# CPT application in Active Power Filtering

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***Abstract* - The current decomposition, based on the Conservative Power Theory (CPT), includes, beside the active, reactive and void components, an unbalanced component too. This way it is possible for the active filter to compensate only the unbalanced component, if desired. This paper analyzes the feasibility of decomposing the current in three-phase, three-wire systems using the CPT. Thus, several case studies were created to verify the current computation. In the first stage, the current decomposition accuracy was tested by simulation in Matlab/Simulink environment, using a non-linear load, balanced and unbalanced. After interpreting the results obtained by simulation, the computation algorithm was experimentally tested on an active filtering system. It will be noticed that for all the studied cases, the CPT theory leads to correct results both through simulation and experimental analysis. Hence, even if the load is unbalanced (different RMS values, of the load current, per phases), after compensation, using the implemented current computation, the load current will have the same RMS value on each phase. Moreover, it is possible to eliminate the reactive and the distorted component if they will be added to the compensating current relation. Thus, the CPT has proven its performance in the active filtering current compensation, irrespective of the load.**

**Keywords** - ***current components; Conservative Power Theory; unbalanced loads; active filter; total and partial compensation.***

## I. INTRODUCTION

The use of home consumers, as well as of industrial consumers, especially static converters, leads to high harmonic distortion in the power grid. In order to obtain the desired waveform and to eliminate the phase shift of the grid current, a shunt active filter can be used.

Shunt power filters work as a generator, injecting harmonic currents which correspond to the harmonic components of the load. Therefore, current concerns regarding shunt power filters are directed towards new algorithms for the compensating currents [1], [2], [6] - [8]. The compensating current will be calculated according to the compensation goal.

An active shunt compensator offers the possibility to compensate not only the current harmonic distortion and reactive component, but also, the current asymmetry.

It must be mentioned that the above features depend, not only on the compensator, but also, on the compensating current computation algorithm. In order to compensate only the current asymmetry, the compensating current computation algorithm must contain the unbalanced current component which can be added, if desired, to the compensating current.

In this paper, the current decomposition, using the CPT will be analyzed [3] – [5]. In the first stage, the current computation was verified by simulation and after that the implementation feasibility was experimentally tested on an active filtering system.

## II. CPT CURRENT COMPONENTS FOR SHUNT ACTIVE FILTERING

The actual section will present the current components definition based on the CPT, in order to use them for the compensating current computation. The current terms are defined collectively, by making reference to an equivalent balanced load absorbing the same active power and reactive energy of the analyzed load.

The load current is the sum of the active, reactive and void currents [3] – [5].

$$\underline{i}_L = \underline{i}_a + \underline{i}_r + \underline{i}_v , \tag{1}$$

where the notation $\underline{i}$ means the column vector containing the three phase components of $i$ ($i_R$, $i_S$, $i_T$).

Each current component is defined as follows [3] – [5]:

*1a) Balanced active current:*

$$\underline{i}_a^b = \frac{\boldsymbol{P}}{\boldsymbol{U}^2}\underline{u} = G^b \underline{u} , \tag{2}$$

where:

- **P** is the three-phase active power of the load:

$$\boldsymbol{P} = P_R + P_S + P_T ; \tag{3}$$

- **U** is the RMS grid voltage defined as follows:

$$\boldsymbol{U} = \sqrt{U_R^2 + U_S^2 + U_T^2} ; \tag{4}$$

- $G^b$ is the equivalent balanced conductance.

*1b) Unbalanced active current* (accounts for the asymmetrical behavior of the various phases)**:**

$$\underline{i}_a^u = \underline{i}_a - \underline{i}_a^b \Rightarrow \underline{i}_{an}^u = \left(G_n - G^b\right)u_n , n = 1 \div N \tag{5}$$

*2a) Balanced reactive current:*

$$\underline{i}_r^b = \frac{\langle \underline{\hat{u}}, \underline{i} \rangle}{\|\underline{\hat{u}}\|^2}\underline{\hat{u}} = \frac{\boldsymbol{W}}{\boldsymbol{\hat{U}}^2}\underline{\hat{u}} = B^b \underline{\hat{u}} \tag{6}$$

where:

$\langle \hat{u}, i \rangle = \dfrac{1}{T}\displaystyle\int_0^T \hat{u} \cdot i \, dt$ is the internal product;

$\hat{u} = \omega \cdot \left( \displaystyle\int_0^t u(\tau) d\tau - \frac{1}{T}\int_0^T \int_0^t u(\tau) d\tau dt \right)$ is the time integral;

- ***W*** is the three-phase reactive energy absorbed by the load and $B^b$ is the equivalent balanced susceptance.

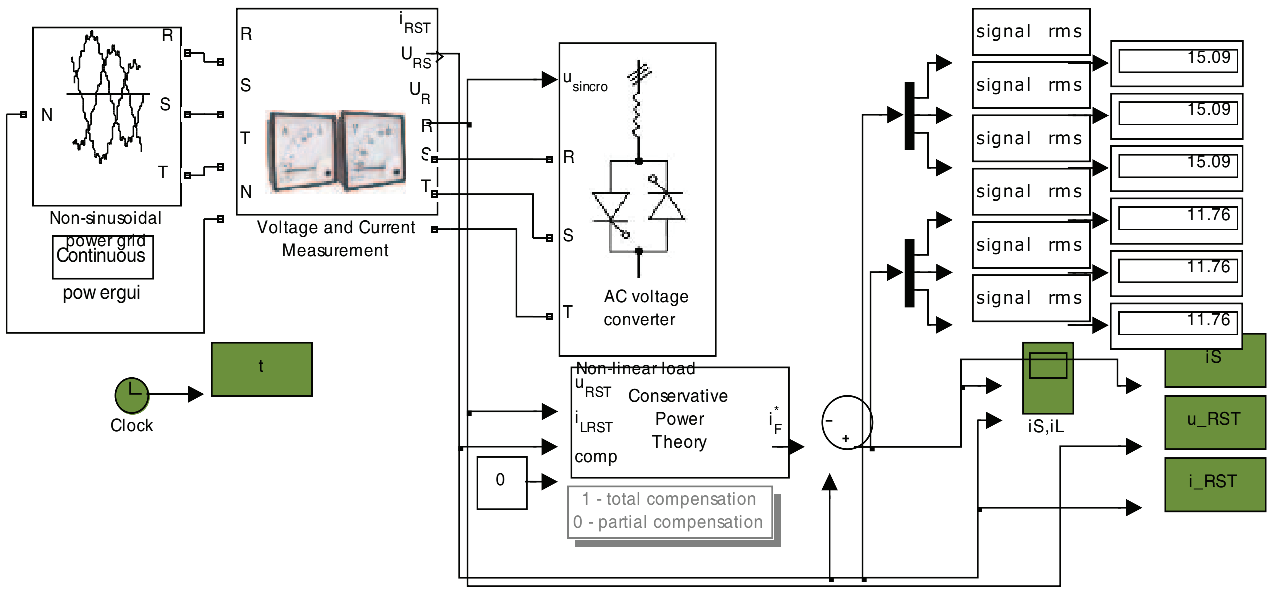


Fig. 1. The virtual filtering system

*2b) Unbalanced reactive current:*

$$\underline{i}_r^u = \underline{i}_r - \underline{i}_r^b \Rightarrow \underline{i}_{rn}^u = \left(B_n - B^b\right)\hat{u}_n, n = 1 \div N \quad (7)$$

*3) Void current* is defined by subtracting the active and reactive current from the load current.

$$\underline{i}_v = \underline{i}_L - \underline{i}_a - \underline{i}_r \quad (8)$$

The compensating current will be calculated from the load current depending on the compensation goals, as follows:

- total compensation – the active filter will compensate the entire non-active current:

$$\underline{i}_F^* = \underline{i}_L - \underline{i}_a \quad (9)$$

- partial compensation – the active filter will compensate only the distorted component:

$$\underline{i}_F^* = \underline{i}_L - \underline{i}_a - \underline{i}_r \quad (10)$$

## III. Case Studies

There were analyzed several case studies containing a symmetrical, as well as, an unbalanced non-linear load.

The case studies were created for a three-phase non-sinusoidal voltage system, in which the current had been calculated with the CPT definitions.

First of all, the CPT current computation was verified by simulation using Matlab/Simulink environment. Subsequently, the computation algorithm was experimentally tested on an active filtering system.

This section will be related to the simulation study, the following one being dedicated to the experimental results.

### *A. Symmetrical non-linear load*

The symmetrical non-linear load consists of a three phase AC voltage converter, with an inductive passive load, which absorbs a RMS value of 15 A, being supplied by a non-sinusoidal voltage system (THD$_u$ = 2.3%) (Fig. 1). The analyzed load being non-linear, the load current and the grid voltage have not identical shape and phase (Fig. 2).

Compensating the reactive and the distorted components, it will remain only the active current, whose value is zero because of the inductive character corresponding to the passive load (Fig. 3).

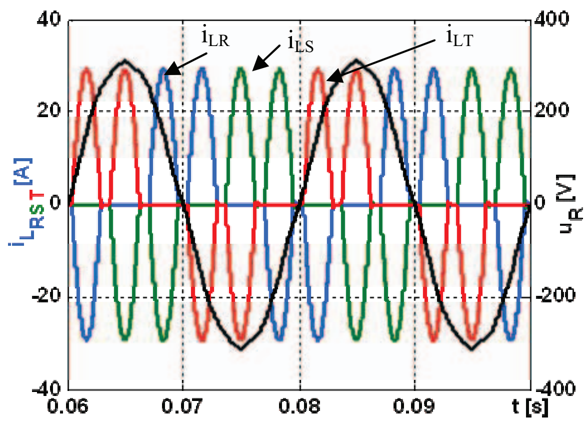


Fig. 2. The grid voltage and the non-linear load currents

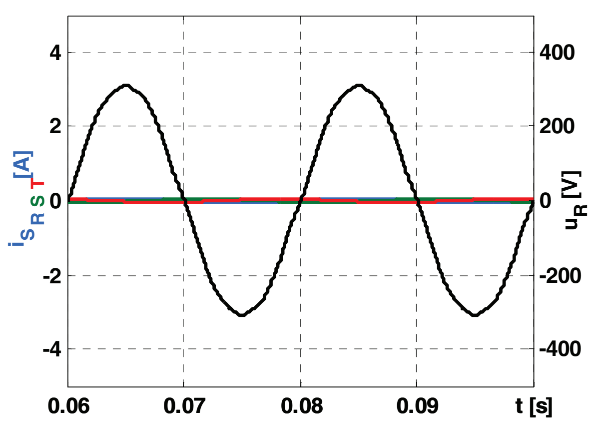


Fig. 3. The grid voltage and the source currents for total compensation

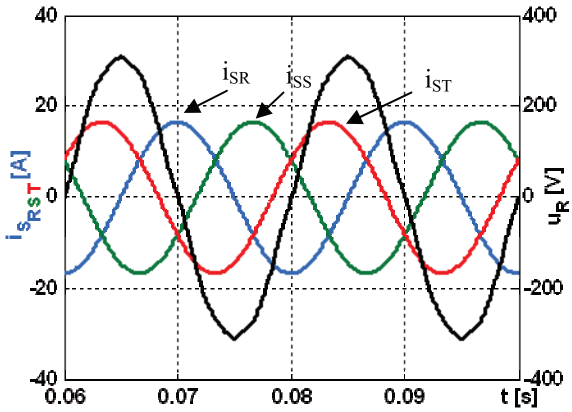


Fig. 4. The grid voltage and the source currents for partial compensation

In the partial compensation case, the distorted component was removed, the RMS value of the current being reduced from 15.09 A to 11.76 A. The obtained result can be validated by the current waveform which, after the compensation, is sinusoidal and keeps the phase shift because the reactive current was not eliminated (Fig. 4).

### B. *Unbalanced non-linear load*

In order to prove that the CPT gives good results, even if the load is unbalanced, it was analyzed the same non-linear load which was mentioned at section A, but this time, the phase current RMS values were different as follows: 15, 15 and 10 A (Fig. 5).

The waveforms corresponding to the total compensation mode will not be presented in this case because, as it was mentioned previously, compensating the reactive and the distorted components, it will remain only the active current, whose value is zero (because of the inductive character corresponding to the passive load).

On the other hand, after the partial compensation, the current RMS value of each phase was modified to the values corresponding to a balanced current system: 9.85, 9.85, 9.85 A, proving the CPT capability of efficiently compensating not only the current distortion, but also, the current unbalance (Fig. 6).

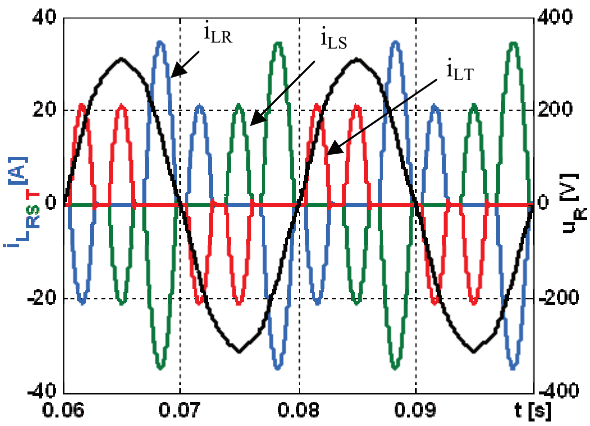


Fig. 5. The grid voltage and the unbalanced non-linear load currents

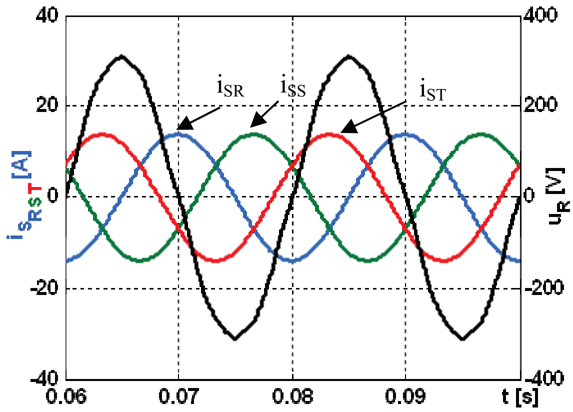


Fig. 6. The grid voltage and the source currents for partial compensation

## IV. Experimental Results

As it was mentioned, after the simulation analysis, the CPT computation was experimentally tested on an active filtering system consisting of:

- the three-wire power inverter;
- the 1[st] order interface filter consisting of three special coils having an inductance of 4.4 mH;
- the control system based on the dSPACE DS1103 acquisition board;
- the analyzed non-linear load, which is a three phase AC voltage converter, with an inductive passive load.

The command and control section of the system is a Matlab/Simulink model which uses DS1103 specific library blocks (Fig. 8).

This model is compiled and loaded to the DS1103 program memory.

The adopted current controller is a three-phase fixed band hysteresis controller. The hysteresis band is set up to 1 A, considering the maximum current value of 25 A.

The blocks which determine the three-phase current and voltage systems are necessary because the experimental active filter has only two transducers for each measured current or voltage system. So, because the power inverter has a three-wire configuration, the blocks compute the third component of the current using the two measured components.

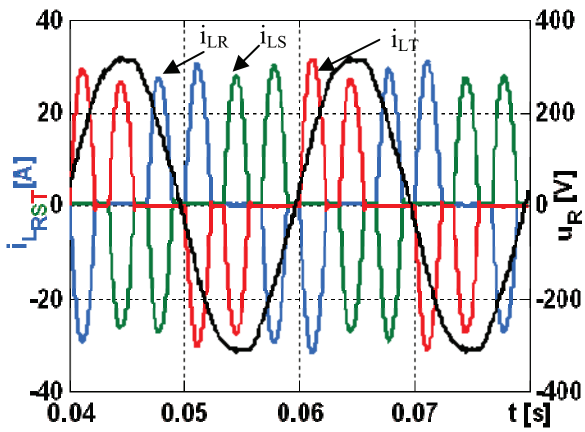


Fig. 7. The grid voltage and the non-linear load currents

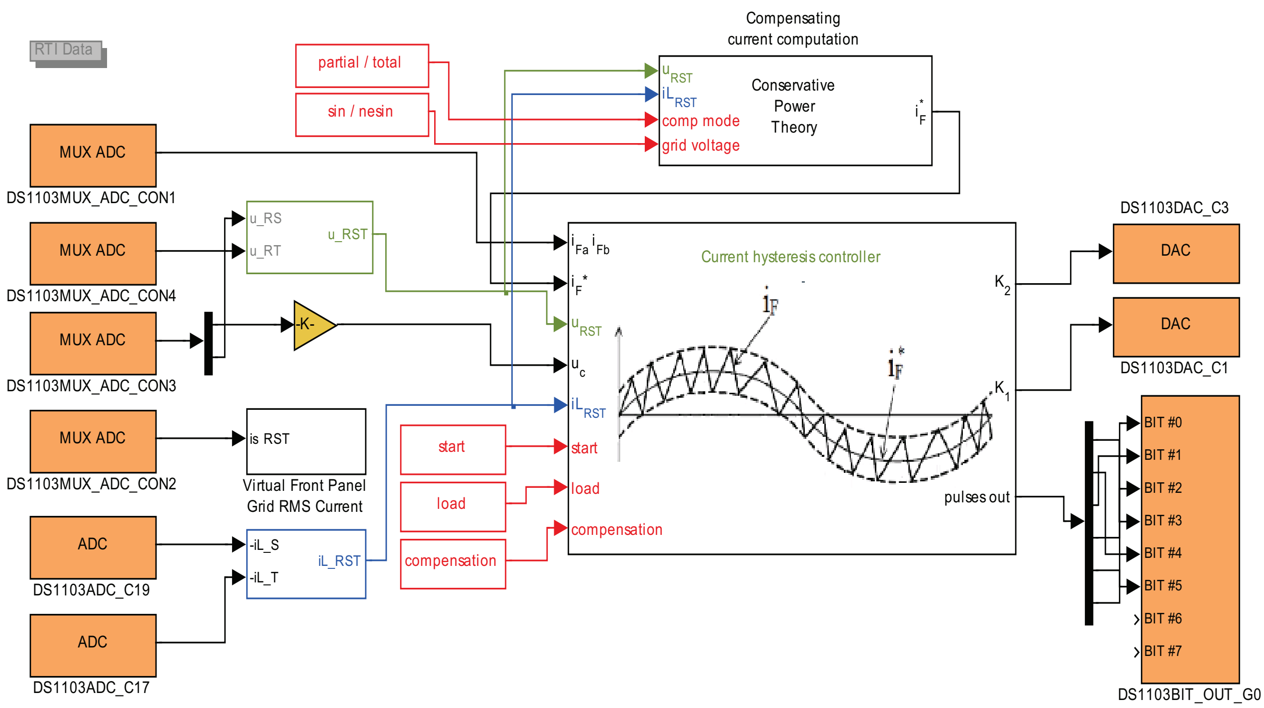


Fig. 8. The Simulink model which implements the active filter current computation and control algorithm

For the grid voltage, the three phase voltages are obtained using the measured line voltages ($u_{RS}$, $u_{RT}$). Moreover, because of the transducers position, the currents absorbed by the non-linear load are measured with opposite sign to the real.

*A. Symmetrical non-linear load*

For the 1st analyzed case, the non-linear load which is a three phase AC voltage converter, with an inductive passive load, absorbs a RMS value of approximately 15 A per phase. The exactly current RMS values of each phase are: 14.74, 13.68 and 14.44 A. Thus, comparing these values to the simulation case, they are different among the phases, the calculated asymmetry factor of the grid current having a value of 6.01%. In this case, the load can be considered as a symmetric one, the asymmetry being too low.

The specified asymmetry can be also observed by analyzing the load current waveforms, for each phase, which are illustrated in Fig. 7.

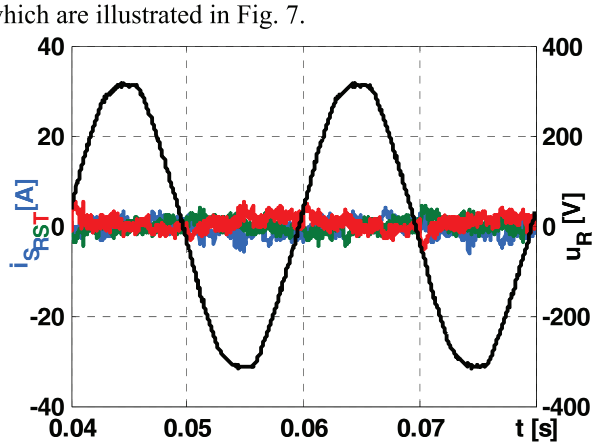


Fig. 9. The grid voltage and the source currents for total compensation

After the total compensation all the non-active components of the load were eliminated.

Thus, the RMS value of the current being absorbed from the grid dropped to 1.61, 1.51 and 1.68 A (Fig. 9).

This was because the analyzed load could not absorb active power, absorbing only reactive and distorted power. The load was designed for testing the active power filter operation.

The total harmonic distortion factor, after the total compensation, is not edifying because the grid current RMS value is very low being given only by the losses in the power inverter and by the auxiliary current necessary for the control and protection stages.

In addition, to emphasize the CPT capability of compensating the distorted component, the harmonic RMS current was also computed. Thus, it dropped from 10.94, 10.07 and 10.67 A to 0.93, 0.89 and 1.08 A.

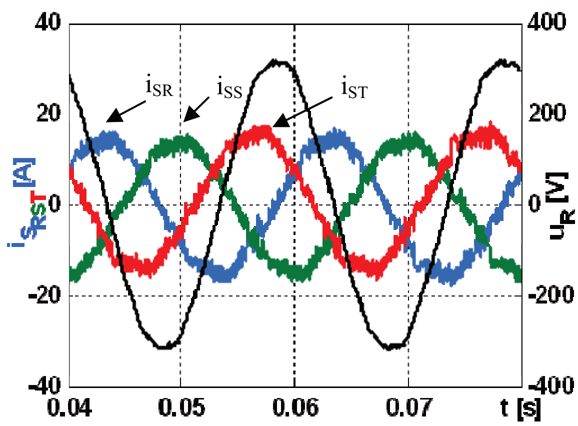


Fig. 10. The grid voltage and the source currents for partial compensation

In case of partial compensation, only the distorted component was eliminated (Fig. 10), the grid current RMS value decreasing to 10.74, 10.3 and 10.73 A.

The grid current shapes are almost sinusoidal, the partial harmonic distortion factor (for the first 51$^{th}$ harmonics) being reduced from 65.32, 60.30 and 64.58% to 5.26, 5.12 and 5.52%. Having the PHD values, the resulted filtration efficiency per phase is: 12.4, 11.78 and 11.69.

Because the RMS values of the load current were different among the phases, another important factor was computed, i.e. the asymmetry factor. Thus, after the compensation, the value of the above factor dropped from 6.01% to 2.56%.

It is worth mentioning that the asymmetry factor of the grid voltage had a value of 1.73%. Therefore, the remaining unbalance is due to the grid voltage asymmetry, the RMS grid voltage values being: 225.7, 222.8 and 229.6 V.

*B. Unbalanced non-linear load*

In order to prove the good results of the CPT implementation, regarding the asymmetry compensation, it was considered the previously load, this time with a higher unbalance. So, the RMS load current values for each phase are: 15, 14.46 and 9.32 A, having the waveforms illustrated in Fig. 11.

The load was analyzed for both partial and total compensation mode. When the compensating current was calculated using relation (9), all the non-active currents were removed (Fig. 12). Talking about the same non-linear load, which did not absorb active power, the value of the remaining current is very low, almost zero. After compensation, the harmonic RMS current was reduced from 10.95, 10.39 and 6.25 A to 0.96, 0.50 and 0.90 A.

For partial compensation, the compensating current is calculated with relation (10), and the phase shift between the grid voltage and current shows that the reactive component is still present (Fig. 13). The grid current RMS values were reduced, by compensation, to 9.63, 8.81 and 9.38 A.

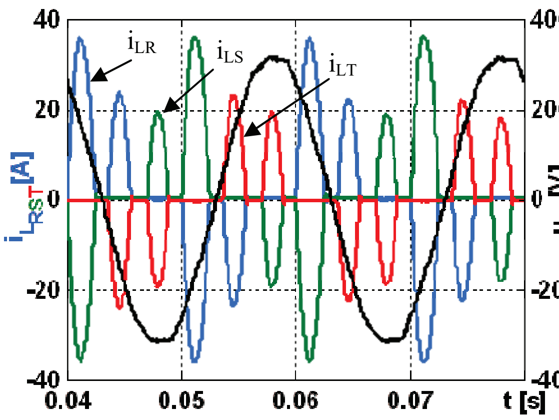


Fig. 11. The grid voltage and the unbalanced non-linear load currents

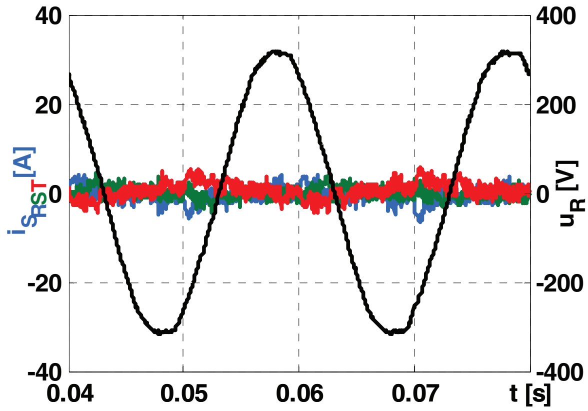


Fig. 12. The grid voltage and the source currents for total compensation

The resulted grid current shapes are approximately sinusoidal and the PHD factor decreases from 69.66, 68.62, 44.76% to 5.29, 5.69 and 4.89%. These values lead to a filtration efficiency of 13.16, 12.04 and 9.15.

Even if the asymmetry is much higher than before, i.e. an asymmetry factor of 33.31%, the CPT capability of compensating the current unbalance is proved one more time. Thus, after the compensation, the asymmetry factor dropped to 5.16%.

As it was noticed before, the remaining unbalance of the current was because of the grid voltage asymmetry. The measured grid voltage RMS values were: $U_R = 225.9$V, $U_S = 223.2$V, $U_T = 229.5$V, obtaining a grid voltage asymmetry factor of 1.6%.

The fact that the remaining unbalance of the current is not due to the compensation method inefficiency can be proved by analyzing the simulation results obtained using Matlab/Simulink environment (Fig. 6).

The grid current RMS values, after the compensation, are equal for all phases (9.85 A), the grid voltage RMS values being equal, so that the grid current system is equilibrated.

In the experimental case, taking into consideration the grid current asymmetry factor reduction, it can be concluded that the grid current system is equilibrated after compensation.

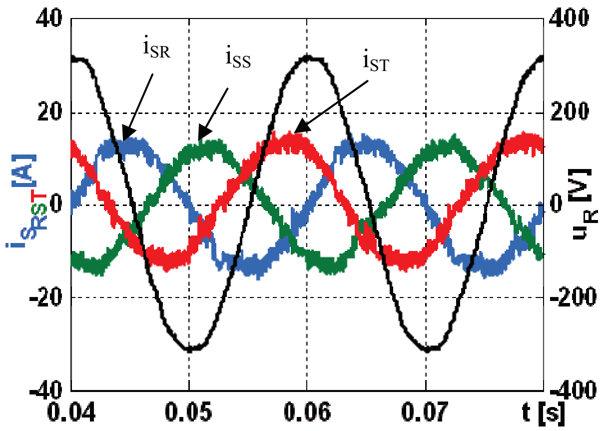


Fig. 13. The grid voltage and the source currents for partial compensation

## V. Conclusions

The results obtained by the Conservative Power Theory implementation, in active filtering, are good in the simulation case, as well as, in the experimental one. It was shown that the CPT method, by its current components, allowed both partial and total compensation, being an advantage when the reactive power compensation is not necessary.

Moreover, an unbalanced current component is defined, thus, it can be compensated, if desired, only the unbalanced current.

The result obtained by simulation are good, the current waveform, after the compensation, being sinusoidal. In case of partial compensation it keeps the phase shift because the reactive current is not eliminated.

On the other hand, for total compensation, because of the inductive character of the passive load, the current absorbed from the grid is zero, all the non-active components being removed.

The experimental results are also positive, the current harmonic distortion factor and also the load current asymmetry being reduced, after compensation. It must be mentioned that, because of the grid voltages asymmetry, the resulted grid current system has not the same RMS value for each phase.

However, taking into consideration the grid current asymmetry factor reduction, it can be concluded that the grid current system is equilibrated, after compensation.

Thus, the CPT capability of efficiently compensating not only the current distortion, but also, the current unbalance was validated by simulation, as well as by the experimental results.

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## References

[1] H. Akagi, E. H. Watanabe, M. Aredes, "Instantaneous Power Theory and Applications to Power Conditioning," Wiley-IEEE Press, 2007.

[2] L. S. Czarnecki, "Currents' Physical Components (CPC) in Circuits with Nonsinusoidal Voltages and Currents (Part 2: Three-Phase Linear Circuits)", EPQU Journal, Vol. XXII, No. 1, 2006, pp. 3-13.

[3] P. Tenti, "Conservative Power Theory Seminar: A theoretical background to understand energy issues of electrical networks under non-sinusoidal conditions and to approach measurement,accountability and control problems in smart grids", UNICAMP – UNESP Sorocaba, August 2012.

[4] P. Tenti, P. Mattavelli, "A Time-Domain Approach to Power Term Definitions under Non-Sinusoidal Conditions", 6th International Workshop on Power Definitions and Measurements under Non-Sinusoidal Conditions, Milano, October 13-15, 2003.

[5] P. Tenti, P. Mattavelli, Tedeschi Elisabetta, "Compensation Techinques Based on Reactive Power Conservation" , Electrical Power Quality and Utilisation, Journal vol. XIII, No. 1, 2007.

[6] Popescu Mihaela, A. Bitoleanu, M. Dobriceanu, "Compensation-Based Current Decomposition", Proceedings of World Academy of Science, Engineering and Technology, vol. 37, January 2009, pp. 598-603.

[7] Popescu Mihaela, Bitoleanu A., Dobriceanu M., "On the Current Decomposition Based on Instantaneous Apparent Power Vector", *Proc. of the 10th IASTED International Conference on Power and Energy System*, Baltimore, Maryland, USA, April 16-18, 2008, pp. 120-125.

[8] Y. Xu, L. M. Tolbert, J. D. Kueck, D. T. Rizy, "Voltage and Current Unbalance Compensation Using a Parallel Active Filter", Power Electronics Specialists Conference, June 2007, pp. 2919 – 2925.