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# THE STUDY OF QUALITY INDICATORS OF ELECTRICAL ENERGY IN ELECTRICAL RAILWAY TRANSPORT

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ABSTRACT: In this work is presenting the study of the electric current's parameters and characteristics, obtained by means of an electric power's quality analyzer. The measurements were made into an AC railway electric traction substation of 27 kV, during more hours, being registered momentary and average values. The data acquired with the electric power's quality analyzer were registered into a computing system, for their further analysis. In order to achieve the adaption between the analyzer's input measures and the traction line's values, the measurements were made in the secondaries of the voltage and current transformers existent in the traction substation.
KEYWORDS: electric power's quality, active power, reactive power, apparent power, harmonic distortion factor, power factor, electric power's quality analyzer

## ❖ INTRODUCTION

The three-phased systems were conceived and achieved to operate in symmetric balanced regimes. In these regimes, all the component elements: generators, transformers, lines and consumers present identical circuit parameters on each phase, and the currents' and voltages' systems in any section are symmetric. If one of the grid's or consumer's elements gets out-of-balance, the regime becomes non-symmetric and the current and voltage systems are losing their symmetry.

The most unfavorable consequence of the voltage unbalance is the circulation of some additional current component (negative and zero) that lead to additional losses, parasite couples at AC electric motors, wear increase, etc.

A prime cause of the unbalances comes from the grid elements: i.e. the non-symmetric space disposition of the aerial electric lines' conductors is translated by impedance differences for the grid's phases, being in this way a source for unbalances. A transposition of the aerial lines' conductors allows, however, the reduction of this unbalance up to the level it becomes negligible. The main cause for non-symmetries is the consumers' supply, great part of them being unbalanced, single-phased and connected between two phases of the grid, or between a phase and null.

The most important unbalances are produced by the high-power industrial single-phased consumers, connected to the medium or high voltage electric grids, e.g: transformation stations for supplying the railway electric traction, welding installations, single-phased electric furnaces, etc.

The non-symmetries provoked by these loads are accompanied most of the times also by other forms of perturbations: harmonics, voltage shocks, voltage holes, etc.

The effects of the current unbalances, indicated by the appearance of the negative and zero sequence components, lead to the increase of longitudinal losses of power and active energy in electric grids. [1]

## ❖ WORK'S PRESENTATION

Conditions for quantities analysis of the harmonic components in the structure of a signal are [58],[71]:

*a) Harmonic level* – is the ratio, expressed as a percentage of the effective amount of harmonics considered (Fk) and the effective value of the fundamental F1

$$\gamma_K = \frac{F_k}{F_1}\cdot 100\,[\%] \tag{1}$$

*b) The deforming residue* – represent wave that is obtained from the given wave when is eliminated fundamental harmonic

$$F_d = \sqrt{F^2 - F_1^2} \tag{2}$$

*c) Global distortion coefficient (non-sinusoidal shape*) - is defined as the ratio, expressed as a percentage of the effective value of deforming residue and the one of fundamental.

$$d = \frac{F_d}{\sqrt{F^2 - F_0^2}} = \frac{\sqrt{\sum_{k=2}^{\infty} F_k^2}}{\sqrt{\sum_{k=1}^{\infty} F_k^2}} \cong \frac{\sqrt{\sum_{k=2}^{\infty} F_k^2}}{F_1} \cdot 100\,[\%] \tag{3}$$

a) Total harmonic distortion, is defined similarly to global distortion coefficient except that the overall distortion is taken into account the first 50 harmonics

$$THD = \sqrt{\sum_{k=2}^{50} \left(\frac{F_k}{F_1}\right)^2} \cdot 100\,[\%] \tag{4}$$

b) Partially weighted harmonic distortion introduced to ensure that when increased rank, descending harmonic and relationship is defined by

$$THD_P = \sqrt{\sum_{k=2}^{50} k \cdot \left(\frac{F_k}{F_1}\right)^2} \cdot 100\,[\%] \tag{5}$$

c) The deformation coefficient of non-sinusoidal periodic wave, $\Delta F$ has the expression

$$\Delta F = \frac{|a-b|}{c} \cdot 100\ [\%] \tag{6}$$

where: *a* represent y-coordinate of the curve representative for the given periodic wave;
*b* represent y-coordinate of the curve representative for the fundamental harmonic of the given wave, corresponding to the same x-coordinate as for "a";
*c* represent curve amplitude representative for the fundamental harmonic. Determinations of the current harmonics, as well as the THD factor, are made with a three-phased energy analyzer which allows the computing of these parameters according to the following relations.

RMS values for voltage and current:

$$V_{rms}(i) = \sqrt{\frac{1}{N} \cdot \sum_{n=0}^{N} V(i,n)^2} \tag{7}$$

where: $N$ represent the number of samples for the acquisition time;
$V_{rms}$ single RMS voltage $i+1$ phase; $Vavg[i] = Vrms[i]$

$$U_{rms}(i) = \sqrt{\frac{1}{N} \cdot \sum_{n=0}^{N} U(i,n)^2} \tag{8}$$

where: $U_{rms}$ compound RMS voltage $i+1$ phase $Uavg(i) = Urms(i)$

$$Arms(i) = \sqrt{\frac{1}{N} \cdot \sum_{n=0}^{N} A(i,n)^2} \tag{9}$$

where: $Arms(i)$ - Effective current phase $i+1$; $Aavg(i) = Arms(i)$

Computing of harmonic:

By FFT (16 bits) 1024 samples on 4 cycles without windowing (CEI 1000 – 4-7). From real and imaginary parts, each bin computed on each phase $V_{harm}$, $U_{harm}$ and $A_{harm}$ in proportion to the fundamental value and the angles $V_{ph}$, $U_{ph}$, and $A_{ph}$ between each bin and the fundamental.

This computing is done by the following principle:

Module in %: $mod_k = \frac{c_k}{c_1} \times 100$; angle in degree: ${}_k = \arctan\left(\frac{a_k}{b_1}\right)$

$$\text{With} \begin{cases} c_k = |b_k + ja_k| = \sqrt{a_k^2 + b_k^2} \\ b_k = \frac{1}{512} \sum_{s=0}^{1024} F_s \times \sin\left(\frac{k\pi}{512} s + {}_k\right) \\ a_k = \frac{1}{512} \sum_{s=0}^{1024} F_s \times \cos\left(\frac{k\pi}{512} s + {}_k\right) \\ c_o = \frac{1}{1024} \sum_{s=0}^{1024} F_s \end{cases} \tag{10}$$

$c_k$ is the amplitude of frequency $f_k = \frac{k}{4} f_1$, $F_s$ is sampled signal, $c_o$ is the DC component, $k$ is the ordinal number (spectral bin).

Computing of the distortion factor (DF):

There are computed two global values that give the relative quantity of harmonics: total harmonic distortion (THD) against the fundamental and the distortion factor (DF) and DF against the effective value (RMS).[2]

$$V_{thd}(i)=\frac{\sqrt{\frac{1}{2}\sum_{n=2}^{50}V_{harm}(i,n)^2}}{V_{harm}(i)} \qquad U_{thd}(i)=\frac{\sqrt{\frac{1}{2}\sum_{n=2}^{50}U_{harm}(i,n)^2}}{U_{harm}(i)} \qquad A_{thd}(i)=\frac{\sqrt{\frac{1}{2}\sum_{n=2}^{50}A_{harm}(i,n)^2}}{A_{harm}(i)} \qquad (11)$$

$$V_{df}(i)=\frac{\sqrt{\frac{1}{2}\sum_{n=2}^{50}Vharm(i,n)^2}}{Vrms(i)}; \qquad U_{df}(i)=\frac{\sqrt{\frac{1}{2}\sum_{n=2}^{50}Uharm(i,n)^2}}{Urms(i)} \qquad Adf(i)=\frac{\sqrt{\frac{1}{2}\sum_{n=2}^{50}Aharm(i,n)^2}}{Arms(i)} \qquad (12)$$

Multiplying the voltage’s harmonics factor with the current’s harmonics factor, results the power’s harmonics factor. Differentiating the voltage’s harmonic phase angle with the current’s harmonic phase angle, results the power’s phase angle.

- different ratios $PF(i)=\frac{W(i)}{VA(i)}$ power factor, phase $i+1$

Cosinus angle between the voltage’s fundamental and the phase current $i+1$

$$\cos[\ (i)]=\frac{\sum_{n=0}^{N-1}VF(i,n)\cdot AF(i,n)}{\sqrt{\sum_{n=0}^{N-1}VF(i,n)^2}\cdot\sqrt{\sum_{n=0}^{N-1}AF(i,n)^2}} \qquad (13)$$

Total power factor of various types of energy

$$PF3=\frac{PF(0)+PF(1)+PF(2)}{3} \qquad (14)$$

Active energy consumed $i+1$ phase;

$$Wh(0,i)=\sum_{Tint}\frac{W(i)}{3600} \qquad (15)$$

Reactive inductive energy consumed $i+1$ phase;

$$VARhL(0,i)=\sum_{Tint}\frac{VAR(i)}{3600} \ \text{for}\ VAR(i)\geq 0 \qquad (16)$$

Reactive capacitive energy consumed $i+1$ phase.

$$VARhC(0,i)=\sum_{Tint}\frac{VAR(i)}{3600} \ \text{for}\ VAR(i)\leq 0 \qquad (17)$$

The measurements were made in the traction station CFR Deva, by means of the electric power quality’s analyzer CA 8334B. During the data acquisition it was caught a passing from one supply transformer to another power factor or distortion factor. Further is presented the variation form of the line voltage and current at a given moment (Fig. 1). One can notice a reduced modification in the voltage form, and a pronounced one in the current’s variation form.

Variation of the power factor’s measures PF (Fig. 2), of the voltage’s harmonic distortion factor $V_{thd}$ (Fig. 3) and of the current’s harmonic distortion factor $I_{thd}$ (Fig. 4) is presented during the entire acquisition period, where from can be determined the fluctuation of the determined measures, fluctuation that leads to distortions in the general power supply grid [3].

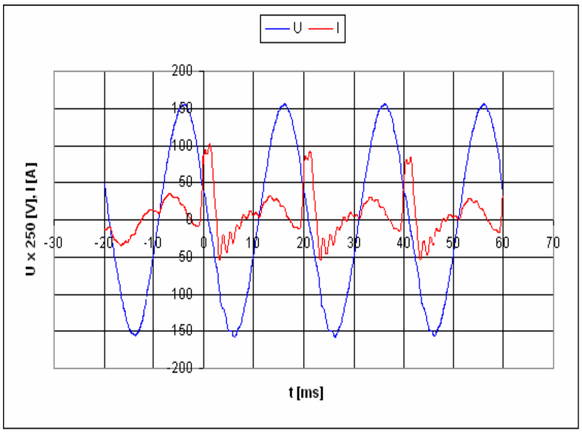

Figure 1. Variation form U,I

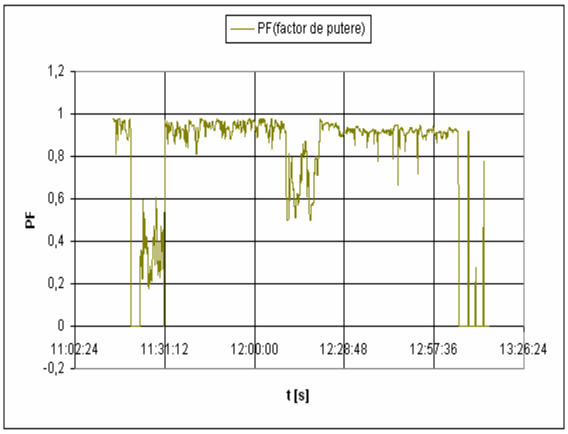

Figure 2. Power factor

Depending on these obtained values, can be designed diverse compensation systems of the perturbations introduced in the grid [4][5].

Within the AC electric traction of 50Hz with DC motors and implicitly with converters [6], was obtained a harmonic distortion factor of the voltage (Fig. 5), relatively reduced, of 4,5% in conditions of a normal traffic, and the values of the voltage harmonics are also reduced.

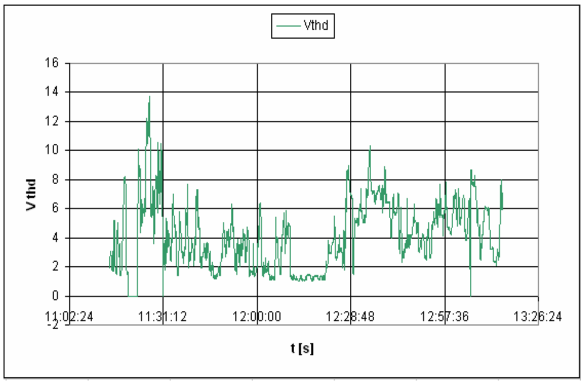

Figure 3. Voltage's harmonic distorsion factor

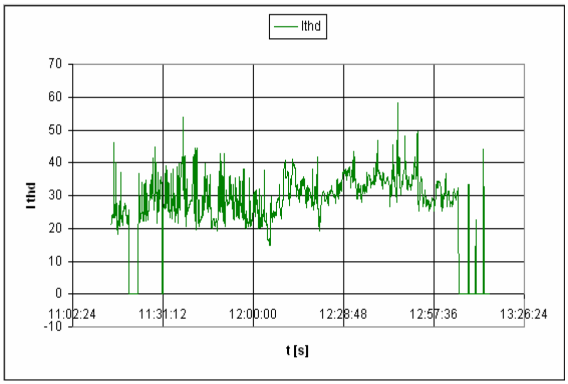

Figure 4. The current's harmonic distorsion factor

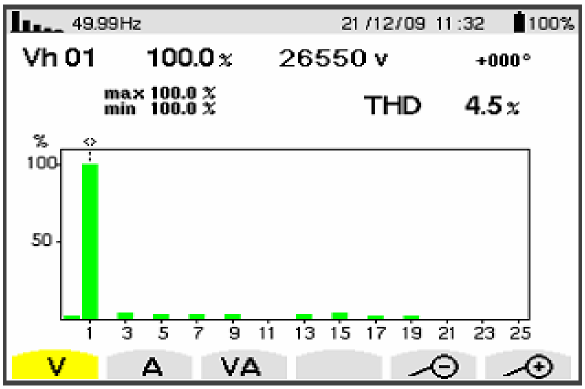

Figure 5. Values of the voltage harmonics

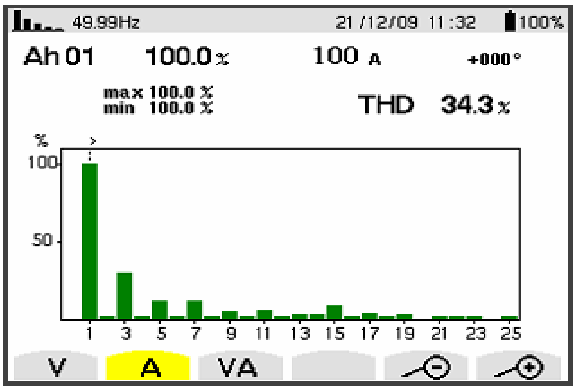

Figure 6. Values of the current harmonics

For the current harmonics (Fig. 6) things are changed, we have high THD of 34,3% and harmonics' individual values also high, up to 25% from the fundamental harmonic, that should be eliminated.

For eliminating the current harmonics, can be introduced passive filters of LC type [4][5], that should eliminate the low-rank harmonics, and for the superior rank ones it can be used the solution of the active power filter, which cannot be connected on the locomotive but only in the traction station. Dimensioning of the passive filters (for the harmonics 3,5,7 can be made on the minimum reactive power criteria, thus being possible to reduce the reactive power consumption [1].

The LC-type filters use coils with variable inductivity by modifying the iron core's penetration depth inside the copper winding. By modifying the inductance, it is modified the LC circuit's tuning frequency, influencing the current absorbed from the power supply system, both as value and shape. For the computing of L and C elements, it was chosen the minimum reactive power criteria.

For each current harmonic that is possible to be introduced is used such a resonant circuit. The elements of each filter are dimensioned in such way that for the resonance frequency that coincides with the respective current harmonic frequency result impedance very small.

$$Z_k = k\omega_1 L - \frac{1}{k \cdot \omega_1 \cdot C} \tag{18}$$

where: $Z_k$ is the equivalent impedance of the resonant circuit for the harmonic of k order (the equivalent resistance of the coil of capacitors and electric connection elements were neglected).
$\omega_1$ = fundamental current pulsation.
Pulsation:

$$\omega_k = k\omega_1 = \frac{k}{\sqrt{LC}} \tag{19}$$

is quite the resonance pulsation of LC circuit.

Usually, the absorbing filters are installed for the harmonics with the highest amplitudes, which correspond in general to the low order of harmonic.

Designing of filters' inductivity and capacity is made by applying of some algorithms that could be differentiated first depending on the filters' role from the viewpoint of reactive power compensation on the fundamental. All the resonant circuits will have capacitive character on the fundamental's frequency, so they will produce, no matter what, a capacitive transversal compensation of the network.

Even though this is a rare solution, it could be taken into account in boundary situations when the deformant regime in current is very pronounced. Even the reactive power compensation is not a primary objective, the filter will generate in the grid reactive power on fundamental. Therefore, the filter's dimensioning criteria, more specifically of the capacity from its componency, is to minimize the installed capacitive reactive power (which, beside a minimum cost of the battery, leads to a minimum influence on the active power circulation in the grid):

$$Q_c = Q_{c\,min} \tag{20}$$

This reactive power will have two components corresponding to the two above mentioned currents, the current corresponding to the fundamental and the current corresponding to harmonic k on which the resonance is taking place:

$$Q_c = Q_{c1} + Q_{ck} = U_c^2 \cdot \omega_1 \cdot C + \frac{I_k^2}{k \cdot \omega_1 \cdot C} \tag{21}$$

where: $Q_{c1}$ - reactive power supplied by the filter's capacitor on fundamental;
$Q_{ck}$ - reactive power supplied by the filter's capacitor on k harmonic;
$U_c$ - voltage at the capacitor's terminals;
$I_k$ - harmonic current that follows to be filtered.

Making the partial derivate depending on the capacity of the installed capacitive reactive power equation and canceling it, we obtain the equation of the filter's capacity:

$$C = \sqrt{\frac{1}{k}} \frac{I_k(k^2 - 1)}{U_1 \cdot \omega_1 \cdot k^2} \tag{22}$$

The L filter's coil inductivity is determined from the resonance condition of the filter's LC:

$$L = \frac{1}{\omega_k^2 C} = \frac{1}{k^2 \cdot \omega_1^2 \cdot C} \tag{23}$$

By introducing of such resonant filters on the odd harmonic frequencies, we can study the influence on each filter in part, as well as the effect of many filters connected in parallel. Beside the amplitude value, is aimed also the phase-difference introduced by each harmonic against the fundamental.

Will be analyzed the current harmonics for three different loading situations of the generator, respectively three values for the slide potentiometer, at three different supply voltages [1][7][8].

## ❖ CONCLUSIONS

From the analysis of the obtained graphics, can be seen the need to reduce the existent perturbations in the grid. Introduction of the passive filters beside the active filter only reduces the harmonics' values, without having a major influence upon the reactive power and especially upon the non-symmetry of the supply system. The passive filters can be connected either on the locomotive, or in substation, their dimensioning being specific to each case in part. The non-symmetries introduced in the grid by the single-phased supply of the railway electric traction system can be reduced only in the traction substation; therefore we must act on more plans simultaneously to obtain satisfactory results regarding the reduction of the perturbations induced in the supply grid.

For a better study is needed to examine the variation form of voltage and current on the train in case of normal traction. Depending on the results obtained can find appropriate ways to compensate harmonic regime.

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