Study of the deforming regime introduced in the power supply grid by the electric locomotives equipped with DC motors

CORINA DANIELA CUNȚAN IOAN BACIU GABRIEL NICOLAE POPA ANCA IORDAN Electrical Engineering and Industrial Informatics Department Polytechnic University of Timișoara Revoluției str. no 5, Hunedoara, code 331170 ROMANIA ioan.baciu@fih.upt.ro, corina.cuntan@fih.upt.ro, popa.gabriel@fih.upt.ro, iordan.anca@fih.upt.ro

http:// www.fih.upt.ro

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. Also, are analyzed the various possibilities of compensating the effects produced by the consumers, e.g. by the locomotives equipped with DC motors, in order to reduce the reactive power, the current harmonics or the voltage harmonics, respectively the reactive power and harmonics simmultaneously. 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 secondary of the voltage and current transformers existent in the traction substation.

Key-Words: electric power's quality, active power, reactive power, apparent power, harmonic distorsion factor, power factor, electric power's quality analyzer.

1 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 nonsymmetries 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]

2 Theoretical Issue

Within this further analysis will be considered a grid having a concrete, simple configuration, presented in fig. 1. It's about an equivalent consumer, unbalanced and deforming, connected into a grid of 20kV, an electric line that links the consumer to the source, the latest consisting in the medium voltage bars of a transformer station.

In this work is analyzed the operation of the power supply system for the following cases:

- no intervention of any nature for improving the

operation regime;

- action should be taken only for compensating the reactive power or for reducing the current harmonics;

- action will be taken for compensating the reactive power and reducing the current harmonics.



Fig, 1 The simplified electric diagram of the grid considered for study

CEDD - equivalent unbalanced and deforming consumer;

ICEF - compensating-balancing-filtration installation;

For each of these situations are dimensioned the compensation installations, is calculated the currents circulation in the consumer-compensator unit, and then are determined the necessary indicators for analyzing the interdependency of the optimization actions.[9]

In case there's no intervention of any kind to improve the operation regime, the correspondence between the symmetric and sinusoidal regimes in the currents, and the unballanced and non-sinusoidal ones also in the currents, can be made by harmonic decomposition of the phase currents' curves, followed by a decomposition of the harmonic currents on phases in suitable symmetric components. Thus, the sum of the active power losses on the three phases of the grid element upstream the non-symmetric and unbalanced receiver, in case of the electric locomotive's supply line:

$$\Delta P = 3 \cdot \sum_{k=1}^{\infty} \left(r_{dk}^2 + r_{ik}^2 \right) \cdot R_k \tag{1}$$

The electric resistance can be considered the same in the plan of all harmonics, equal to the one of direct sequence. The value of the losses calculated by this expression will be compared with the minimum value, obtained in conditions of total compensation of the reactive power on fundamental and filtration of all current harmonics of superior rank, injected by the consumer in the grid.

The power factor calculated using the power

losses is given by the relation 2.

$$k_{p} = \frac{I_{d1} \cdot \cos \varphi_{d1}}{\sqrt{\sum_{k=1}^{\infty} \left(I_{dk}^{2} + I_{ik}^{2}\right)}} = \frac{\cos \varphi_{d1}}{\sqrt{1 + k_{ni1}^{2} + \sum_{k=2}^{\infty} \frac{\left(I_{dk}^{2} + I_{ik}^{2}\right)}{I_{d1}^{2}}}}$$

$$k_{p} = \frac{\cos \varphi_{d1}}{\sqrt{1 + k_{ni1}^{2} \cdot \left(1 + \sum_{k=2}^{\infty} \gamma_{lik}^{2}\right) + \sum_{k=2}^{\infty} \gamma_{ldk}^{2}}} \qquad (2)$$

From the power factor expression's analysis is found that this emphasizes both the non-symmetric regime, by means of the disymmetry coefficient k_{ni1} , and the non-sinusoidal one, by the level of the harmonic currents of direct and reverse sequence for the harmonics of rank higher than one, γ_{Idk} and γ_{Iik} .

Regarding the effect of the three elements, respectively the reactive power's circulation on fundamental, the currents' unbalance respectively their non-sinusoidality upon the loss increase in the grid, this is different. If is considered the loss reduction by reactive power compensation, and the current harmonics reduction as being:

$$\frac{\Delta P}{\Delta P_{min}} = \frac{1 + k_{ni1}^2 \left(1 + \sum_{k=2}^{\infty} \gamma_{Iik}^2\right) + \sum_{k=2}^{\infty} \gamma_{Idk}^2}{\cos^2 \varphi_{d1}}$$
(3)

Thus, the sensitivity of the loss reduction against the dampening of the current harmonics is given by the relation:

$$\frac{\partial (\Delta P / \Delta P_{min})}{\partial \gamma_{Iik}} - \frac{2k_{ni1} \cdot \gamma_{Iik}}{\cos^2 \varphi_{d1}}$$
(4)

respectively:

$$\frac{\partial (\Delta P / \Delta P_{min})}{\partial \gamma_{Idk}} - \frac{2 \cdot \gamma_{Idk}}{\cos^2 \varphi_{d1}}$$
(5)

and against the power factor's improvement on fundamental:

$$\frac{\partial (\Delta P / \Delta P_{min})}{\partial \cos \varphi_{d1}} = -\frac{2}{\cos^3 \varphi_{d1}} \left[1 + k_{nil}^2 \left(1 + \sum_{k=2}^{\infty} \gamma_{Iik}^2 \right) + \sum_{k=2}^{\infty} \gamma_{Idk}^2 \right]$$
(6)

By analyzing the expressions (4), (5) and (6) as well as if are taken into account the usual values of the measures that intervene in these relations, it results that the optimization actions' efficiency concerning the power loss reduction is given, as importance, by:

- reactive power compensation for the power factor's improvement;
- current harmonics' dampening.

In case is acting only for compensating the reactive power, if it's not taken into account the

presence of the unballanced and non-sinusoidal regime, for the power factor's improvement is performed a symmetric transversal capacitive compensation. The values of the compensation currents, the same on each phase, are determined from the cancelling condition of the direct sequence current's reactive component corresponding to the

fundamental (after compensation) $\cos \varphi_{d1}^{c} = 1$;

$$I_m \left(\underline{I}_{d1}^2 \right) = 0 \tag{7}$$

Out of which is obtained:

$$(I_{Rr1} + I_{C1}) + (I_{Sr1} + I_{C1}) + (I_{Tr1} + I_{C1}) = 0$$
 (8)
It results:

$$I_{C1} = -\frac{1}{3} (I_{Rr1} + I_{Sr1} + I_{Tr1})$$
(9)

In the above relations I_{Rr1} , I_{Sr1} , I_{Tr1} are the reactive currents on the fundamental from the three phases, and I_{C1} reactive compensation current on fundamental. Relation (9) can be obtained also from the condition of minimizing the active power losses on fundamental, on the upstream grid element.

$$\Delta P_{l} = \left[I_{Rd}^{2} + \left(I_{Rd} + I_{Cl}\right)^{2} + I_{Sd}^{2} + \left(I_{Sd} + I_{Cl}\right)^{2} + I_{Td}^{2} + \left(I_{Td} + I_{Cl}\right)^{2}\right] R_{l} = min$$

Putting now the condition:

$$\frac{\partial(\Delta P)}{\partial(I_{C1})} = 0 \tag{10}$$

for I_{C1} is obtained exactly the relation (9). If compensation is achieved by means of a compensator Y, dimensioning of its reactive elements is achieved even with the compensation current resulted by applying the relation (9).

In this case, it does not intervene upon the currents' reverse sequence component on fundamental, but instead the direct sequence reduced component is from I_{d1} to $I_{d1} = I_{d1} \cos \varphi_{d1} = R_e (\underline{I}_{d1}),$ I_{d1} respectively $\cos \varphi_{d1}$ being the direct sequence current, e.g the power factor on fundamental. Accordingly, the disymmetry coeficient on fundamental, after compensation, becomes:

$$k_{ni1} = \frac{I_{i1}}{I_{d1}\cos\varphi_{d1}}$$
(11)

increasing the more harder the power factor before compensation is smaller. So, the regime's non-symmetry degree is boosting.

In case when is acting only for filtration of the current harmonics, the actual solution, the more often met, due to the technical-economical advantages provided at diminishing of the deforming regime produced by the great consumers connected in the distribution networks, represents the harmonic absorbing filters, which, in fact, are LC resonant series circuits mounted transversal, between the grid and ground. We shall refer here to the simpler version of such filter, constituted mainly by a single series inductivity with a capacity, called band-pass filter of order I (Fig. 2).[1]



Fig. 2. Single-wired electric diagram of a band-pass filter of order 1 for an ideal FTB ($R_k=0$).



Fig. 3. The equivalent characteristic impedancepulsation for an ideal FTB ($R_k=0$).

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 it results very small impedance.

$$Z_k = k \,\omega_1 L - \frac{1}{k \cdot \omega_1 \cdot C} \tag{12}$$

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).

 ω_1 = fundamental curent pulsation. Pulsation:

$$\omega_k = k \,\omega_1 = \frac{k}{\sqrt{LC}} \tag{13}$$

is quite the resonance pulsation of LC circuit.

To be noticed that for pulsations that are smaller than the resonance one, $\omega < \omega_k$, $Z_k < 0$, so it has a capacitive character and for pulsations higher than the resonance one, $\omega > \omega_k$, $Z_k > 0$, having inductive character. The form of Z_k characteristic depending on pulsation is shown in figure 3.

The resonant circuit is passed-through by:

- 1. the current corresponding the fundamental, against which it shows a capactive character;
- 2. the current corresponding the harmonic on which the resonance takes place (shortcircuited), against which it shows a practically null impedance;
- 3. the currents corresponding the harmonics existing in the grid, but for which are not provided resonant circuits, against which the impedance's character depends on the harmonic's order.

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

So, considering a certain resonant circuit, it can be assumed that there are resonant circuits (in operation) for all harmonics of inferior rank and that the amplitude of the harmonic currents of superior rank through the considered resonant circuit is neglectable, because, for frequencies superior to the resonance one, this presents a relatively high inductive reactance, that increases by the harmonic's order. Therefore, the analysis of the thermal and electric demands of the resonant circuit's elements is made in the hypothesis that this is passed-through only by the current corresponding the fundamental and by the current corresponding the harmonic on which the resonance takes place. Setting-up of the filters' inductivity and capacity values is made by applying some algorithms that can be differentiated first depending on the filters role from the viewpoint of the reactive power's compensation on fundamental.

All the resonant circuits will have a capacitive character on the fundamental's frequency, so they will produce a transversal capacitive compensation of the grid. Therefore, we'll diferentiate two main types of dimensioning criteria of the resonant circuits:

A - for circuits with filtration main role

B - for circuits with double role: compensation-filtration.

In our case, is not taken into account neither the reactive power's circulation, nor the unbalance of the load currents, and is acting only for filtration of current harmonics. For dimensioning the filters will be used a type-A criteria.

Even though this is a rare solution, it could be

taken into account in boundary situations when the deforming regime in curent is very pronounced. Even the reactive power compensation is not a primary objective, the filter will generate in the network 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 batery, leads to a minimum influence on the active power circulation in the network):

$$Q_c = Q_{c \min} \tag{14}$$

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

$$Q_c = Q_{c1} + Q_{ck} = U_c^2 \cdot \omega_1 \cdot C + \frac{I_k^2}{k \cdot \omega_1 \cdot C}$$
(15)

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 to be filtered.

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

$$C = \sqrt{\frac{1}{k}} \frac{I_k (k^2 - 1)}{U_1 \cdot \omega_1 \cdot k^2}$$
(16)

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

$$L = \frac{1}{\omega_k^2 C} = \frac{1}{k^2 \cdot \omega_1^2 \cdot C} \tag{17}$$

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 more filters connected in parallel. Beside the amplitude's value, is aimed also the phase-shift introduced by each harmonic against the fundamental.[1][7][8]

When is acting for compensating the reactive power and filtration of the current harmonics, situation often met in practice and consisting in integration of the capacitor batteries used for compensating the reactive power on fundamental, in harmonic filters, usually of FTB1 type.

The used filters are three-phased filters in Y connection, for their dimensioning being used B-type criteria, e.g. the filters will play also the role of

compensating the reactive power on fundamental.

The capacity value of the filter's capacitor battery is determined from the condition that, on fundamental, the current absorbed by the filter (I_{c1}) to be just the current necessary for the compensation of the imaginary component of the direct sequence current given by the relation (9).

Therefore, the filter will deliver on each phase, on fundamental, the reactive power:

$$Q = U_f \cdot I_{c1} \tag{18}$$

Two situations are distinct here:

a) it is filtered one single harmonic I_k , so the filter contains a single unit source that shoud achieve also the reactive power compensation. In this case, it can be written:

$$Q = \frac{U_f^2}{X_{c1} - X_{L1}} = \frac{U_f^2}{\frac{1}{\omega_1 C_k} - \omega_1 L_k}$$
(19)

where, if we replace L_k expressed from the filter's resonance tunning condition:

$$L_k = \frac{1}{k^2 \omega_1^2 C_k} \tag{20}$$

is obtained:

$$Q = \frac{k^2}{k^2 - 1} U_f^2 \cdot \omega_1 \cdot C_k \tag{21}$$

where from:

$$C_k = \frac{k^2 - 1}{k^2} \cdot \frac{I_{cl}}{U_f \cdot \omega_l}$$
(22)

In the above relations $(X_{c1} - X_{L1})$ is the filter's capacitive reactance on fundamental, calculated as difference between the reactances corresponding to the fundamental, the capacity C_k and inductivity L_k of the filter, and U_f the grid's phase voltage.

b)there are filtered more harmonics (k=5,7,...m) so the filter will contain m units, the reactive power necessary for the compensation on fundamental being distributed between these.

One of the methods for solving the filters' dimensioning according to this criteria, consists in mounting the same coil, of inductivity L, on each resonant circuit.

The phase reactive power necessary for compensation on fundamental shall be written as a sum of the reactive powers related to all resonant circuits:

$$Q = \sum_{k=5,7...}^{m} \frac{U_f^2}{\frac{1}{\omega_l C_k} - \omega_l L} = \sum_{k=5,7...k^2 - 1}^{m} \frac{k^2}{U_f^2} U_f^2 \omega_l C_k = \frac{U_f^2}{L} \sum_{k=5,7...k^2 - 1}^{m} \frac{1}{(23)}$$

Thus, is deducted the expression of the coils inductivity form the filter's componency:

$$L = \frac{U_f^2}{Q} \sum_{k=5,7...}^m \frac{1}{k^2 - 1}$$
(24)

and then from the resonance condition written for every filter, the capacities of their capacitors C_k (k=1,2,...m).

Is found that both in case a) and in case b) the dimensioning of the filters' capacities and inductivities do not depend directly by the effective values of the harmonic currents, these appearing only at the verifications of electric and thermal demands.

Can be concluded that by compensating the reactive power and harmonics' filtration, the effective values of the currents on the three phases are decreasing. In fact, the compensation being symmetric, it's not affected the reverse sequence component of the currents from the grid. [1]



Fig. 4 Power converter diagram

Compensation of the superior rank harmonics is achieved by using the power active filters that complete the LC-type passive filters used for compensating the low rank harmonics.

The active filters represent a new technical solution that allows the power electronics that causes the distorsion of the voltage and current taken from the supply grid, to be be used for improving the form of the same voltages and currents.

In fig 4. is presented the power circuit of an active filter. This is a controlled converter composed by a DC circuit with capacitors and by a threebranch bridge with tyristors and free-regime diodes. Connection to the AC grid is made by a low-pass filter. Each branch is controlled by a frequency ranged between 5 - 10 KHz. The low-pass filter achieves the insulation of this frequency by the grid's frequency.

The harmonic filters can be placed at the user or at the electric power supplier. The filters from the power suppliers are of high powers and, for now, in the most cases it's about passive filters. The users can place the filters in PCC, where from is undertaken a global current information, in such way to compensate the harmonics generated by the assembly of the equipments installed at the la user (global compensation). Another placement version, prefered in some cases by the user, is putting the active filter in the connection point of an important consumer, generator of current harmonic, the current information taken from here allowing the compensation of that consumer's harmonics (individual compensation).

A special interest presents the combination betwen the parallel active filter and the parallel passive filter. The passive filter from figure is designed in such way to eliminate greatly the low harmonics, i.e. 5,7,11,13 that have an important weight, and the active filter is dimensioned for a more reduced rated current, because it should only eliminate the rest of the undesired spectre of the load current. Such structure allow the cost cuts in approaching the medium power applications, but the number and dimensions of the necessary power components represent a disadvantage. Also, because of the passive filter's fix structure, the solution is adequate for loads of which spectre is known and previously studied. Further addition of some consumers can lead to the passive filter's overload. The active filter from fig. 4 is mounted in series with the capacitor battery for compensating the reactive power, or with a passive filter. The active filter's topology is of current-controlled voltage inverter. The main advantage of this configuration consists in dimensioning of the semiconductor devices at a level four times reduced than into an equivalent parallel active filter, passive filter (filters tunned on harmonics 5 and 7 in the described structure), or the filter formed by the transformer's magnetization inductivity, together with the capacitor battery, in the described structure relieves in great part the active filter.

P-Q-N method fore active filters' control.

Utilisation of a feature of the active and reactive power: in case of sinusoidal voltage supply, the mediate active and reactive power taken from the grid is made on the first harmonic. Because the voltage is not perfectly sinusoidal, is used a PLL circuit that generates a voltage in phase with the fundamental but of amplitude equal with unit. The active power calculated by means of this voltage is $p=3\cdotU\cdot\Gamma\cos\varphi$ and the reactive power $q=3\cdotU\cdot\Gamma\sin\varphi$, where φ is the phase-shifting factor between voltage

and current of fundamental harmonic. In order to improve the performances of this method and to simplify the calculations, instead of the three instantaneous voltages we'll use the outputs of three PLL generators that will produce three sinusoidal signals of amplitude one and in phase with the supply voltage's fundamental.

$$\begin{bmatrix} u_{\alpha} \\ u_{\beta} \\ u_{0} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}^{*} \begin{bmatrix} u_{a} \\ u_{b} \\ u_{c} \end{bmatrix}$$
(25)
$$\begin{bmatrix} i_{\alpha} \\ i_{\beta} \\ i_{0} \end{bmatrix} = \sqrt{\frac{2}{3}}^{*} \begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\sqrt{\frac{3}{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}^{*} \begin{bmatrix} i_{a} \\ i_{b} \\ i_{c} \end{bmatrix}$$
(26)

We can obtain:

 $p = u_{\alpha} * i_{a} + u_{\beta} * i_{\beta}$ - instantaneous active power $q = u_{\beta} * i_{\alpha} - u_{\alpha} * i_{\beta}$ -instantaneous reactive power $n = u_{0} * i_{0}$ - instantaneous homopolar power

In order to define these powers, is appealed the transformation $\alpha,\beta,0$ of a 4-wired three-phased system, with the phase measures u_a, u_b, u_c (that can be voltages or currents), resulting the components $u_{\alpha}, u_{\beta}, u_{\rho}$:

$$\begin{cases} u_{O} = \sqrt{\frac{2}{3}} \left(\frac{1}{\sqrt{2}} u_{a} + \frac{1}{\sqrt{2}} u_{b} + \frac{1}{\sqrt{2}} u_{c} \right) \\ u_{\alpha} = \sqrt{\frac{2}{3}} \left(u_{a} - \frac{1}{2} u_{b} - \frac{1}{2} u_{c} \right) \\ u_{\beta} = \sqrt{\frac{2}{3}} \left(\frac{\sqrt{3}}{2} u_{b} - \frac{\sqrt{3}}{2} u_{c} \right) \end{cases}$$
(27)

or as matrix form:

$$\begin{bmatrix} u_{o} \\ u_{\alpha} \\ u_{\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_{a} \\ u_{b} \\ v_{c} \end{bmatrix}$$
(28)

By matrix reversing (1.14) are obtained the measures u_a, u_b, u_c :

$$\begin{bmatrix} u_{a} \\ u_{b} \\ u_{c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{vmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{vmatrix} \begin{bmatrix} u_{o} \\ u_{\alpha} \\ u_{\beta} \end{bmatrix}$$
(29)

This solution allows the determination of the fundamental harmonic based on the active and reactive power calculation (by averaging the instantaneous value). At the base of this technique lays the fact that the transfer of active and reactive power defined as product between the fundamental voltage harmonic and real currents is only made on the first current harmonic, the rest of current harmonics don't give power.



Fig. 5 The active filter's

Unfortunately, in certain applications the supply voltage from the source contains also superior

harmonics. From this reason, at the power calculation is not used anymore this voltage, but the voltage given by a PLL circuit achieved by software and implemented on a DSP that provides at output sinusoidal signal in phase with the fundamental harmonic and amplitude equal with unit. This signal is subtracted from the grid's total current and, thus, is obtained the current given by the superior harmonics that represents the reference with changed sign of the active filter (Fig. 5)

The distorted power is the one directly responsible for the electromagnetic energy's oscillations between source and load. The reactive power exists practically in each phase, as the reactive currents (that occupy a part from the load conductors' section).

Determinations of the current harmonics, as well as the THD factor, are made with a three-phased energy analyzer which alows the calculation of these parameters according to the following relations. RMS values for voltage and current:

$$V_{rms}(i) = \sqrt{\frac{1}{N} \cdot \sum_{n=0}^{N} V(i,n)^2}$$
(30)

where: *N* represents the number of samples for the acquisition time;

 V_{rms} single RMS voltage i+1 phase; Vavg[i] = Vrms[i]

$$U_{rms}(i) = \sqrt{\frac{1}{N} \cdot \sum_{n=0}^{N} U(i,n)^2}$$
(31)

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

$$Arms(i) = \sqrt{\frac{1}{N} \cdot \sum_{n=0}^{N} A(i,n)^2}$$
(32)

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

Harmonic's calculation:

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 calculation is done by the following principle:

Module in %:
$$mod_k = \frac{c_k}{c_l} \times 100$$

angle in degree: $\varphi_k = \arctan\left(\frac{a_k}{b_l}\right)$

With
$$\begin{cases} c_{k} = |b_{k} + ja_{k}| = \sqrt{a_{k}^{2} + b_{k}^{2}} \\ b_{k} = \frac{1}{512} \sum_{s=0}^{1024} F_{s} \times sin\left(\frac{k\pi}{512}s + \varphi_{k}\right) \\ a_{k} = \frac{1}{512} \sum_{s=0}^{1024} F_{s} \times cos\left(\frac{k\pi}{512}s + \varphi_{k}\right) \\ c_{o} = \frac{1}{1024} \sum_{s=0}^{1024} F_{s} \end{cases}$$
(33)

 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]

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

$$A_{thd}(i) = \frac{\sqrt{\frac{1}{2} \sum_{n=2}^{50} A_{harm}(i,n)^2}}{A_{harm}(i)}$$
(34)

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

$$Adf(i) = \frac{\sqrt{\frac{1}{2} \sum_{n=2}^{50} Aharm(i,n)^2}}{Arms(i)}$$
(35)

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 + l

$$cos[\varphi(i)] = \frac{\sum_{i=0}^{N-1} \nabla F(i,n) \cdot AF(i,n)}{\sqrt{\sum_{n=0}^{N-1} VF(i,n)^2} \cdot \sqrt{\sum_{n=0}^{N-1} AF(i,n)^2}}$$
(36)

Total power factor of various types of energy $PF_3 = \frac{PF(0) + PF(1) + PF(2)}{2}$ (3)

$$F3 = \frac{11(0) + 11(1)}{3}$$
(37)

Active energy consumed
$$i + 1$$
 phase;

$$Wh(0,i) = \sum_{T \ int} \frac{W(i)}{3600}$$
 (38)

Reactive inductive energy consumed i + 1 phase;

$$VARhL(0,i) = \sum_{T \text{ int}} \frac{VAR(i)}{3600} \text{ for } VAR(i) \ge 0$$
(39)

Reactive capacitive energy consumed i + 1 phase.

$$VARhC(0,i) = \sum_{T \text{ int}} \frac{VAR(i)}{3600} \text{ for } VAR(i) \le 0$$
(40)

The measurements were made in the CFR Deva traction station, 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, moment refound as power variation, or power factor, or distorsion factor. Further is presented the variation form of the line voltage and current at a given moment (Fig. 6).



Fig. 6 Variation form U,I



Fig. 7 Power factor

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. 7), the active power P (Fig. 8), the reactive power Q (Fig. 9), the apparent power (Fig. 10), the voltage's harmonic distorsion factor V_{thd} (Fig. 11) and the current's harmonic distorsion factor I_{thd} (Fig. 12) is presented during the entire acquisition period, where from can be determined the fluctuation of the determined measures, fluctuation that leads to distorsions in the general power supply grid [3].



Fig. 8 Active power

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 implicitely with converters [6], was obtained a harmonic distorsion factor of the voltage (Fig. 11), relatively reduced, of 4,5% in conditions of a normal traffic, and the values of the voltage harmonics are also reduced.



Fig. 9 Reactive power



Fig. 10 Apparent power



Fig. 11 Voltage's harmonic distorsion factor



Fig. 12 The current's harmonic distorsion factor



Fig. 13 Values of the voltage harmonics



Fig. 14 Values of the current harmonics

For the current harmonics (Fig. 14) 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.

From the power factor's variation form analysis (fig. 7), one can notice that in major situations these exceed the value of 80%, except the case when it was passed from one transformer to another, at time moments 11^{20} - 11^{31} and return on the initial transformer at times 13^{05} - 13^{15} .

Another case represents the moment from times 12^{10} - 12^{20} when was not existing a main consumer on the line, moment refound also in the acive, reactive and apparent power's graphics,.

From the power graphics (fig. 8, 9, 10) one can notice the variation of these measures' values, cu with average values of approximately 2,5MW at active power, 0,8MVAR for reactive power and respectively 3MVA for the apparent power, finding also the reactive power's inductive or capacitive character.

The THD variation for current (fig. 7) is presenting us high and very high values on the entire measuring period, values that have to be reduced to an average value under 5%.

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].

3 Conclusion

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 determination mode of the LC filter elements taking into account the minimum reactive power criteria is not sufficient for compensating the reactive power, which was found that it has an important value in the presented situation.

For an efficient study, it should be introduced in circuit the passive and the active filters, and then restarted the measurements to determine the reactive power in the new situation. The situation imposes an automatic monitoring and adjusting system of these parameters concerning the distortions compensation in real time.

The passive filters can be connected either on the locomotive, or in substation, their dimensioning being specific to each case in part. The nonsymmetries introduced in the grid by the singlephased 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.

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