Monitoring Power Quality in Electric System for Transportation as basis for Probabilistic Analysis

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Abstract **- The paper deals with the possible implementation of probabilistic methods for defining the disturbance spectrum generated by electric traction unit sand by ac industrial supply network in different operating conditions.**

In the work, an experimental data set is used to analyze the disturbances present in the electric systems for transportation currently in use in Italy and in other European countries, based on static power conversion stations and dc supply feeders. The collected data constitute the basis for developments of a probabilistic analysis that can bring to the definition pf stochastic model for the future power quality studies in electric traction networks.

Keywords **– Electric traction, harmonic pollution, contact line, experimental survey, power quality, power electronic.**

I. Introduction

The main purpose of public transportation service is to ensure, in any operational situation, the safety and regularity of the service provided by rolling stocks. To this end, it is necessary that the harmonic disturbances generated by traction units conform to the compatibility limits with the signaling system set up for traffic control.

Electrified transport systems are complex ones; they continue to evolve, both during their design stage and during manufacturing, but also throughout their long period in service. Therefore, because of their complexity and technical developing, they are difficult to define, evaluate, or monitor in terms of reliability. The “continuity” aspects were traditionally divided from the “quality” ones, but recently, with the widespread use of electronic control devices, it is difficult to set a border between "continuity" and "quality" and this latter has become the main topic.

A system reliability decrease in terms of quality (i.e. distorted waveforms, voltage variations, frequency shifts, unbalances, electromagnetic disturbances) can cause damages as the lack of continuity of the supply or dangerous conditions. As an example the telecontrol devices are sensitive to electromagnetic phenomena, or the signaling relays could be susceptible of errors in presence of harmonic currents and voltages.

This paper aims to show a possible harmonic emission spectrum of an electrical conversion sub-station for electric traction (ESS) in the operating conditions of the transportation system.

Without impairing the general validity of the report, reference was made to the railway traction system in operation in Italy: a direct current power system supplied via overhead line with return via rails. The supply voltage has a harmonic spectrum that is influenced by the switching frequency of the switches present in the conversion system (50 Hz and its multiples) and by the presence of operating anomalies in the industrial network. In addition, harmonic components can be found associated with the train run on the system due to the drives present on board.

Going into more detail, an experimental investigation was made on the voltage and current waveforms, and therefore their harmonic pollution, depending on the type of operation in different hours for several days [1].

The collected data are a point of departure for characterizing the anomalies of the voltage waveshape present in the industrial distribution network that supplies the traction systems through a statistic model proposed in the paper [2].

At the end some interesting comments on the results obtained conclude this paper with some objective criticism on the limitations of the survey.

II. Description of the Traction System

To get the area of research and the problem it represents into perspective, it will be necessary to start with a brief description of the 3 kV dc traction system and especially of the characteristics of the harmonic emission.

A. Fixed Plant and Equipment

This research is the outcome of a technical co-operation with RFI S.p.A., the North Central Area of the Florence Infrastructure Department, who have kindly made available their instrument tests, measurements section and the railway installations, performing the measurement campaign under the university direction.

In particular, reference and quote are relevant to experimental data recorded during the measurements performed on the ESS of Empoli (in Tuscany - Italy) which

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supplies the railway line between Firenze and Pisa and a part of Pisa's railway junction.

In Italy, as it is showed in Fig. 1 the ESS' are directly supplied by a station of the industrial network, or by primary High Voltage (HV) lines (66 kV, 132 kV, 150 kV) [3].

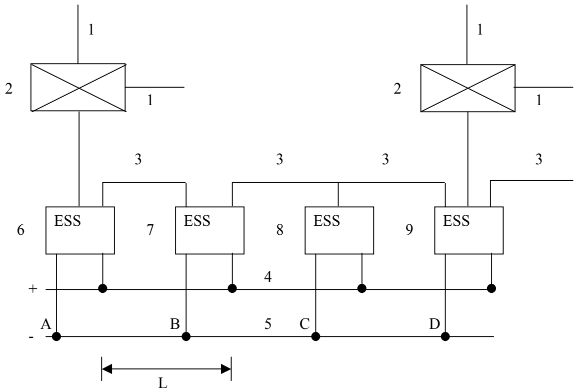

Fig. 1. Diagram of supply of a dc electric traction system. 1) HV ac lines. 2) Electric power substation of ac industrial network. 3) HV ac Primary lines of traction system. 4) Railway dc overhead lines. 5) Rails. 6-7-8-9) Substations of conversion. L) Distance among ESS'.

As regards the routes followed by the primary supply (three-phase lines) serving the Empoli's ESS of the RFI's system, these consist of a 132 kV HV line (about 5 km long).

With regards to the ac/dc conversion, there are two conversion units, each one consisting of two 132 kV / 2.75 kV transformers with load ratio-variators and a short circuit voltage equal to 7 % and a rated power of 5.75 MVA. The converters are so connected that they set up a twelve-pulse reaction, thus containing the ripple and therefore the harmonic frequency spectrum.

As regards the conversion systems, these consist of diode rectifiers; apart from these, in the secondary bus-bars of the transformers, there is a 100 kVA three-phase transformer for supplying the ac auxiliary services of the ESS.

This equipment has the following features [4]:

- 2 Graetz bridges, connected in parallel.
- Maximum rectified no-load voltage: 4 kV.
- Unit power: 5.4 MW.
- Voltage drop within the rated current: not exceeding 30 V.
- Internal short-circuit current:13 kA.
- Cooling: natural air.

Voltage drops and conversion from the ac system to dc system are not sufficient to inject into the contact line a perfectly direct current following the ripple present. To avoid disturbances to plant and equipment (in the form of noise as regards telephone lines adjacent to the contact line and, especially, due to incompatibility with the signaling circuits on the rail) and excessive heating of the traction motors, these harmonics are eliminated, or at least reduced by suitable LC passive filtering systems [4].

In this specific case, the filter used in the RFI's ESS examined here is made up as follows (Fig. 2):

Series inductor [5]:

- Rated value: 6 mH.
- Inductance variation: 0 – 20 %.
- Rated resistance at 20 °C (dc): 11 mΩ.
- Rated operating voltage (dc): 3.6 kV.
- Rated current (dc): 2.5 kA.
- Cooling: natural ventilation.
- Insulation class: F.

Parallel capacitor [6]:

- Rated value: 30 μF.
- Number of legs in parallel per filtering unit: 6.
- Number of filtering units in parallel: 3.
- Total filtering capacity: 3 x 120 μF.
- Rated operating voltage (dc): 6 kV.
- Rated current: 25 A.
- Cooling: natural ventilation.

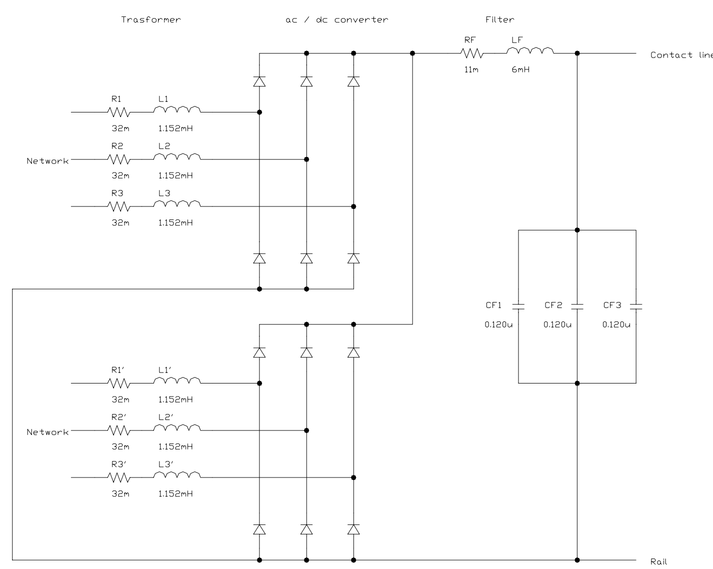

Fig. 2. Scheme of the ESS, considered for the data collection campaign.

B. *Rolling Stock*

The circuit configuration of equipment on board rolling stock is intrinsically linked with the type of supply [7].

In Italy there are several kinds of locomotives and traction units which operate on "Firenze – Pisa" railway . These ones can be listed as follows:

- Traditional or reostatic locomotives equipped with dc traction motors and system of resistors (dated on 1930 – 1960, for example FS E 646 or FS ALe 582).
- Electronic locomotives (1st generation) equipped with dc traction motor and chopper step-down

(dated on 1970 – 1985, for example FS E 633, FS E 632 and FS E 652). Direct or one stage configuration (see Fig. 3).

- Electronic locomotives (2nd generation) equipped with ac traction and inverters (dated on 1980 – 2002, for example FS ALe 426[1] or FS E 402). Indirect or two-stage configuration.

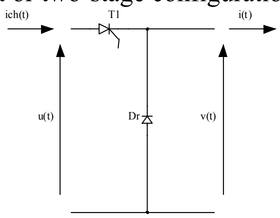

Fig. 3. Simplified diagram of an one-stage converter.

Indirect or two-stage configuration consists of two cascade converters: the input converter has a dc output that supplies an intermediate stage equipped with a filter. Downstream of this, there are the loads in general, or else those supplied by one or more choppers or inverters. This configuration is used both in setting up traction converters and for converters in the auxiliary service supply.

In the Italian railway system, the input converter is a chopper and the downstream one is an inverter (see Fig.4).

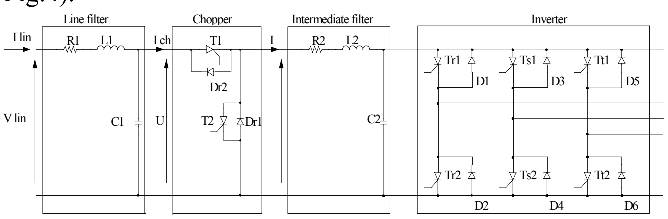

Fig. 4. Circuit diagram of a double-or two-stage converter.

III. Description of Experimental Survey

The purpose of the line measurements is to record the voltage and current harmonic spectrum on the dc side of a twelve-pulse ESS.

The line measurements consist in recording the voltage and current flowing from the dc side of a twelve-pulse ESS by means of experimental data acquisition.

The goal is to obtain a sample of data for validating a probabilistic model of the traction system in which the voltage at the contact line is set in a way that take into account the ESS operation and the trains interactions.

Voltages and currents have been recorded by means of an acquisition system with sample frequency of 10 kHz during 48 hours of operations of ESS. Each measurement set is 20 s long for a total recorded time of about 70,000 s.

The investigation on the harmonic analysis of the obtained data was limited in the frequency range between 0 Hz and 2 kHz for a good exploitation of the measurement instrumentation precision.

Thanks to the versatility of the data acquisition system it has been possible to make measurements in different operation of the ESS, at different levels of power delivered to traction line. This one can be identified by the level of the dc current of the line: high dc current value corresponds to heavy traffic on the line;low value of dc current close to zero corresponds to the “no load” condition of the ESS.

During the measurement process a reference level of dc current is established, then when the line current reaches this level, the acquisition data system starts to record the samples of dc voltage and of dc current for 20 s and so on. Reference levels for dc current can be decided by the operator.

IV. Results of Experimental Survey

The results obtained from the measurements above described permit to characterize the interaction between the Empoli’s ESS, other ESS supplying the traction line, and the trains present on line.

The following operating conditions are considered with reference to three different cases identified by three different values of the line current (See Fig. 5).

CASE A) – High level of the absorbed power by the traction loads. The reference value of dc current for data acquisition is set to 1500 A.

CASE B) – Medium level of the absorbed power by the traction loads. The reference value of dc current for data acquisition is set to 500 A.

CASE C) – Low level of the absorbed power by the traction loads. The reference value of dc current for data acquisition is set to < 500 A (in particular 200 A) and this case of the data acquisition is manual and not automatic as in the other cases.

Different windows of the data recorded are processed in order to evaluate the harmonic components of the traction line voltage. The amplitude of the windows is selected in 0.4 s, in this way it is possible to correctly use the Fast Fourier Transform [8], based on the sample frequency of the collected measurements.

The error on the measured harmonic components, according to the implemented instrumentation is 5 % of the measured value.

It is important to underline that the cases reported in the paper are a small picture of the total recorded data object of the survey. They are here reported as an interesting selection to show the level of the voltage harmonic pollution and to permit useful comments on the nature of the disturbances.

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[1] Treno ad Alta Frequentazione" so-called T.A.F. trains, in service on the Italian Railways, now operated by Trenitalia S.p.A.

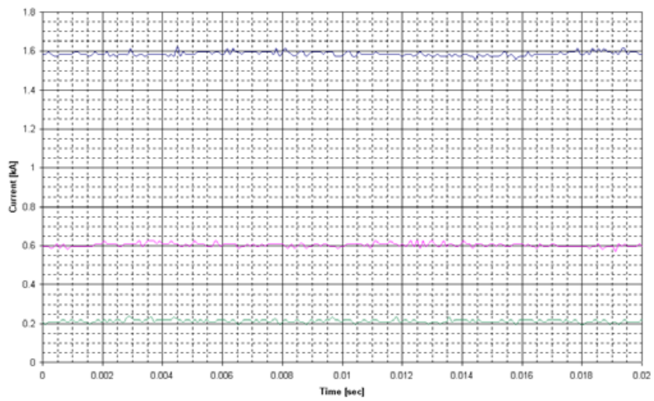

Fig. 5. Traction line current delivered by the Empoli's ESS with three different levels of the reference dc current. Case A: 1500 A – Case B: 500 A – Case C: 200 A.

Table 1 shows the results of the harmonic analysis [9] of the line voltage in the three cases of operation listed above. In the Table 1 only the components greater than 0.15 % of the rated dc voltage (3 kV) are reported. This because the acquisition system was not provided by signal filtering devices and harmonic components with amplitudes lower than that threshold are not worthy of consideration.

TABLE 1
HARMONIC ANALYSIS OF THE VOLTAGE IN THE 3 CASES OF OPERATION. THE AC COMPONENTS ARE EXPRESSED AS RMS VALUE

f [Hz]	LINE VOLTAGE Case A [V]	LINE VOLTAGE Case B [V]	LINE VOLTAGE Case C [V]
0	3820	3718	3879
25	-	0.4	-
50	8.2	8.3	17.1
65	-	0.4	-
70	1	-	-
75	0.82	0.37	0.7
100	0.6	0.6	0.4
150	4.7	4.7	3.2
300	1.5	1.0	1.0
600	-	-	0.4
1040	-	0.46	-

V. COMMENTS ON EXPERIMENTAL DATA

The results reported in Table 1 show frequency components of the line voltage concentrated at the low frequency values. In particular the component at the 50 Hz frequency of the ac main network that supplies the ESS, is the highest in term of amplitude.

The presence of these components are associated to asymmetrical distribution of currents during the switching periods of the switch branches in the converters.

The presence of the characteristic frequencies of the 12 pulse ac–dc converter (300 Hz and its multiple) are limited by the presence of the passive LC filters, described in Section II, on the dc side of the ESS. These filters are very effective also for frequencies over 300 Hz as testified by the limited values of these components reported in Table 1.

It is interesting to note the presence of voltage components at frequencies that do not have an immediate theoretical explanation these latter are due to different phenomena.

- Currents of signaling system which ensures the safety and the regularity of the flow of railway traffic.
- Physical phenomenon of electric arcs between pantography and overhead line. In this case the magnitude of harmonic disturbance depend on speed of train and on electric energy absorption when the separation happens.
- Physical phenomenon of beats[2] among converters on board of rolling stock.
- Physical phenomenon of beats between converter on board of a train and the ones of ESS.
- Physical phenomenon of beats among converters of different rolling stocks supplied by the same ESS.
- Induced disturbances by electric industrial network supplying the ESS's voltage.

VI. STATISTICAL MODEL

The next goal in the research project is the study of the performance of the traction power quality by means of a statistical model [10].

The resolution algorithm presents the following steps:

- STEP 1. Determination of the sample mean [11]of the voltage amplitude for each kth frequency, random variable A_k, which is present in the harmonic spectrum of the overhead line's voltage

  $$\overline{(A_k)_m} = \frac{1}{n} \cdot \sum_{i=1}^{n} A_{ik} \text{ ,}$$

  in which the index i represents the i-th observation of the voltage amplitude at the k-th frequency.
  The sample mean represents the best estimator of the expected value:

  $$\mu_k = E[A_k] = \int_{-\infty}^{+\infty} x \cdot f_{A_k}(x) dx \text{ ,}$$

  in which $f_{A_k}(\cdot)$ represent the probability density of the random variable.

- STEP 2. Determination of the "concentration" of observations around the expected value. The variance

[2] They may be defined as the composition, or rather interference, of the harmonics generated by individual converters when in operation: the result is a harmonic spectrum involving a multitude of frequencies.

(central moment of inertia of the probability masses) of the random variable A_k

$$VAR[A_k] = E\left[(A_k - E[A_k])^2\right],$$

is estimated by the unbiased sample variance:

$$S_{A_k}{}^2 = \frac{1}{n-1} \cdot \sum_{i=1}^{n} \left(A_{ik} - \overline{(A_k)_m}\right)^2 ,$$

- STEP 3. Determination of the covariance between the random variables A_k and A_h (harmonic voltage at the k^{th} and h^{th} frequency) defined as:

$$COV[A_k, A_h] = E[(A_k - E[A_k]) \cdot (A_h - E[A_h])].$$

The best unbiased estimator for the above quantity is:

$$S_{A_k A_h}{}^2 = \frac{1}{n-2} \cdot \sum_{j=1}^{n} \sum_{i=1}^{n} \left(A_{ik} - \overline{(A_k)_m}\right)\left(A_{jh} - \overline{(A_h)_m}\right).$$

It is thus possible to estimate the covariance matrix associated with the totality of the harmonic voltage observations recorded.

$$\Sigma = \begin{bmatrix} VAR[A_1] & & & COV[A_1, A_m] \\ & & COV[A_h, A_k] & \\ & COV[A_k, A_h] & VAR[A_j] & \\ COV[A_m, A_1] & & & VAR[A_m] \end{bmatrix}$$

The estimator for Σ is:

$$\overline{\Sigma} = \begin{bmatrix} S_{A_1}{}^2 & & & S_{A_1 A_m}{}^2 \\ & & S_{A_h A_k}^2 & \\ & S_{A_k A_h}{}^2 & S_{A_j}{}^2 & \\ S_{A_m A_1}{}^2 & & & S_{A_m}{}^2 \end{bmatrix}$$

It may be noted that this matrix can involve a considerable computing effort, given that from n observations and m voltage harmonics we have a covariance matrix whose dimension is m^2 and with $m + \frac{m^2 - m}{2}$ quantities to determine.

- STEP 4. Representation of the frequencies present in the emission spectrum of the ESS, amplitudes of the voltage harmonics recorded, and the number of observations associated in a hypothetical space – see Fig.6.

It is presumed that that the probability density function represented by the dc voltage emission spectrum in of the ESS, harmonic by harmonic, occurs according to normal distribution; in addition, it is assumed that the measuring program on the RFI S.p.A. installations may confirm the experimental data recorded in the course of research [2], that is that the associated Gaussian curve reaches its maximum near the value indicated for each harmonic, possibly in the absence of symmetry in respect of the expected of each distribution.

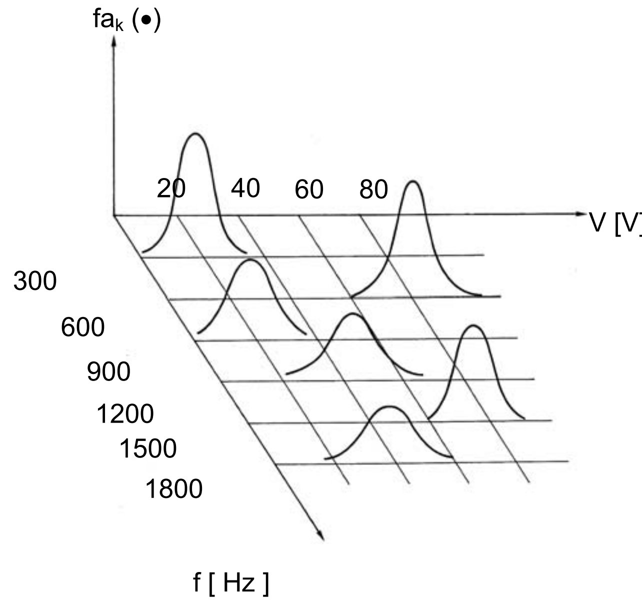

Fig.6. Diagram of the harmonic spectrum. The probability density of the corresponding voltage amplitude random variable is shown at each frequency.

- STEP 5. Should the statistical survey, starting with the experimental recordings, characterize normal probability distribution function for each voltage harmonic, use of the deterministic model for the rolling stock, a linear link between input (voltage of the contact line) and output (harmonic emission in terms of current) would make it possible to obtain a probabilistic representation of the analytical type of the disturbances generated.

If, on the other hand, it were not possible to have a Gaussian representation of the voltage harmonics on the overhead line and/or by adapting a more detailed analysis of the working of equipment on board trains, the problem would become non-linear, so that the statistical model would have to be implemented. From the latter it would be necessary to obtain series of numerical simulations (MONTECARLO method), being a sample from n observations of the m voltage harmonics recorded, in such a way as to define the most consistent emission spectrum profile.

Subsequently, it would be necessary to start on a new series of numerical simulations of the deterministic model, representing the rolling stock [7], in order to check on compliance with compatibility as between the traction systems and other equipment under various operating conditions, as previously done with the "real case" in Fig. 7 and reported on in the subsequent section.

Concerning to the accuracy of the probabilistic model, it is possible to underline the following comments.

While deterministic model determines the exact outcome with a math tolerance that depends on deterministic equation accuracy, the probabilistic one determines the probabilities of the possible outcomes. The solution of the equations in probability model brings to a set of average values and relevant standard deviations for the harmonic present in ESS' voltage.

The probability values and average ones for a random quantity can be found experimentally by computing the relevant frequencies and the sample means in a large number of outcomes of random experiments.

The accuracy of the probabilistic factors is associated to the correspondence of the probability density curves to the standard ones where the "average value" and the "deviation" are defined in mathematical way. The error related to this approximation of the probability density of the random variable $f_{A_k}(\cdot)$ are reported in [10].

VII. Conclusions

The spread of power electronics in the area of electric traction makes it necessary to determine instruments and establish methods for assessing the harmonic content of the currents absorbed by electronic converters, which are the cause of susceptibility to the disturbances to which signaling circuits and more generally, the electrical and non-electrical equipment present in the vicinity of the traction system, are prone.

The present paper is a part of a more general research project that is aiming at an accurate model of electric traction system, especially about fixed plants.

The final purpose is to realize a total model of the traction supply system able to describe the behavior of ESS in randomly operating conditions.

This paper has focused attention on the evaluation of harmonic pollution in the traction line voltage and current waveforms. Recourse was made to experimental research aimed at determining the dc voltage waveshape that may statistically occur on any railway line subjected to heavy traffic.

The future developments of this research will include the setting-up of a statistical model of the traction system. As has been shown, this aspect is of considerable importance, given that the regulations governing compliance with compatibility between the traction circuit and the signaling system have also tended to define stochastic values.

VIII. References

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IX. Biographies

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