs.

When it comes to compare quantitatively simulation and measurement results, several criteria may be adopted, that depend also on the nature of the problem and the expected behavior of the system [4][5]. The most intuitive and widely accepted criteria are those of the mean error, maximum error and mean square error. However, it is possible to focus on the underlying dynamic behavior of the system and on the expected shape of the response curves, to extract features that convey more information than raw data: for example, a dynamic system is often described in terms of its poles and zeros, that is the resonance frequency and associated peaks in the response, to which a factor of merit or damping factor is associated; between peaks and deep valleys there are portions of the curve featuring more regular slopes, that are as important as the peaks and depend on different factors; also the convexity of the response may be evaluated going to a more detailed and refined analysis.

II. DESCRIPTION OF THE PROBLEM

The frequency response of a railway system as far as rolling stock emissions are concerned reflects in the pantograph impedance (that is the so-called "hot path"), besides the distribution of the return current among the parts of the return circuit [2]. Specific responses and characteristic behavior of the traction line may be put in relationship not only to the geometry of the line conductors, but also to circuit elements and electrical and material parameters values.

Even if measurements are always preferred to evaluate rolling stock emissions and to assess its compatibility, it

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is also evident on one side that it is not possible to experimentally test widely changing system parameters (as they might be in the whole life of the system) and that they are not under the experimenter's control, and that some worst-case situations and uncommon parameters combinations are possible only in a simulated environment, in order to assess the safety margin of the real system. Moreover, and this is one of the objectives of the EUREMCO project [7], it is attractive and advantageous to evaluate the expected variability of different supply systems residing in different countries, but sharing the same overall structure, e.g. the voltage level and the type of distribution, in order to extend the validity of experimental results (and even simulation results) obtained at a specific site.

Since experimental activities on real systems are expensive and need a great effort in terms of organization, using modeling and simulation might be a viable solution to the assessment of emissions and the compatibility with signaling and communication equipment, provided that the simulation tool is able to give reliable and credible results. The validation of the simulation model is carried on by comparison to the pantograph impedance curves resulting from measured pantograph voltage and current; the chosen system is the Italian high speed network [6].

A. The real system: 2x25 kV 50 Hz high speed line

The 2x25 kV 50Hz line is a single-phase system, characterized by the use of two active conductors, one at +25kV that feeds the train along the line, and another one, named negative feeder, at -25 kV that carries the return current out from the supply cell where the train resides. The traction line is isolated into supply sections, delimited by neutral sections; for each supply section the voltage has a phase shift, due to the connection to a different pair of the HV phase conductors, in order to balance the loading of the traction line on the HV network. The traction system is fed by Electrical Substations (ESS) located every about forty to fifty kilometers, with autotransformers (AT) distributed every about ten to fourteen kilometers, forming what we have called "supply cells" along the line. The AT action is such that the return current leaving the train and flowing through the running rails is recalled into the negative feeder, closer to the positive catenary conductor. This reduces the overall loop inductance of the traction line (and thus the longitudinal voltage drop) and the magnetic field emissions. ESS ad AT transformers have two windings, one connected to the catenary at +25 kV and the other one to the negative feeder at -25 kV; the center terminal in common to the two windings is connected to the running rails. The running rails are bonded to the other conductors of the return circuit at earth potential (the overhead earth conductor, or "earth rope", and the through earth collector, or buried earth conductor); when track circuits are present on the track, the bonding is made by means of impedance bonds, that decouple the track circuits from the earthed return circuit, bonding the running rails only for common mode currents, and not for the differential component used by the track circuits [3]. Impedance bonds are two magnetically coupled windings with a center terminal: the two ends are connected to the rails and the center terminal to the rest of the return circuit. This connection may occur to the earth rope or to the through-earth collector (accessible through branched connections) or to the earthed poles supporting the catenary. It is also quite common that signaling, communication and security systems located in cabins and shelters along the line are fed from the 25 kV catenary with a pole-mounted transformer.

B. The electric traction network model

Several details and elements of the real system shall be included and modelled adequately for accurate predictions of system response. In the present case, where the hot path of the traction supply circuit is considered, the main electrical and network elements are included:

- substation transformers and autotransformers, by means of an equivalent circuit that considers windings reactance and resistance, including losses (with an average figure of copper and iron losses), skin effect and proximity effect;
- cables are used to connect these machines and their effect on the traction line behaviour is relevant, in particular for the added capacitance;
- traction line and its cross section, including all traction conductors (geometry and material properties); for parameters that cannot be determined by calculation, such as the conductance to earth of rails and through-earth collector, a sensitivity analysis is performed; skin effect and losses of running rails and their effect on resistance and internal inductance are considered [2];
- impedance bonds are modelled as coupled transfomers; their influence on the results is in reality marginal and thus their position was adjusted and made corresponding to some other longitudinal elements when possible to reduce the number of nodes and to simplify the model; on average the separation is 1500 m in relationship to the type of track circuit used.

III. VARIABILITY OF MEASUREMENT DATA

The measurement data used in this paper come from test campaigns performed late in 2012 within the EUREMCO project [7]. The measurement campaign was performed with a BB36000 locomotive manufactured by Alstom and owned by SNCF, following a speed profile formed of three phases: acceleration, coasting/cruising, braking. Measurements data are sampled at 50 kS/s and analyzed with Fourier transform over windows of 100 ms (10 Hz resolution), using a Hann window and 50% of overlap for a total of 9 windows over a time interval of

0.5 s. When calculating the pantograph impedance by ratioing voltage and current spectra, only odd harmonics of the 50 Hz fundamental are used: among them the low order ones are normally influenced by the supply, while above about 1 kHz rolling stock influence is relevant.

Several elements contribute to the overall error that affects the comparison of simulation and measurement data for validation [4][5]. Measurement data themselves are affected by errors in the measurement chain (related to the uncertainty of the measurement chain), errors due to noise and external influence (such as abnormal distortions of the supply, besides the usual broadband noise), error in the exact instantaneous train operating condition and position. The latter are related more closely to the validation task. Pantograph impedance curves are compared for validation and the measurement results are meaningful only if the train absorbs a significant current, that is in acceleration and braking conditions; however it is quite common that an acceleration ramp is intermingled with short intervals of time in which the throttle is released, with slight speed reductions because of train inertia, but pantograph current drops instantaneously to insignificant values; the same may be said during braking. Regarding train positions, since the impedance curves are quite sensitive to the position along the line and they change progressively while moving between two substations, a positioning error of only one train length may result in a significant shift of some of the impedance curve characteristics. The effective train position is calculated by integrating the speed from a starting point that is annotated in the recorded data and checking with some GPS referenced points; however, due to operator's misunderstanding of the chainage signs, transcription errors, approximations and round-offs, the positioning error is estimated as large as about 400 m.

Voltage and current spectra used to calculate the pantograph impedance are affected by noise and measurement uncertainty; the resulting impedance values may be subject to a significant uncertainty for extremely small values of voltage and current components.

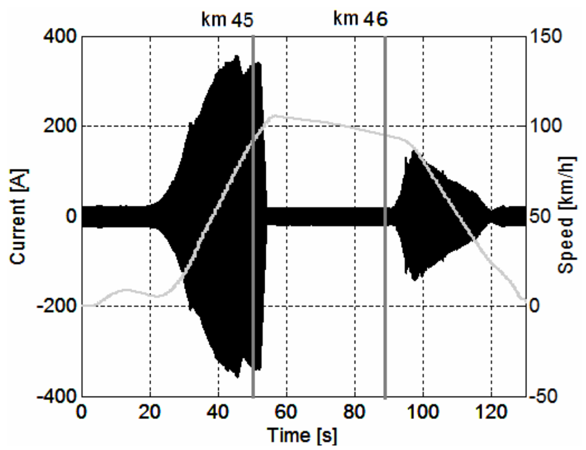


Fig. 1. Absorbed current and speed profile

It is known from theory [1][2] that the position along the line of a moving rolling stock determines the frequency and the amplitude of the anti-resonance peaks; this holds true in general and may be clearly seen on a simple transmission line. For more complex networks behavior is more complex: train position is extremely important to establish the reference curves used for the validation. In order to evaluate the dispersion of the measured impedance curves, standard deviation σ is calculated of a sample of spectra distributed over a time interval for which the train position does not change appreciably. For this reason a 1.5 s time interval is chosen using 100 ms windows and 50% overlap. The mean impedance curve and its dispersion are calculated on the 29 windows sample; the $\pm 1\sigma$ intervals indicate the dispersion of the data. Acceleration and coasting conditions are considered at km 45 and 46, with an absorbed fundamental current of about 200 Arms and 10 Arms, respectively. The results are shown in Fig. 2 to Fig. 5.

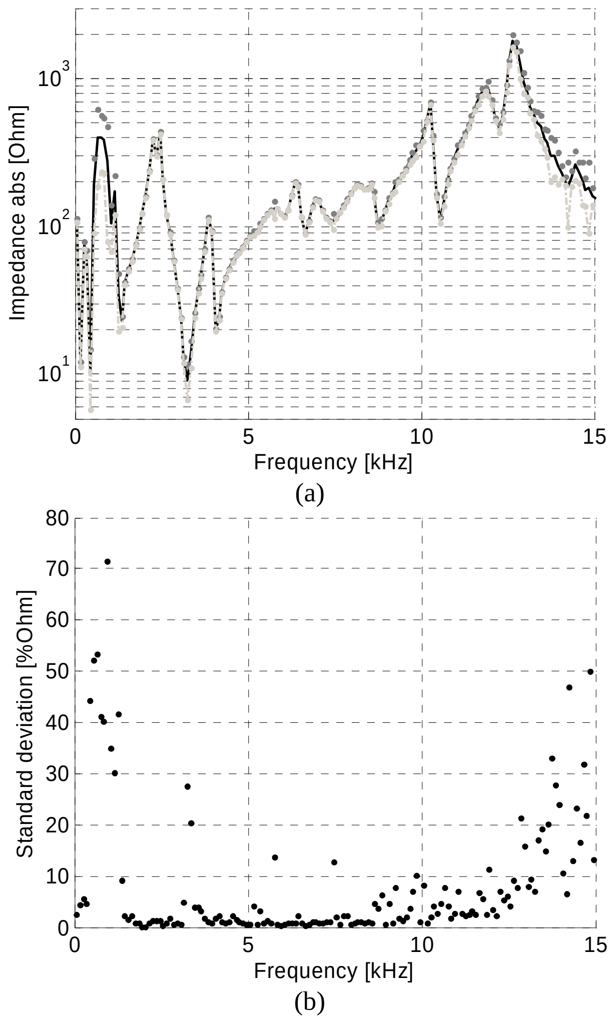
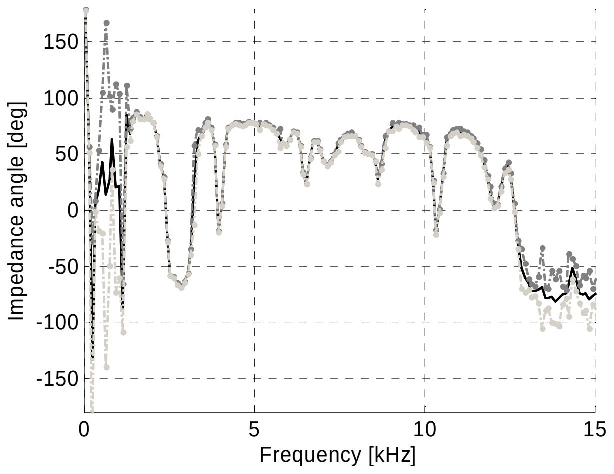
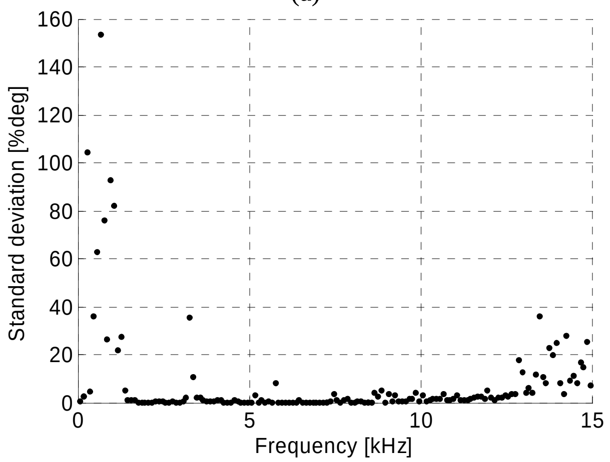


Fig. 2. Uncertainty of the pantograph impedance module at km 45 for spectra computed over a 1.5 s time interval: (a) mean value $\pm 1\sigma$, (b) normalized standard deviation

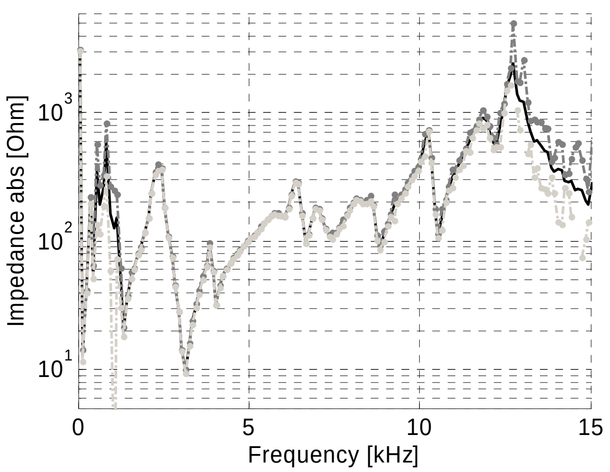


(a)

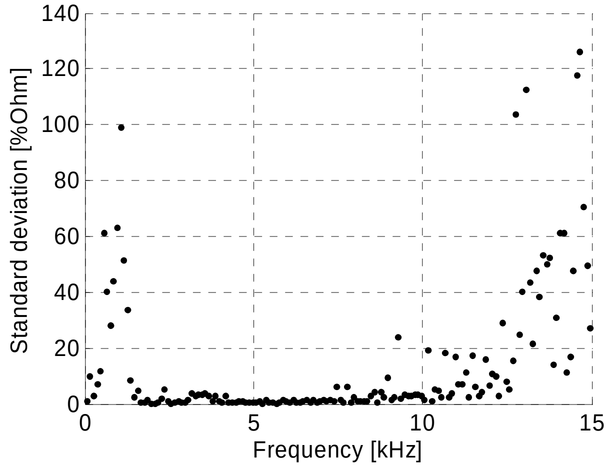


(b)

Fig. 3. Uncertainty of the pantograph impedance phase at km 45 for spectra computed over a 1.5 s time interval: (a) mean value $\pm 1\sigma$, (b) normalized standard deviation

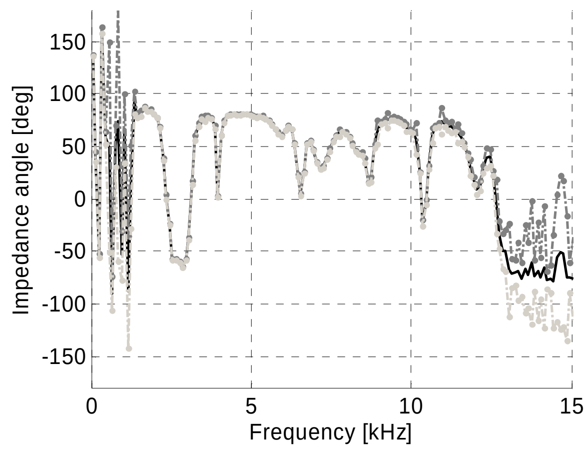


(a)

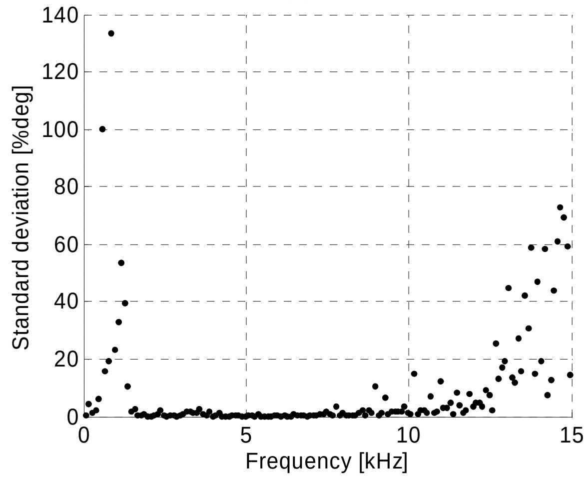


(b)

Fig. 4. Uncertainty of the pantograph impedance module at km 46 or spectra computed over a 1.5 s time interval: (a) mean value $\pm 1\sigma$, (b) normalized standard deviation



(a)



(b)

Fig. 5. Uncertainty of the pantograph impedance phase at km 46 for spectra computed over a 1.5 s time interval: (a) mean value $\pm 1\sigma$, (b) normalized standard deviation

All curves show the largest dispersion at low frequency (below 1250 Hz) and at high frequency (above 14 kHz). The module standard deviation is lower than that of phase. Moreover, the standard deviation is lower for km 45, when the absorbed current is larger. Such large values of standard deviation of the measured reference curves pose serious problems in using those frequency intervals for validation, in particular at high frequency, where the points with large dispersion are much more.

The low order harmonics are mainly due to the power supply system (and in particular to asymmetry and harmonic distortion of the High Voltage network). The locomotive characteristic harmonics resulting from the on-board PWM front-end converters have the first group located around the switching fundamental, that is usually between 1500 and 2500 Hz. On the contrary, the auxiliary converters are responsible for some low-order harmonics.

IV. VALIDATION RESULTS

A. Visual comparison

The comparison of experimental and simulation results for pantograph impedance is shown in Fig. 6 and 7. The two pairs of curves refer to two different positions and current absorptions.

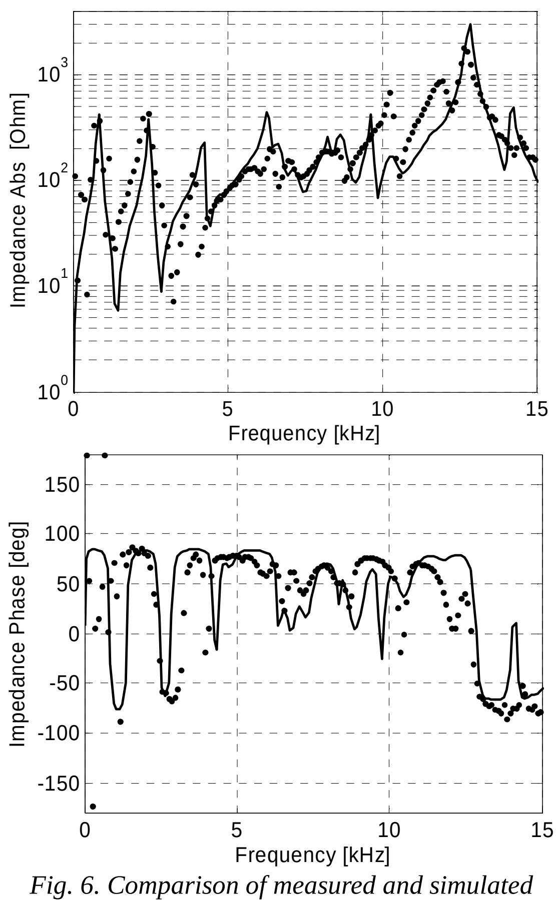


Fig. 6. Comparison of measured and simulated pantograph impedance: module and phase at km 45

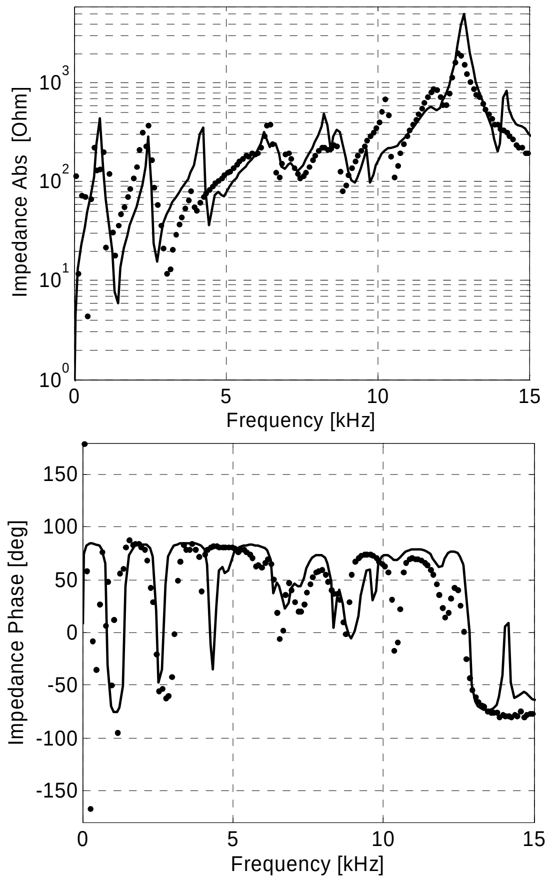


Fig. 7. Comparison of measured and simulated pantograph impedance: module and phase at km 47

The main resonance peaks are correctly simulated with a substantial correspondence of the resonance frequency and amplitude; some peaks are overestimated by the simulated results, such as at 4, 6.5, 13 and 14 kHz for Fig. 6. Around 10 kHz there is a shift in the resonance and anti-resonance frequencies and a much higher excursion of resonance and anti-resonance peak for the measured data. At very low frequency the quality of the measurement results used for the comparison is poor, since only the characteristic odd harmonics could be used: besides the poor frequency resolution at low frequency, up to about 1 kHz there is a prevalence of the supply network harmonics. In general, however, the curve behavior is similar.

Matching is worse for phase than for amplitude, even if there is a general agreement, with some discrepancies in damping factors.

B. Evaluation of validation performance

Validation is then performed more quantitatively, using performance indexes proposed in the literature, that quantify and weight errors in amplitude, slope, concavity, using values and derivatives of simulated and experimental results and aiming at a balanced weighted global index. Many methods quantifying the goodness of fit were evaluated in [8] and the best for this kind of problems are selected and briefly reviewed. We name them “validation performance indexes”, or VPI.

The “Theil inconsistency coefficient” [12] evaluates the differences between the curves squared; its value ranges between 0 and 1, with lower values indicating a better matching between the curves.

The “Zanazzi-Jona correlation factor” [13] is designed to accentuate slopes rather than the amplitude; the output value depends on how the normalization is done, using the simulated or the measured data as reference. The index ranges between 0 and 1, with lower values corresponding to a high correlation between the curves.

The “Van Hove correlation factor” [15] is calculated starting from five different indexes that evaluate separately errors of amplitude, slope and number of peaks. Then the five indexes are assembled into one single overall rms.

IELF (Integrated against Error Low Frequency) index [16] computes the difference between two curves using a logarithmic horizontal axis.

One last method is used that, besides numeric values, gives an overall judgment of the degree of fitness, similar to a visual comparison: FSV (Feature Selective Validation) [17]-[20]. This is the most complex and elaborated method and was adopted as the standard [18] for the validation of electromagnetic field simulation. The results obtained at four different positions at km 45, 46, 47 and 48 are shown in Table 1 and Table 2.

Position [km]		**45**	**46**	**47**	**48**
Theil		0.274	0.496	0.338	0.499
Zanazzi Jona		$0.161\ 10^{-4}$	$0.201\ 10^{-4}$	$0.196\ 10^{-4}$	$0.211\ 10^{-4}$
IELF		38.292	41.14	44.52	75.31
Van Hove	RV	3.196	1.952	4.825	2.016
	RV1	0.482	0.611	0.457	0.669
	RV2	0.417	0.890	0.466	0.987
	RV3	0.083	0.083	0.083	0.083
	RV4	1.363	1.192	1.523	1.207
	RV5	2.819	1.103	4.530	1.084

(a)

Position [km]		**45**	**46**	**47**	**48**
Theil		0.394	0.363	0.373	0.361
Zanazzi Jona		$0.215\ 10^{-4}$	$0.301\ 10^{-4}$	$0.265\ 10^{-4}$	$0.264\ 10^{-4}$
IELF		45.41	38.42	44.80	38.43
Van Hove	RV	1.689	1.667	1.582	1.604
	RV1	0.557	0.511	0.544	0.534
	RV2	0.531	0.458	0.481	0.452
	RV3	0.149	0.185	0.147	0.187
	RV4	1.202	1.153	1.086	1.108
	RV5	0.889	0.970	0.880	0.906

(b)

Table 1. Validation Performance Index of (a) module and (b) phase (Theil, Zanazzi-Jona, IELF, Van Hove) for km 45, 46, 47 and 48

Position [km]	**45**	**46**	**47**	**48**
ADM	Very good	Very good	Good	Very good
FDM	Very good	Good	Good	Good
GDM	Good	Good	Good	Good

(a)

Position [km]	**45**	**46**	**47**	**48**
ADM	Good	Good	Good	Good
FDM	Good	Good	Good	Good
GDM	Fair	Fair	Fair	Fair

(b)

Table 2. Validation performance with the FSV method for (a) module and (b) phase for km 45, 46, 47 and 48 (ADM=Amplitude Difference Measure, FDM=Feature Difference Measure, GDM=Global Difference Measure)

V. CONCLUSIONS

This preliminary work aims at analyzing the problem of the validation of numeric simulation models of electrical systems by means of experimental data. The chosen approach is pragmatic: verifying the consistency of the used experimental data and selecting performance indexes that weight correctly what a visual comparison identifies as the most relevant features of the simulated and experimental curves. A thorough literature search and analysis was performed and five performance indexes have been selected and tested on a real problem, the simulation of a section of the Italian High Speed Line, for which experimental results are available. The validation is performed by comparing pantograph impedance curves and the preliminary results are encouraging: not only the general accuracy of the model is good, but consistency between the various indexes has been found, as well as a general agreement between the preliminary evaluation of the experimental data used as reference data and the goodness of fit of simulated and experimental results. The latter indicates that the variability and uncertainty of the experimental data condition the goodness of fit and the assessable quality of the simulation results.

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