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Developments of Power Quality Studies in Electric Transportation System

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Summary: **The paper deals with the update studies on Power Quality for electric traction systems. Probabilistic methods of analysis are presented both for the supply lines and the rolling stocks. Simulation software tools are created for disturbance propagation studies and examples of application are reported with reference to the Italian railway case.**

Key words:
power quality, electric transportation, traction converter, probabilistic methods

1. INTRODUCTION

In the general field of reliability analysis for transportation systems, the "continuity" aspects were traditionally divided from the "quality" ones. 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 in the technical literature on this field. A system decrease in terms of quality (i.e. distorted waveforms, rms voltage variations, frequency shifts, unbalances, electromagnetic disturbances) can cause damages as the lack of continuity of the supply or dangerous conditions. For this reason the harmonic founded quantities, even with small amplitudes, are significant because they can introduce disturbances into the plant and in the equipment devoted to the signal system that assure the safety of the traffic control.

The resultant problems are really complex, but it is possible to highlight the following:

1. right side failure: a way free from other trains is seen as occupied. This condition is not a risk for the security, but it is not tolerable during the project and operation phase;
2. wrong side failure: it is the opposite situation. A receipt relay referred to an occupied way is wrongly excited and this can cause an inopportune freeway signal. This is surely a more dangerous situation to avoid with an accurate project and operation control.

The standards regarding the possible harmonic emission in a traction system are not univocal, due to the different systems used in all Europe. Considering this situation, each transportation society has established its own standard, based on its conducted studies.

Regarding the harmonic components present in the rolling stock current, it is important to consider problems such as interferences with signalling system or the power leaks due to the current harmonics. Moreover, with the use and developing of frequency variable converters there are evident problems in using a strictly deterministic standard.

For this reason probabilistic studies have been developed, in order to adapt standards to real cases [1, 2].

2. PROBABILISTIC STUDIES: HARMONIC EMISSION'S STANDARD LIMITS

As above mentioned, the need of probabilistic studies, instead of deterministic ones, is always more evident, and standard's organisations are movining in this direction.

In Italy, for example, starting from a deterministic harmonic compatibility table (the train could not exceed the limit values dictated from that table) dated 1976, it has been passed to a more adequate solution for the new realty. In fact, the FS-ANIE 1996 harmonic compatibility table, reported in Figure 1, is now in use. This standard regulates the current harmonic presence and consequently the circulation of those trains that produce such problems, controlling the current amplitude as a function of the associated frequency.

In the table of Figure 1, the values are obtained under the hypothesis of the worst case, which is the contemporaneous

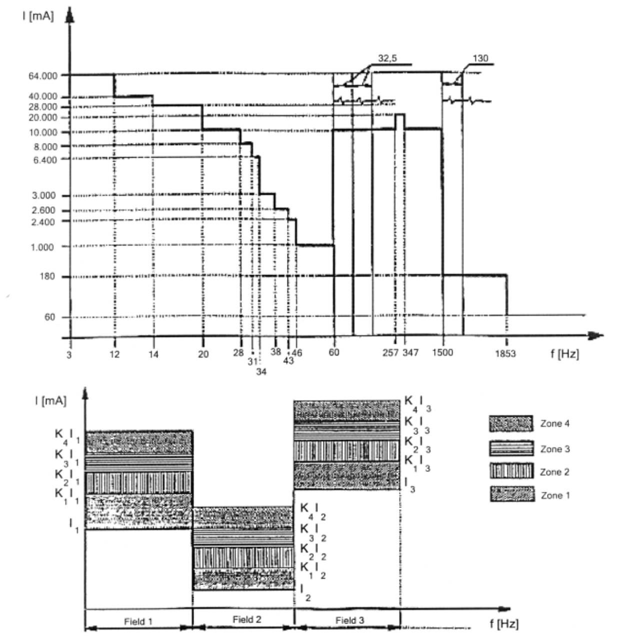

Fig. 1. 1996 FS-ANIE Table for harmonic compatibility levels in Italian traction plants

Table 1. Acceptation zones of Figure 1.

Zone	Gap [mA]	Probability
1	$I_n \cdot (k_1 - k_0)$	P_{1MAX} $(7.77x10^{-2})$
2	$I_n \cdot (k_2 - k_1)$	P_{2MAX} $(2.62x10^{-3})$
3	$I_n \cdot (k_3 - k_2)$	P_{3MAX} $(3.46x10^{-5})$
4	$I_n \cdot (k_4 - k_3)$	P_{4MAX} $(7.96x10^{-11})$

Table 2. Coefficient values.

K_0	1
K_1	1,5
K_2	1,75
K_3	2,5
K_4	3,5

presence of four trains. The acceptable value for each train is then the fourth part of the value given in the table.

What is new in this standard is that it comes from a probabilistic study. That means there are not fixed limits, while the values indicate the possible probability to exceed the limits imposed by the current amplitude at different frequencies. This new approach gives a less restrictive selection of the admitted trains, without impairing the security and efficiency of the system.

From the Figure 1 it is possible to note that the Table presents some frequency gaps, called fields, and for each of them it has been fixed a current limit I_i. In each field there are four amplitude areas, called zones, limited from a current value I_n and two different coefficients k_j and k_{j-1}. To the zone j, with an amplitude of $I_n \cdot (k_j - k_{j-1})$, corresponds a maximum probability of P_{jMAX} following Table 1 indication.

In Table 2 the coefficient's values are reported.

Considering I_n, representing ¼ of the nominal value given in Fig 1, only a train that exceeds at maximum P_{1MAX} is admitted to circulate in zone 1, P_{2MAX} in zone 2 and so on. It's never possible to exceed the zone 4 limit.

3. SYSTEM DESCRIPTION

Considering the important role of probabilistic studies, a research project has been developed in order to investigate probabilistic methods able to analyze the harmonic disturbances on a railroad plant. This is a wide research involving the whole traction system, starting from the interaction with the industrial supply system, the rolling stock design and the circuit's reclosures by rails (Fig. 2).

Each part of this system can be seen at first as a stand alone sub-system. Once each system is well studied, it's possible to find out the final model able to represent the interaction between all of these sub-systems. Without impairing the general validity of the study, it has been taken as reference the railway traction system in operation in Italy: a direct current supplied system via overhead line with return via rails [3].

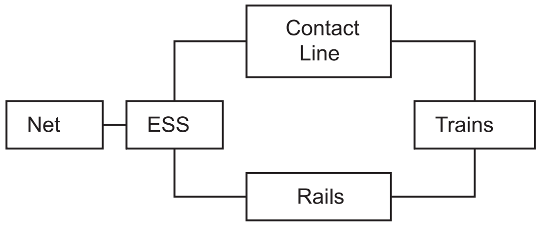

Fig. 2. Block diagram of the whole system for electric interaction

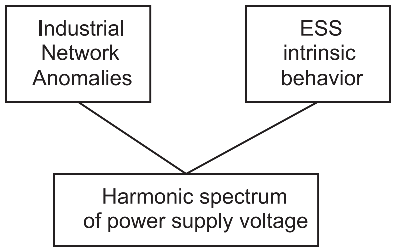

Fig. 3. Block diagram of the fixed plant

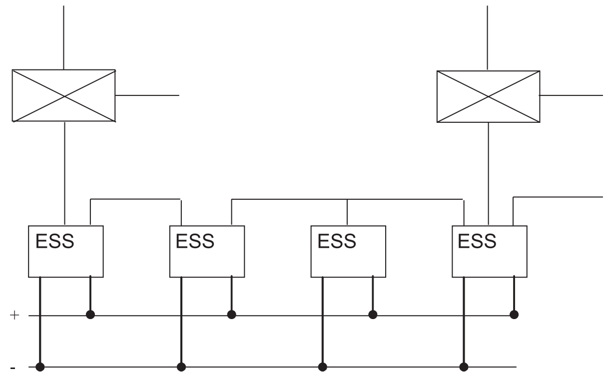

Fig. 4. Traction supply system

3.1. Fixed plants

The fixed plant can be represented by a block diagram as in Figure 3.

The industrial network anomalies are obtained by experimental measurements. Regarding the ESS intrinsic behaviour, it's necessary to consider the switching frequency of the conversion system.

The emission spectrum of the electrical substation (ESS) comes from the interaction between both ESS and industrial network probability density of events, evaluating harmonics by harmonics [4]. This spectrum can be influenced by the passive parameters, such as the resistance R and the inductance L of rails and the contact line, by the harmonic emission of rolling stock and by the presence of the passive LC filters on the dc side of the ESS.

The traction supply system is reported in Figure 4.

Three-phase primary lines supply through power conversion substations the traction circuit (contact line and rails).

In the ESS the high ac voltage is transformed in dc (3 kV) necessary to supply the contact line. Each converter unit has modular structure, standardized with a nominal power of 3.6 or 5.4 MW.

3.2. Rolling stocks

The fixed plant has to interact with devices on board of trains. Their simplified representation is reported in Figure 5.

A wide literature is available on electric drives and their impact on Power Quality [5, 6], while few investigation are made on the auxiliary services that nowadays constitute an important load, considering the development of the train conforts expecially in high speed applications.

In this section, the train auxiliary circuit system are studied, in order to determine not only the parameters characterizing the input filter, modeled by a LC circuit, but also the harmonic components injected in line and on board of the train. Harmonics caused by the converters supplying the auxiliary services [7].

Even in this case a statistical analysis is performed for evaluating the contribution of each device to the whole system.

In a modern train, the auxiliary services are supplied by the circuit described in Figure 6. There are two chopper devices, the main one for the auxiliary service's supply voltage stabilization, and the second one dedicated to the dc user's supply and an inverter for the ac user's supply. In addition, there are three filters, each one characterized by the three electric parameters inductance, capacitance and resistance; in particular this last one represents all the parasite resistances of the filter and of the electric connections between the components.

In order to solve the circuit and to calculate the current absorbed by the train, some semplifications are done:

— the converters and relative loads are substituted by parallel current ideal generators. They represent the Fourier series components of the total absorbed current from each converter. Passing to the fasorial domain, the same circuit has to be considered for each considered frequency (Fig. 7).
  Varying the frequency, there are different generator's current and voltage values, but also different values of reactances;
— the main chopper is simulated introducing two equivalent electric circuits. The first one (Fig. 8), they ideal voltage generator, representing the voltage at chopper secondary terminals. The second one (Fig. 9) with an ideal current generator representing the current absorbed by the main chopper at the primary terminals.

4. SYSTEM STUDIES

4.1. Fixed plants

The study is applied to a real case of a dc traction railway in operation in Italy, based on static power conversion stations (ESS) and dc supply feeders. In these traction systems the train supply voltage has harmonic spectrum characterized by the switching pulse of the rectifier bridges, by possible

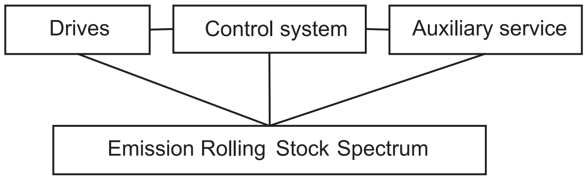

Fig. 5. Block diagram of the train devices

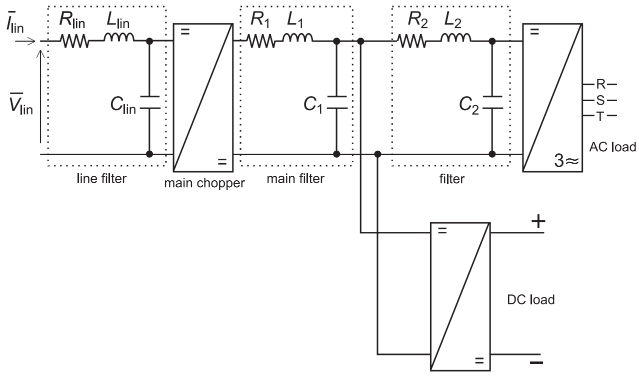

Fig. 6. Auxiliary services supply system

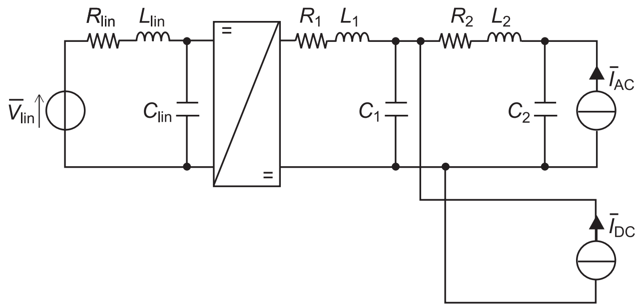

Fig. 7. Modified circuit in the fasorial domain

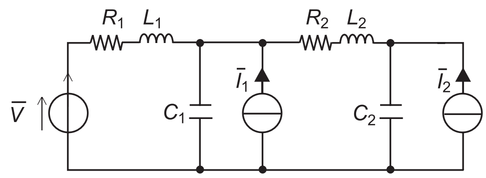

Fig. 8. Branch downstream of the main chopper

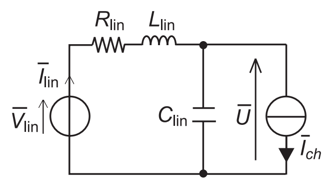

Fig. 9. Branch upstream of the main chopper

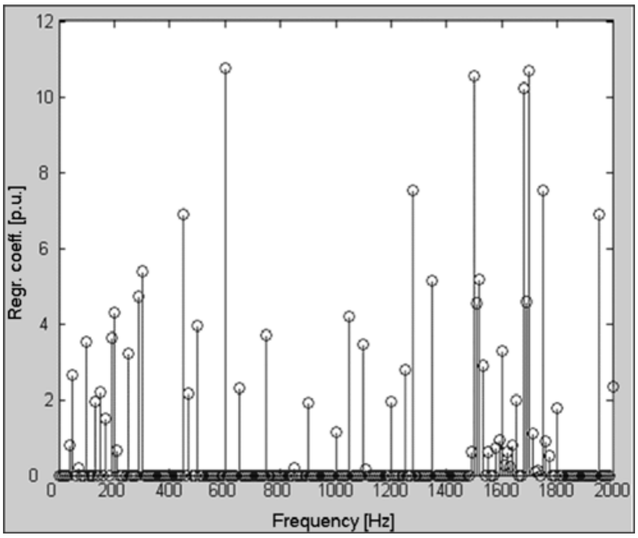

Fig. 10. Regression coefficient of line voltage harmonic components as result of the statistical model in the no-load condition

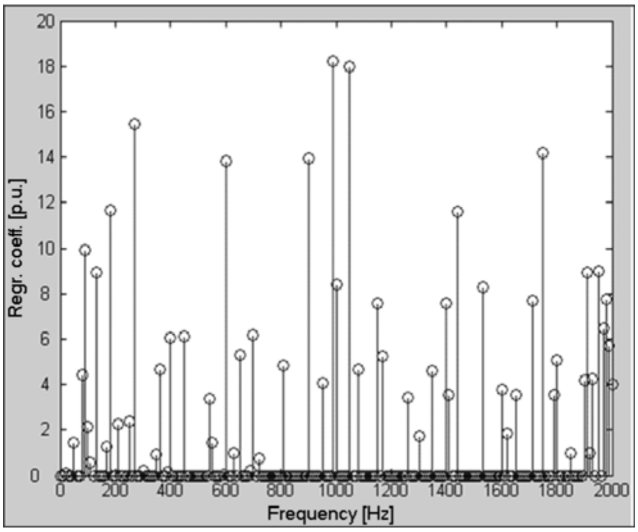

Fig. 11. Regression coefficient of line voltage harmonic components as result of the statistical model in the case of load current conditions

disturbances that affect the ac supply network and by the interaction between the converters on board devoted to supply traction motors and auxiliary services on the trains.

In particular, experimental data recorded by RFI SpA during measurements made on the ESS of Empoli (in Tuscany - Italy) which supplies the railway line called "Florence – Pisa" and a part of Pisa's railway junction, have been used [8].

These measurements constitute the point of departure for characterizing the anomalies of the voltage wave shape present in the traction feeders: further experimental data have been acquired to provide an adequate number of samples for purposes of characterizing and validating the proposed statistical model. For a clear performance description of the supply system, measurements in two operating conditions have been investigated: one with load current absorption (rolling stock passing through) and the other with no current absorption (no-load condition). With the first series of recordings it is possible to assess the line harmonic disturbances caused by the whole traction system (industrial network, ac/dc conversion power unit and rolling stocks); while, with the second series of data, it is possible to determine the interaction between the considered ESS and the next ones and the harmonic pollution due to disturbances present in the industrial power supply network.

Once the experimental data have been acquired, the implementation of the statistical model follows, thanks to a software program [9] that determines the regression linear indexes by a statistical model permitting to define the harmonic disturbance components in any general operating condition. The statistical model is set and compared with measurements performed on a real railroad plant. In case of low value of dc current, corresponding to the "no load" condition, reported in Figure 10, the supply voltage spectrum is affected from the twelve-pulse reaction of the ESS converters and from the voltage harmonic pollution in the main network that supplies the ESS. As the converters are 5.4 MW twelve-pulse rectifiers, the harmonic components of the voltage on dc side have frequencies equal to $f = 12 \times k \times 50$ Hz (with $k = 1, 2, 3\ldots$). For this reason it is justifiable the presence of a harmonic component at 600 Hz in the harmonic spectrum of the voltage on dc side. For the asymmetrical distribution of currents during the switching periods of the switch branches in the converters, interharmonics can also appear, for example components concentrated at the 100 Hz, 300 Hz, and 600 Hz frequency values.

In the case of high dc line current value, corresponding to heavy traffic on the line, reported in Figure 11, it is possible to note that there are always the frequency components of 100 Hz, 300 Hz and 600 Hz, but in addition there are also components at frequencies lower than 200 Hz.

These latter are related to the physical phenomenon of beats among the generated frequencies associated to the converters on board of rolling stock or between the converters on board of a train and the ones of ESS or among converters of different rolling stocks supplied by the same ESS. Components at frequencies that do not have an immediate theoretical explanation are due to these phenomena and it is also possible to find system resonance at electronic control device operation frequencies different from those at which suitable LC passive filtering systems are tuned. It is also possible to find out a considerable disturbance component around the frequency of 130 Hz. This is justified considering that in the line taken for the measurement campaign, trains with chopper drive are present and the chopper switching frequency is 132 Hz, during the regular operation.

4.1. Rolling stocks

A program has been realized in order to simulate the double stage converter behaviour and find out both the harmonic analysis of the line current and the input impedance. The harmonic analysis is important to size the filters present in the system and for limiting excessive harmonic disturbances. The input impedance valuation has a theoretical importance, because it is possible to compare it with the equivalent one of the traction circuit. The program created is in Matlab environment [10] and uses the matrix calculation approach.

The system considered in this study deals only with the supply circuit for the train auxiliary service and after its analysis it is possible to conclude the following:

— for single stage converter, it's enough to analyse the converter's output voltage in order to find the harmonic currents. Knowing the output voltage and the load's equivalent circuit, it's possible to have the load's current and then the current absorbed by the converter;
— in the double stage configuration for the traction circuit, there is the phenomenon of beats between different frequencies. For this reason there are components that are not predictable;
— in the double stage configuration for the auxiliary circuit, if users supplied in different electrical ways are presented, it's necessary to consider more coupled converters and then the beat's calculation is more complex than in the traction case.

An important result is found about beat's phenomena, considering the total current absorbed by the main chopper. This current is the sum of two contributes. One representats the isofrequencial component, it is the sum of the currents at a fixed frequency. The other represents the beats, it has a summatory with index evaluable through a combination of converter's frequencies. Considering this, the program has been created in order to evaluate the frequencies generated by the beat's phenomena, building a spectrum of investigation frequencies. Inside this spectrum, the line current is calculated as Fourier sum of the different harmonics at the considered frequency. It was possible to note that the line current feels the distortion caused by the harmonic contribution of the beat's components. Knowing these components, thanks to the created software, it's important to limit their amplitude setting filter's parameters in order to respect the field standards.

This program has been applied to a real case, the train TAF (Train mainly devoted in Italy to urban and sub-urban transportation service with high number of passengers per way), in different configurations:
— TAF engine – winter period;
— TAF engine – summer period;
— TAF trailer – winter period;
— TAF trailer – summer period.

With reference to the first case, Figure 12 reports the current absorbed by the c.c. auxiliary users, while Figure 13 reports the one absorbed by the a.c. users.

In Figure 14 the supply line dc voltage is represented, while Figure 15 shows the obtained line current.

The ac components of the line current are reported in Figure 16 and they represents the harmonic disturbance generated on board.

The harmonic components of the line current, thanks to a good filtering, do not achieve significant values respect to the dc values, both for the engine and trailer. This is true also for the different environment conditions (winter or summer).

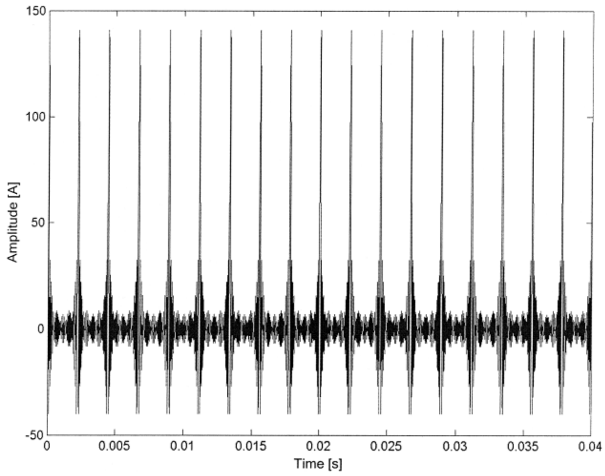

Fig. 12. Current absorbed by the dc auxiliary users

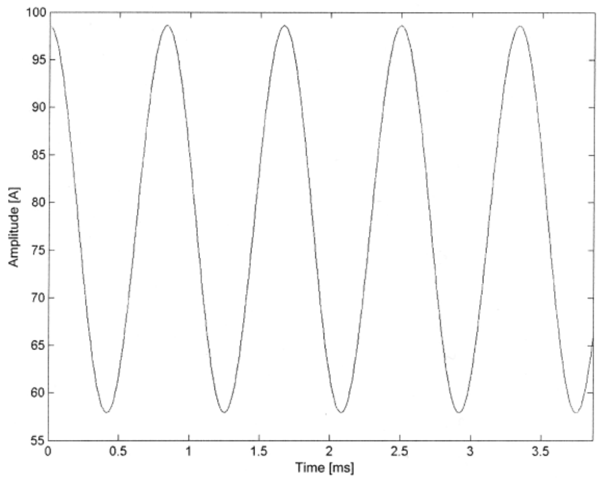

Fig. 13. Current absorbed by the ac auxiliary users

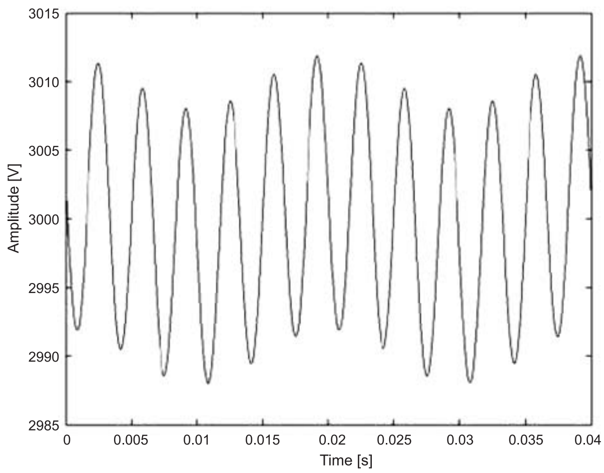

Fig. 14. Supply line voltage in the application case

5. CONCLUSIONS

The paper presents the trend of nowadays studies on electric power quality for transportation systems. The deterministic approach is overpassed by probabilistic studies and also the standards in many countries are moving in this way.

Considering the complexity of the traction systems, a probabilistic analysis of the disturbances is made along the paper both for fixed supply plants and rolling stocks. Reference is made to the Italian case where trains are supplied at 3 kV dc voltage through ac/dc conversion substations. Starting from

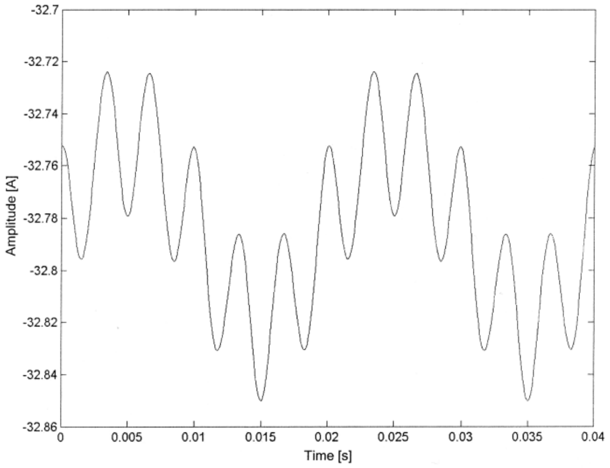

Fig. 15. Line current in the appliacation case

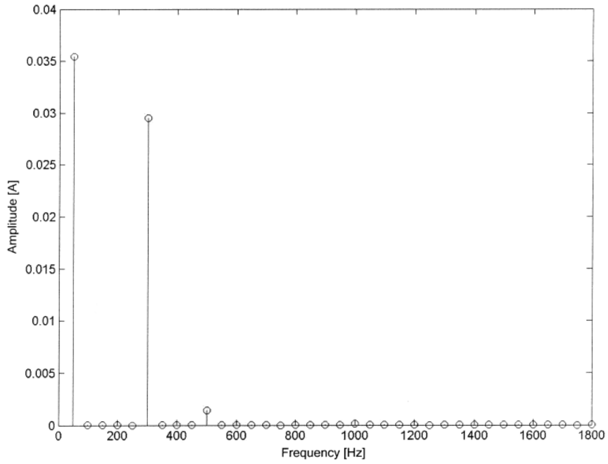

Fig. 16. Harmonic components of the line current

some modelling representations, the study highlights the disturbances present in the line current and voltage, giving a reference in the adopted stochastic methodology of investigation. This latter permits to simulate Power Quality phenomena in a way close to the real cases, without the influence of rapid traction load changes due to the traffic events. Examples of case studied are reported in the paper as application of probabilistic models developed by means of software programs created in Matlab environment.

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