Harmonic Current Reduction in Railway Systems

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Abstract: - This paper deals with the problem of harmonic mitigation solutions in a Romanian traction substation which supplies a railway electric transportation line. The power line measurements were made using an ABB Power+ recorder and analyzer during a whole day. The quantities recorded have been the frequency, the total rms values of the voltage and current, the current and voltage harmonic distortion factors and the first fifteen current and voltage harmonics. The analysis of data shows that the harmonic distortion factor of the voltage is always less than IEEE 519 recommended limit thanks of high power of the transformer comparatively with the power of the load. In order to keep the current distortion within allowed limits, the proposed filter installation must lead to a significant diminution of 3rd and 5th harmonics and a less significant diminution of the superior order harmonics. In this concrete application, the proposed solution for harmonics mitigation is based on passive power filtering. The simulations carried out under Matlab Simulink environment show that the installation of two single tuned filters for third and fifth harmonics plus a high-pass filter for higher order harmonics would reduce harmonics levels and harmonic distortion factor to within acceptable limits even in the most unfavourable situations.

Key-Words: - Railway systems, Harmonics, Harmonic distortion factor, Power quality, Passive power filters

1 Introduction

Proliferation of power electronics loads, such as diode-based rectifier groups supplying DC electric traction motors, produces harmonics distortion as well as many other troubles in the electrical power system. Therefore, the analysis of power quality on a rail system is essential to assess the effects on the adjacent distribution network.

The current harmonics and power quality aspects are very complicated because of the frequent and strong transient regimes. Consequently, some standards and recommendations have been established in order to avoid the potential problems caused by railway harmonics. The most used standard for harmonic pollution limits is IEEE 519-1992.

In addition to its recommendations, there are specific railway standards, such as EN 50238/2003, some general EMC standards that may be applied to railway systems, such as EN 50121 or EN 62236 which are compatible with general EMC standards EN 61000, and in addition, each railway company has developed its own standards [1], [2], [3]. Even proper estimating methods for traction load harmonic have been proposed [4].

Many papers look at improving techniques to assess the power quality of a railway system. Modelling techniques used to simulate electrified railways are adapted to simulate power quality aspects with improved computational efficiency. Efficiency and performance are key factors in railway systems [5] - [8].

Different methods based on either active or passive filtering can be used to reduce the harmonic distortion of the pantograph current of electric traction vehicles [9] - [12].

Active filters have become an attractive harmonics mitigation solution in recent years. Modern active filters are superior in filtering performance, smaller in physical size, and more flexible in application, compared to traditional passive filters [11], [13], [14]. However, even nowadays, the costs involved are quite high, especially at high voltage operation.

Passive filters have always been considered as a good solution to solve harmonic current problems [10]. By using the hybrid topologies, the filtering performances can be significantly improved [15].

Papers dealing with compensation performance have focused their analysis on the design criteria used in the power filters [9], [10]. The class 120 locomotives of the German railways employ a tuned harmonic filter, which is inserted between the pantograph and the high-voltage winding of the input transformer [11].

The objectives of performing survey of harmonic pollution are to identify the voltage and current harmonic distortion levels based on experimental measurements and to provide a concrete mitigation solution.

2 Electrical Supply System

In Romania, the electric power generated by power stations is carried to electric railway substations by 110kV three-phase transmission lines.

The electrical supply system of a railway line provides electric power of the desired characteristics (AC, single phase, 25 kV) to the trains from the high-voltage network by single phase 110kV/25kV transformers. Figure 1 displays the configuration of the system. Each transformer is connected to two phases of the three-phase system. Each section of the line (about 50km of length) is independently fed by a traction substation. Therefore, along of about 150km, the main feeding line is balanced.

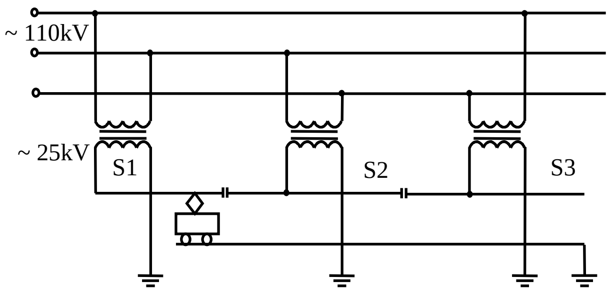

Fig.1 Electrical supply system of the railway line

In the Romanian railway network, there are two types of electric railway locomotives of different powers (5100 kW and 3500 kW). Each railway locomotive is driven by six or four DC electric motors supplied by diode-based rectifier groups (one group for each traction motor).

3 Analyzing Harmonics

The power line measurements were made using an ABB Power+ recorder and analyzer until one day into the 110kV/25kV Cernele transformer station.

The quantities recorded have been frequency, voltage, current, current harmonic distortion factor (*HDI*), voltage harmonic distortion factor (*HDU*) and the first 15 current and voltage harmonics. The step delay time is of about 1 min.

Only a few critical situations are presented in our paper, respectively:
1. Maximum recorded values;
2. The most unfavourable situations relating to *HDI*;
3. The most unfavourable situations from individual harmonics point of view.

The harmonic distortion factor (*HD*) is calculated as the square root of the sum of the squares of the root-mean-square (rms) values of non fundamental harmonics (X_k, k≠1), divided by the rms value of the fundamental (X_1)

$$HD = \frac{\sqrt{\sum_{k=2}^{15} X_k^2}}{X_1}, \qquad (1)$$

where X can be the voltage or the current.

3.1 Supply Voltage Analysis

As the voltage waveform is permanently preserved almost sinusoidal (Fig.2), the harmonic distortion factor of the voltage is less than 5% IEEE 519 recommended limit.

From the recorded data, in the most unfavourable case, the highest value of *HDU* (2%) was generated by the 5th voltage harmonic at the level of 1.66 % of first harmonic (Fig.2).

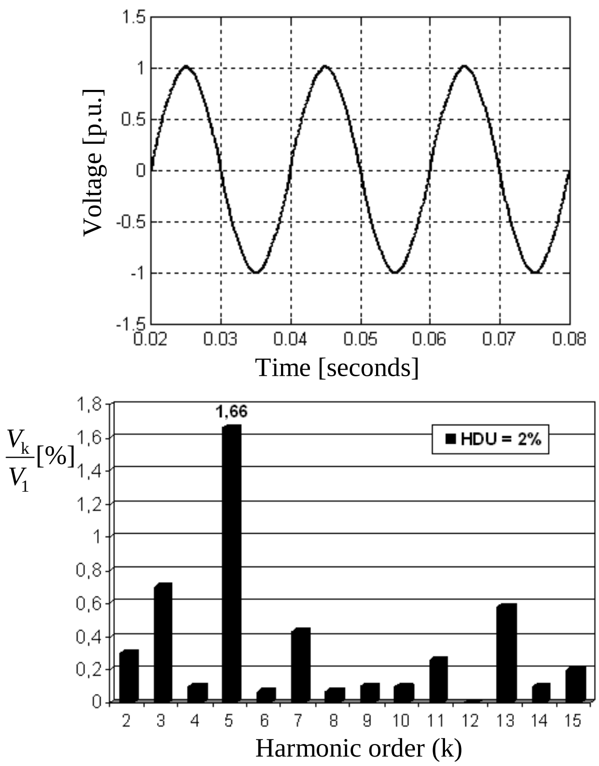

Fig.2 Voltage waveform and its harmonics spectrum

Table 1 shows the IEEE 519-1992 recommended voltage distortion limits.

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Harmonic Distortion (%)
69 kV and bellow	3.0	5.0
69001 V through 161 kV	1.5	2.5
161001 V and above	1.0	1.5

Table 1 Voltage distortion limits according to IEEE 519-1992 Standard

The low value of *HDU* even under strongly distorted current waveform can be explained by the high power of the transformer comparatively with the power of the load.

3.2 Harmonic Distortion of the Current

A self-evident graphic illustration of the pronounced distortion of the current is shown in Fig.3 by the evolution of the harmonic distortion factor of the current during the analysed day.

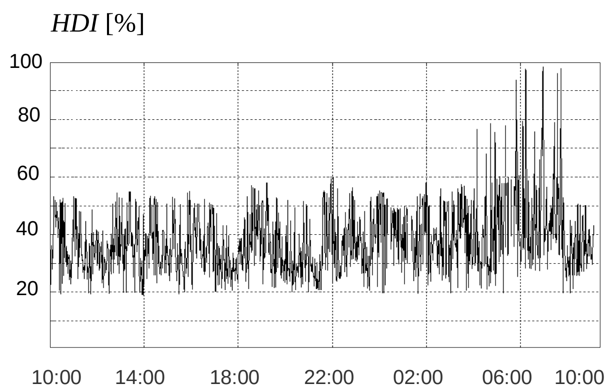

Fig.3. Recorded values of HDI during a day

As it can be seen, the recorded values of *HDI* can be placed into three zones.

The first one corresponds of the high accidental values (80% - 100%) and its energetic influence can be considered insignificant because the recorded values in close vicinity are much lower. These values can be associated with alteration of the contact resistance of the pantograph.

In the second zone, the *HDI* values are between 60% and 80% and they are associated with a high traffic density.

The most recorded values of *HDI* are into the interval from 20% to 40%.

The recorded values of the individual harmonics and the harmonic distortion factor are compared with the IEEE 519-1992 limits for I_{sc}/I_L (the short circuit ratio of the system) equal to 105 (Table 2).

Maximum Harmonics Current Distortion in Percentage of I_L					
Individual Harmonics Order (Odd Harmonics)					
I_{sc}/I_L	<11	$11\leq k<17$	$17\leq k<23$	$23\leq k<35$	*HDI*
<20	4.0	2.0	1.5	0.6	5.0
20<50	7.0	3.5	2.5	1.0	8.0
50<100	10.0	4.5	4.0	1.5	12.0
100<1000	12.0	5.5	5.0	2.0	15.0
>1000	15.0	7.0	6.0	2.5	20.0

Table 2 Current distortion limits for general distribution systems (120 V through 69000 V)

The next figures in this section show several sample power quality phenomena that were generated by the railway system. These include harmonic distortions comprising of 3rd, 5th, 7th, 11th, 13th and 15th harmonic components.

As it can be seen, recorded data make evident the high degree of distortion of the current waveforms and prove the opportunity of power quality analysis.

Table 3 shows the most unfavourable situation relating to *HDI*, but this occurred only three times during the analyzed day.

HDI %	*I*3 %	*I*5 %	*I*7 %	*I*9 %	*I*11 %	*I*13 %
98	88	33.1	17.8	4.8	17.3	14.8

Table 3 Maximum recorded *HDI* and individual rms of significant harmonics as a percentage of the fundamental component

This very high value (98%) is brought about by the significant contribution of the 3rd and 5th harmonics. The former goes beyond the fundamental harmonic (it is 88%) and the latter significantly exceeds the limit of 12% recommended by IEEE 519-1992 standard. Obviously, the current waveform is very strongly distorted in such an accidental situation (Fig.4).

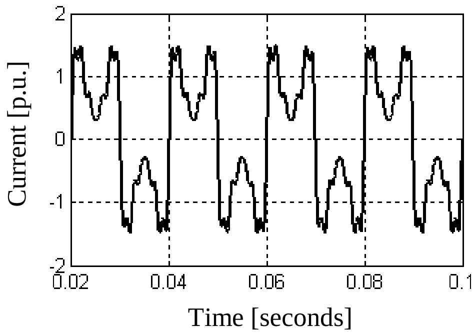

Fig.4 Current waveform for one of the highest accidental values of *HDI* (98%)

The harmonic distortion factor reached many times values over 80% but each of them has been recorded only once and the adjacent recorded values are much lower (Fig. 3). Hence, these situations are not relevant in finding harmonics mitigation solutions.

One of the highest *HDI* values which occurred at least five times a day is 78% (Fig.5). The harmonics spectrum reveals that all the individual odd harmonics are above IEEE 519 limits. The third harmonic has the highest value of about 67%. The significant distortion is emphasized by the current waveform.

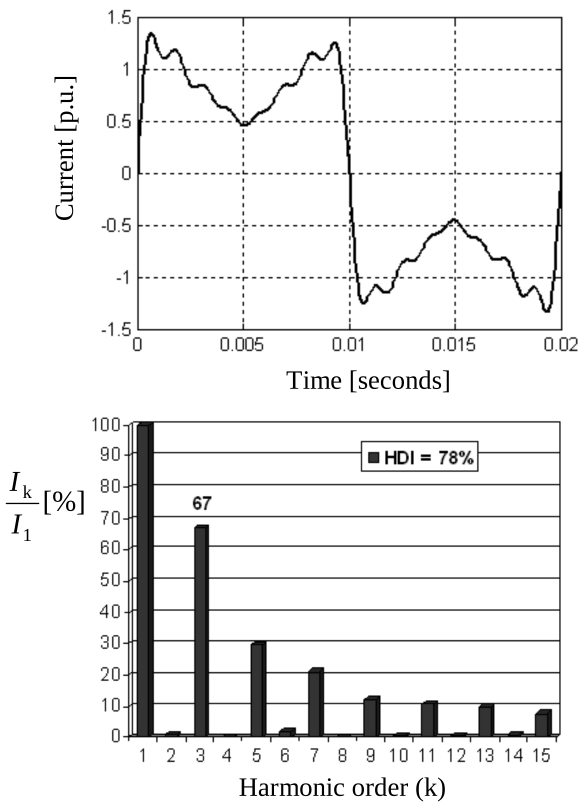

Fig.5 Current waveform and its harmonics spectrum for one of the most unfavorable situations relating to *HDI*

Further, below in this section some unfavourable situations from the individual harmonics point of view are presented.

In Figure 6, the maximum 5th harmonic of about 32.7% and the maximum 7th harmonic of about 29.3% were taken into consideration. These very high values as well as the important weight of the 3rd harmonic lead to a harmonic distortion factor which exceeds the allowed limit by over 240%.

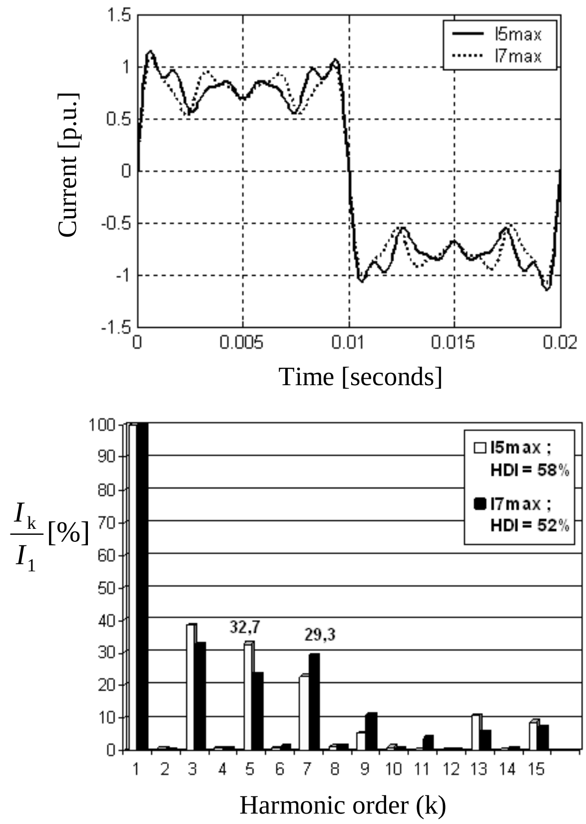

Fig.6 Current waveforms and harmonics spectra for some of the most unfavorable situations from the 5th and 7th harmonics point of view

In the case of maximal recorded values of the 11th and 13th harmonics, the associated limits of the IEEE 519 standard are exceeded by about 270% (Fig.7). The values of *HDI* are much over the standard limit (41% and 42.5% versus 15%).

In spite of these very important values, the only consideration of each of them in the harmonic distortion is not edifying because there are simultaneously significant values of other harmonics. As an example, when the 5th harmonic is maximal, the third and the 7th harmonics are close to it and they have an important weight (Fig.6). Moreover, when the 7th harmonic reaches its maximal value, the third harmonic exceeds it by about 15% and the fifth harmonics is bellow it with only about 20% (Fig.6). Besides, simultaneous significant values of low and high-order harmonics (e.g. 3rd, 5th and 11th or 3rd, 5th and 13th) lead to a high harmonic distortion factor such as 42.5% (Fig.7).

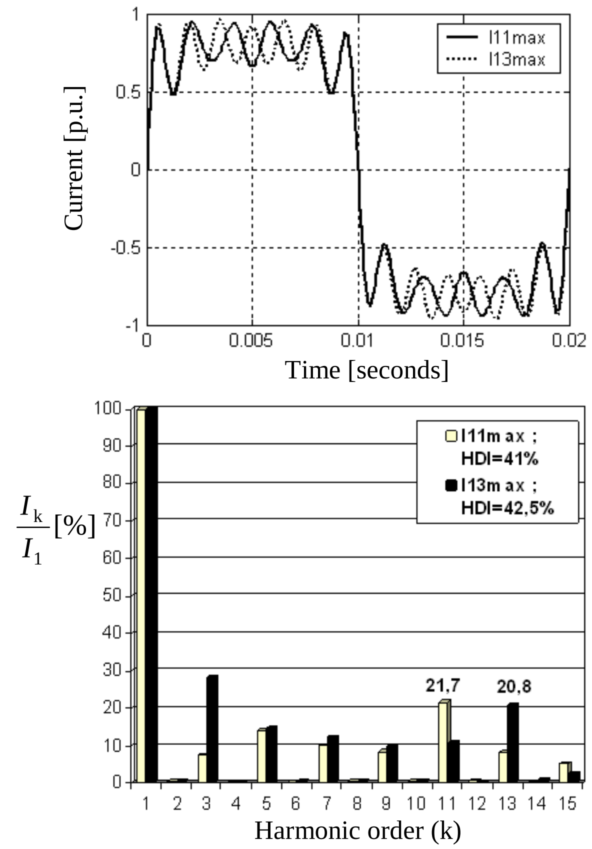

Fig.7 Current waveforms and harmonics spectra for some of the most unfavorable situations from the 11th and 13th harmonic point of view

The previously individual analyzed situations occurred many times during monitored day but they represent only a few situations comparing with others and they give information on the transient regime effects.

Therefore, the general power quality implications can be pointed out by the average values of the current harmonics in the whole monitored day.

If Δt is the time interval between two consecutive recordings and I_j and I_{j+1} are the values recorded at the beginning and at the end of the sample interval, the recorded current can be considered to remain constant at the arithmetic average value,

$$I_{\text{av}\, j} = \frac{I_j + I_{j+1}}{2}, \tag{2}$$

Consequently, the average value for the time interval under consideration $t = N \cdot \Delta t$, where N is the number of Δt samples, is

$$I_{\text{av}} = \frac{\frac{I_1}{2} + \frac{I_{N+1}}{2} + \sum_{j=2}^{N} I_j}{N}. \tag{3}$$

So, the obtained average values of the significant current harmonics during the analysed day are included in Table 4. Then, the current waveform can be reconstituted relying on them (Fig.8).

*I*3 %	*I*5 %	*I*7 %	*I*9 %	*I*11 %	*I*13 %	*I*15 %
27.6	15.2	13.2	3.8	8.3	7.0	3.5

Table 4 Average values of the significant current harmonics recorded during one day

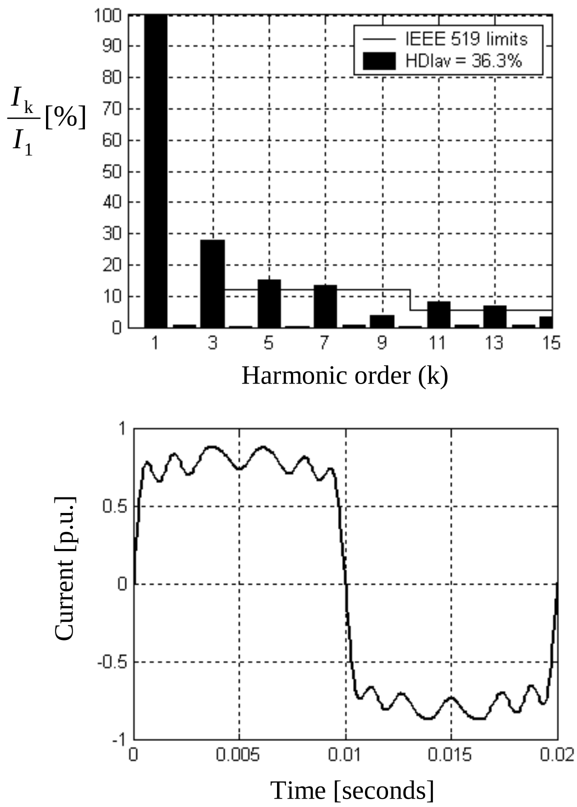

Fig.8 Average harmonics spectrum and the corresponding current waveform profile

As it can be seen in Figure 8, the harmonic distortion factor limit is substantially exceeded (36.3% versus 15%) but it is much inferior of that it was in the previously presented situations.

The highest harmonic level in the harmonic spectrum is about 27.6% (the third harmonic) and it is followed by the values of about 15.3% and 13.2%, which correspond to the 5th and 7th harmonics. All these three levels are above the limit of 12%. Even the 11th and 13th harmonics exceed the recommended limit of 5.5% with about 50% and 27% respectively.

Therefore, electrified railway is one of main harmonic sources in utility and it is necessary to restrict harmonics below recommended limits.

4 Passive filtering solutions

The previous harmonic analysis points out that, in order to keep the current distortion within allowed limits, the proposed filter installation for the analyzed traction load must lead to a significant diminution of 3rd and 5th harmonics and a less significant diminution of the superior order harmonics. As a result, it is expected that the harmonic distortion factor reach the recommended limit of standards.

It is well known that the balanced third harmonic from distribution system do not reach the transmission system because of three phase transformers with delta windings. However, in the case of railway system, which is a single phase load connected phase to phase, it results an unbalanced third harmonic current flowing in the transmission system.

In this concrete application, the proposed solution for harmonics mitigation is based on passive power filtering.

The passive filters consisting of capacitors and inductors are connected in parallel with nonlinear load to provide low-impedance paths for specific harmonic frequencies, thus resulting in absorbing the dominant harmonic currents flowing out of the load.

A given L and a given C have equal absolute reactances at a well-defined frequency, the so-called resonant frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \tag{4}$$

For each frequency there is an infinite multitude of LC pairs with the same resonance frequency but entirely different characteristics within the rest of the frequency range: Big L and small C always provides the higher filtering quality which is to say the impedance rises more steeply on either side, above and below the resonance frequency.

It is usual to set the resonant frequency of the LC circuit at a non-harmonic frequency because compensators may easily be overloaded.

The rating of the reactors is normally given as a percentage of the rated reactive power of the capacitors at 50 Hz. For example, a 5% de-tuning rate means that 1/20 of the voltage drops across L and 21/20 drop across C, subtracting to 100% overall. At 20 times the frequency, say 1000 Hz, the ratio would be reversed, so the resonant frequency where X_L and X_C are equal lies at 224Hz.

The actual value of the low-impedance path for each single-tuned filter is affected by the quality factor of the filter inductor Q,

$$Q = \frac{kX_L}{R}, \tag{5}$$

where X_L is the inductor reactance at fundamental frequency and k is the harmonic order.

The quality factor determines the sharpness of tuning. Usually, a value of Q ranges between 20 and 100 [13].

Another type of passive filter which can be taken into consideration is the high-pass filter. It is a single-tuned filter where the L_h and R_h elements are connected in parallel instead of series. This connection results in a wide-band filter having an impedance at high frequencies limited by the resistance R_h.

The quality factor of the high-pass filter is the quality factor of the parallel R_h - L_h circuit at the tuning frequency,

$$Q_h = \frac{R_h}{L_h \cdot 2\pi f_k}, \tag{6}$$

The analysis of passive filtering performances was made by simulation under Matlab Simulink environment taking into account the passive filters delivered by specialized firms like Nokian Capacitors Ltd, MTE Corporation or Trans-Coil Inc.

4.1 Single tuned passive filters

As discussed above, the main concern in the concrete situation is the significant weight of the 3rd and 5th harmonics.

Therefore, the first proposed solution for passive filtering consists of two single tuned filters for 3rd and 5th harmonics (Fig.9).

A value of 80 was taken into consideration for the quality factor of both tuned filter.

Above all, the performances of this filtering solution are analysed concerning the case of average harmonics distortion of the load current.

As it can be seen in Figure 10, such a filter succeeds in eliminating the tuned harmonic, but also in reducing the 7th harmonic from 13.2% to 11%, which is under the recommended limit of 12%.

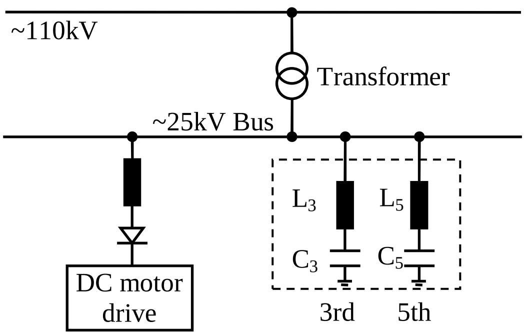

Fig.9 Two single tuned filters in point of common coupling

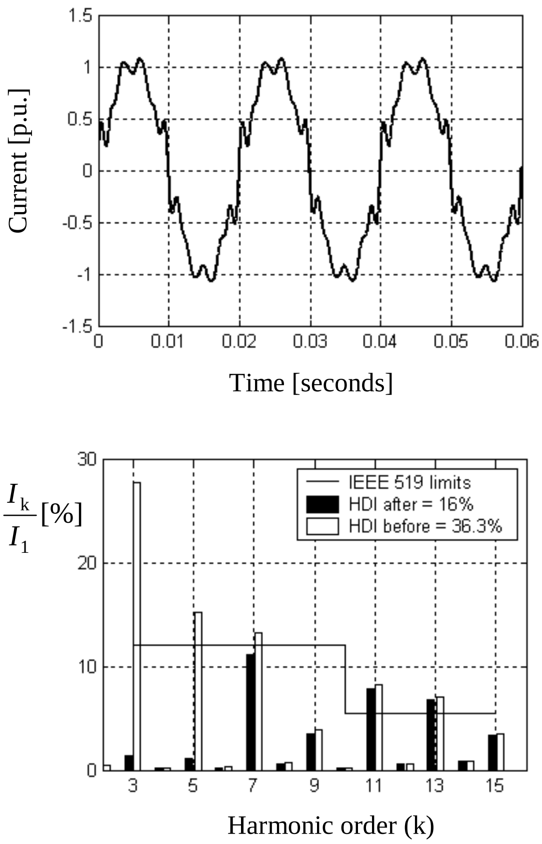

Fig.10 Two single-tuned filters tuned to the 3rd and 5th harmonics in the case of average load current distortion

However, the existence of the 11th and 13th uncompensated harmonics makes *HDI* remain with 6.6% over the recommended value (16% instead of 15%).

As the compensation level is insufficient for the case of average harmonic distortion of the load current during a day, analyzing the filter performances is unnecessary for any unfavourable situation.

4.2 Single tuned passive filters plus a high pass filter

The second passive filtering solution taken into consideration supposes the addition of a high pass filter to the other two single tuned filters mentioned before (Fig.11). A value of 15 is considered for the quality factor of this high pass filter.

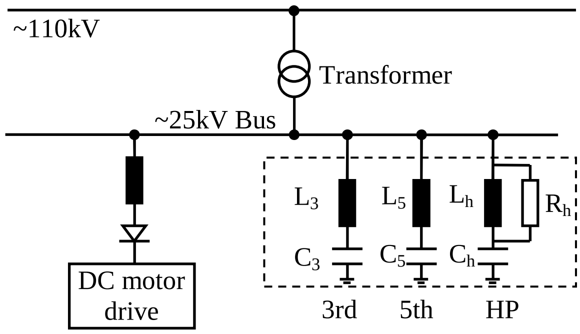

Fig.11 Distribution network including compensation devices

As a result, the supply current waveform is much closer to a sinusoidal one (Fig.12).

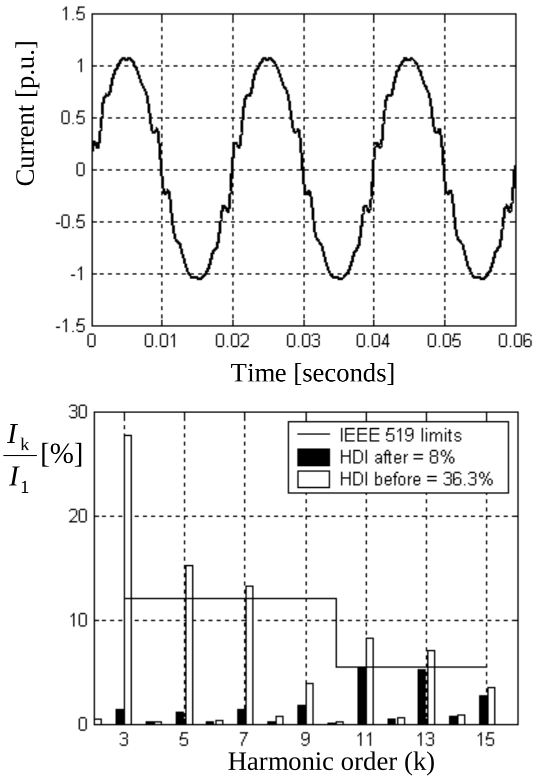

Fig.12 Two single-tuned filters tuned to the 3rd and 5th harmonics and a high-pass filter in the case of average load current distortion

The harmonic spectrum points out the good performances of this filtering solution in the case of the average load current distortion during a day. It can be seen that the 7th harmonic is effectively attenuated, the 13th and 15th harmonics are close under the standard limit and the associated *HDI* value is reduced at 8%.

Further, the performances of the proposed hybrid structure of the passive filter will be analysed in some unfavourable situations relating to individual harmonics.

In Figure 13, the maximum 7th harmonic in the load current is taken into consideration. As it is shown, the filter is able to reduce the 7th harmonic to 3.5%, which is a value much below the recommended limit of 12%. All the harmonics of higher order are below the recommended value and the harmonic distortion factor has a convenient value of 9.3%.

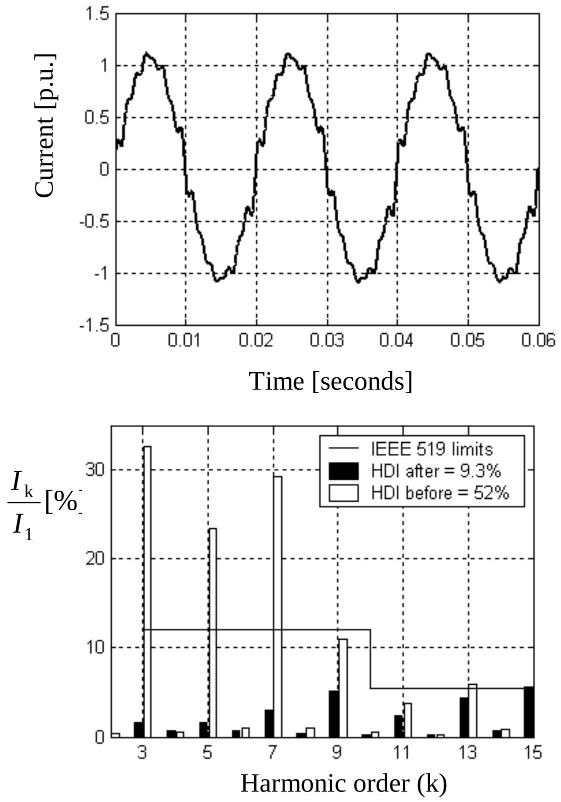

Fig.13 Two single-tuned filters tuned to the 3rd and 5th harmonics and a high-pass filter in the case of maximal recorded value of 7th harmonic

Another unfavourable situation, which may be considered important in determining the high pass filter behaviour corresponds to the maximal value of the 11th harmonic. In spite of high value of about 21.7% of this harmonic, the filter is able to reduce it 3.6 times, so that this new value is very close to the IEEE 519 limit of 5.5%. As the weight of inferior order harmonics in the load current is less important than in the previous case, the new *HDI* value after compensation is with 44% below the recommended limit of IEEE 519 standard (Fig.14).

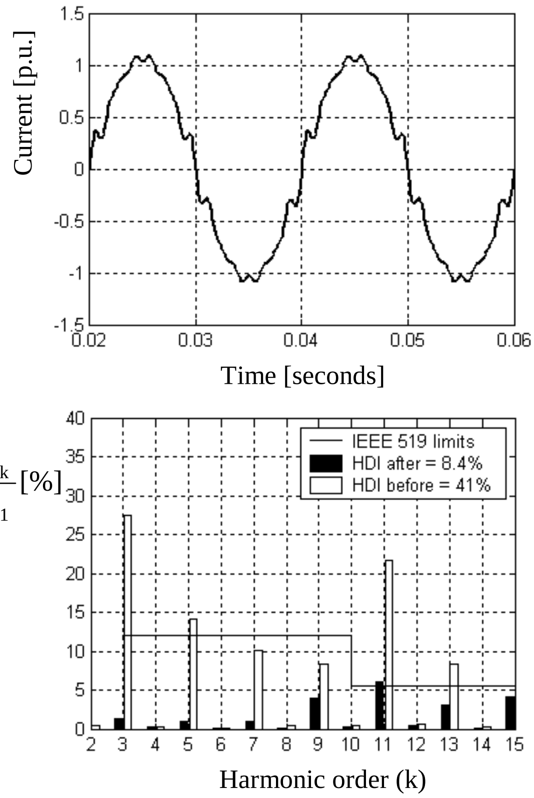

Fig.14 Two single-tuned filters tuned to the 3rd and 5th harmonics and a high-pass filter in the case of maximal recorded value of 11th harmonic

The same situation occurs after harmonics compensation in the most unfavourable case relating to the 13th harmonic in the load current (Fig. 15).

Indeed, the 13 harmonic reaches the 5.5% IEEE 519 limit, which means a 3.8 times diminution. It leads to a *HDI* value much inferior to the allowed limits (7.8% versus 15%).

Even in the worst case concerning the harmonic distortion of the load current, which happened only few times during the analyzed day, the use of the passive power filter having a hybrid structure leads to a value of *HDI* with 20% below the standard limit (Fig. 16). Since the very high value of *HDI* before compensation is principally generated by the significant values of 3rd and 5th harmonics, the very important diminution of the harmonic distortion of about 85% at point of common coupling is the result of the act of single tuned filters. However, the 11th and 13th harmonics remain with approximately 15% bigger than the limit of 5.5%.

The simulation results shown in this section test the compensation effectiveness of the proposed hybrid passive filter.

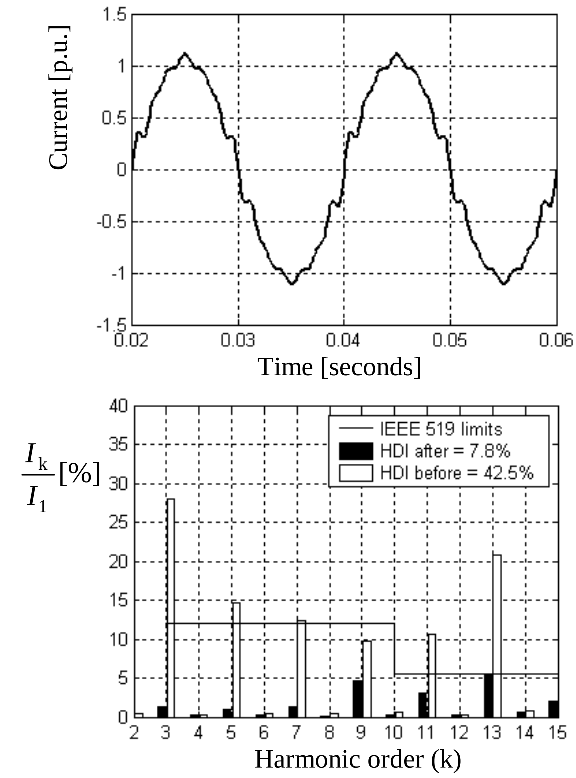

Fig.15 The proposed hybrid passive filter in the case of maximal recorded value of 13th harmonic

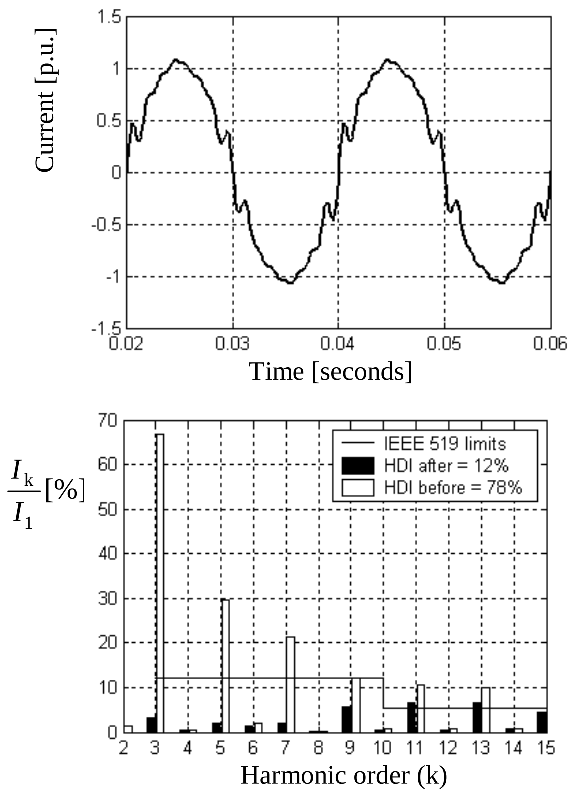

Fig.16 The proposed hybrid passive filter in the case of maximal load current distortion

5 Conclusions

This paper presents a study into harmonic pollution in the railway connection of a traction substation at the 25 kV Romanian distribution network. This connection poses the problem of filtering line current harmonics.

The proposed solution for harmonics mitigation is based on passive power filtering. The analysis of passive filtering performances was made by simulation under Matlab Simulink environment.

Two filtering installations based on single tuned filters and high pass filters were taken into consideration in order to reduce the individual harmonics and the harmonic distortion factor of the current under the recommended limits of the IEEE 519 standard.

Finally, the proposed filter installation consists of three filters – two single tuned filters for 3rd and 5th harmonics plus a high pass filter for higher order harmonics. The results of simulation show that the adopted compensation solution allows respecting the standards even in the worst cases relating to harmonic distortion factor of the load current.

Thus, the harmonic distortion at the points of common coupling would be within the required limits.

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