Study of Indirect Current Control Methods for Urban Traction Active DC Substations

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***Abstract* —Although the high power DC traction substations are using 12 pulse rectifier which have lower distortion than the classical 6 pulse rectifier, considering the high power, the reactive and harmonic components of the absorbed current are harmful to the power grid. The addition of an active compensator to the classical dc traction substation creates the "active substation". The active substation allows bidirectional power flow between the power grid and the DC catenary, which means the active power flow from the power grid to the DC catenary and the recovered power flow from the catenary back to the power grid. At the same time, because the compensator acts like an active filter in the first case and like a power inverter in the last case, both the consumed and recovered power are active powers. To achieve this goal the active compensator must inject current to the point of common coupling, and the typical current controller is the hysteresis regulator. At the same time, the typical approach on the injected current regulation is the direct current control, which implies the closed loop control of the current at the compensator output, i.e. the current through the output inductors. A new approach is the closed loop control of the current absorbed from the power grid, i.e. the indirect control, for which the compensator controls the grid current, and for a given load current, the compensator injected current results from the first two.**

Keywords: *active compensator; indirect current control, DC traction substation.*

I. Introduction

The DC traction substations are powered by a medium voltage three-phase power grid and contain a transformer followed by a diode rectifier. The output rectifier gives a dc voltage having, mostly, the rated values of 750 V (tramways and underground railway, including Bucharest), 1500 V, and so on [1] – [6].

The need to increase the energetic efficiency by reducing the electric energy consumption requires two main actions [2]:

1. The filtering of distorted current absorbed by the traction substations, especially those which contain 6-pulse three-phase bridge rectifiers;
2. The energy recovery developed by the vehicle during the braking process.

In the case of existing systems, just a small fraction of the braking recovered energy is reused and only for auxiliary services. The remaining energy is wasted on the train braking resistances.

In this paper, the indirect current control is analyzed, proposed by the authors for a filtering and regeneration system (SISFREG). This system converts a typical dc traction substation, with 6-pulse three-phase bridge rectifier, in an "active substation", which allows the bidirectional power flow between the power grid and the DC catenary.

In the first section, a brief description of the theoretical definitions is given, followed by the virtual system description and the meaning of each block being presented. The system structure description is followed by the control block structure substantiation based on the indirect current control methods.

Further the paper illustrates obtained performances for both the filtering mode, and the recovery mode. The numerical data corresponds to a traction substation related to Bucharest underground railway system.

In the next chapter, the obtained performances of the virtual system were experimentally validated using an experimental scale model. Because the railway vehicle – catenary aggregate is difficult to be implemented in a scale model, the experimental validation targeted only the traction / filtering operating mode of the system.

In the last section, the conclusions, concerning the performances and the comparative results of the analyzed system, are drawn.

II. The indirect current control

For this new approach regarding the current regulation in the PCC, two directions appear in the literature [7]:

- The direct current control – the classical approach - it assumes that the active compensator inner current loop controls the current injected by the active filter in the point of common coupling. As a result, the current drawn from the power grid is the active (and maybe the reactive) part of the load current, because the non-active current requisite by the load is supplied by the active compensator. In this case, the active compensator control block will compute the nonlinear load non-active current (the compensating current) and also, the active current used by the active compensator to charge the compensating capacitor and to cover the inverter losses. So, the compensating current is prescribed positive to the current loop (because it is generated by the active filter and supplied to the nonlinear load) and the loses covering current is negative because it is absorbed from the power grid by the active filter;
- The indirect current control –assumes that the active compensator current loop controls the grid current at the PCC side, instead of the filter current. This current control method has two directions:

- the desired grid current is obtained based on the distorted load current (using a typical current decomposition method: p-q theory, synchronous rotating reference frame, Conservative Power Theory, etc);
- the desired grid current is obtained based on the dc voltage controller.

A. Desired grid current computation based on the distorted load current

In this case, the loop reference current is the sum of the grid desired current (typically the nonlinear load active current, but it can contain the reactive current, when the partial compensation is desired) and the active filter losses covering current. The losses covering current is the same as in the direct current control and is obtained in the same way, but it summed to the *compensated* current and not subtracted from the *compensating* current (Fig. 1).

So, considering the synchronous rotating reference frame as the decomposition method, and the total compensation, the desired grid current is computed with [8]:

$$\begin{bmatrix} i^*_{Sa} \\ i^*_{Sb} \\ i^*_{Sc} \end{bmatrix} = G_{Lech} \cdot \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} + \begin{bmatrix} i_{Fa} \\ i_{Fb} \\ i_{Fc} \end{bmatrix} \tag{1}$$

Where:

- i^*_{Sa}, i^*_{Sb}, i^*_{Sc}, - grid desired phase currents;
- u_a, u_b, u_c, - grid phase voltages;
- i_{Fa}, i_{Fb}, i_{Fc}, - losses covering (active) currents;
- G_{Lech} - load equivalent conductance, computed with [8]:

$$G_{ech} = \frac{I_{L1}}{U_{S1}} \tag{2}$$

- I_{L1} - RMS value of the load active current fundamental [8];
- U_{S1} - RMS value of the grid voltage fundamental (for distorted grid voltage) [8];

The grid voltage fundamental is computed using the rotating synchronous dq frame [8], and the nonlinear load active current fundamental is computed also using the rotating synchronous dq frame, but adequately shifted and corrected [8].

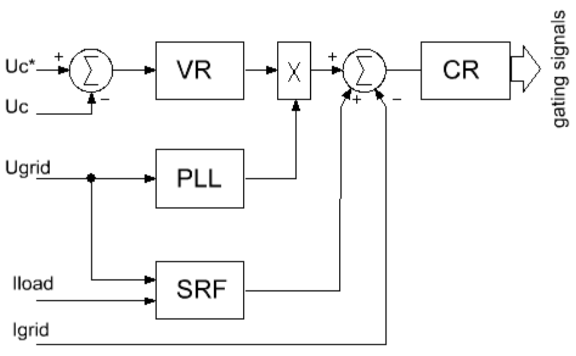

Fig. 1. The active compensator control algorithm based on on the distorted load current

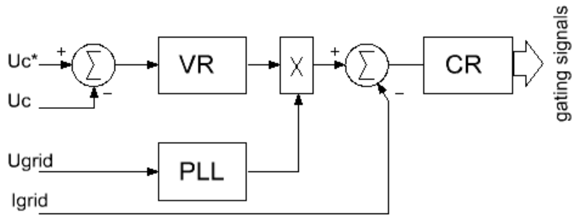

Fig. 2. The active compensator control algorithm based on on the DC-Link voltage controller

B. Desired grid current computation based on the DC-Link voltage controller

For this approach, the grid compensated current can be only the load active current and active compensator losses covering current, so only the total compensation can be obtained (Fig. 2).

This desired current is obtained "automatically" by the DC-Link voltage regulator, because the active current changed by the compensating capacitor to the power grid is proportional to the voltage oscillation across it [9].

So, compensating capacitor voltage oscillations can be used to estimate the active current as follows: the DC-link voltage regulator output (which is a function of the compensating capacitor voltage error, which in turn is the voltage variation across the compensating capacitor) is the amplitude of the active component of the total current drawn from the power grid. This value is multiplied to a unitary amplitude three-phase signals, in phase with the grid voltage and finally prescribed to the current regulating loop.

III. The Virtual System

The virtual system of the active urban traction dc substation is illustrated in Fig. 3 and corresponds in fact to the both studied cases, because the necessary modifications were made in the current regulating loop.

As it can be seen, the system is composed of three major parts:

- the 20 kV, distorted, three-phase power grid;
- the classical DC traction substation modeled by the three-phase diode rectifier followed by the block implementing the catenary with the trains accelerating or braking;
- the active compensator / braking energy recovery system which includes besides the compensator itself the grid transformer and the separating circuit.

The Simulink model also contains auxiliary blocks, used for the computation of power quality indicators, meters, oscilloscopes, etc.

The model has two functional sequences:

- traction / filtering mode;
- braking energy recovery mode.

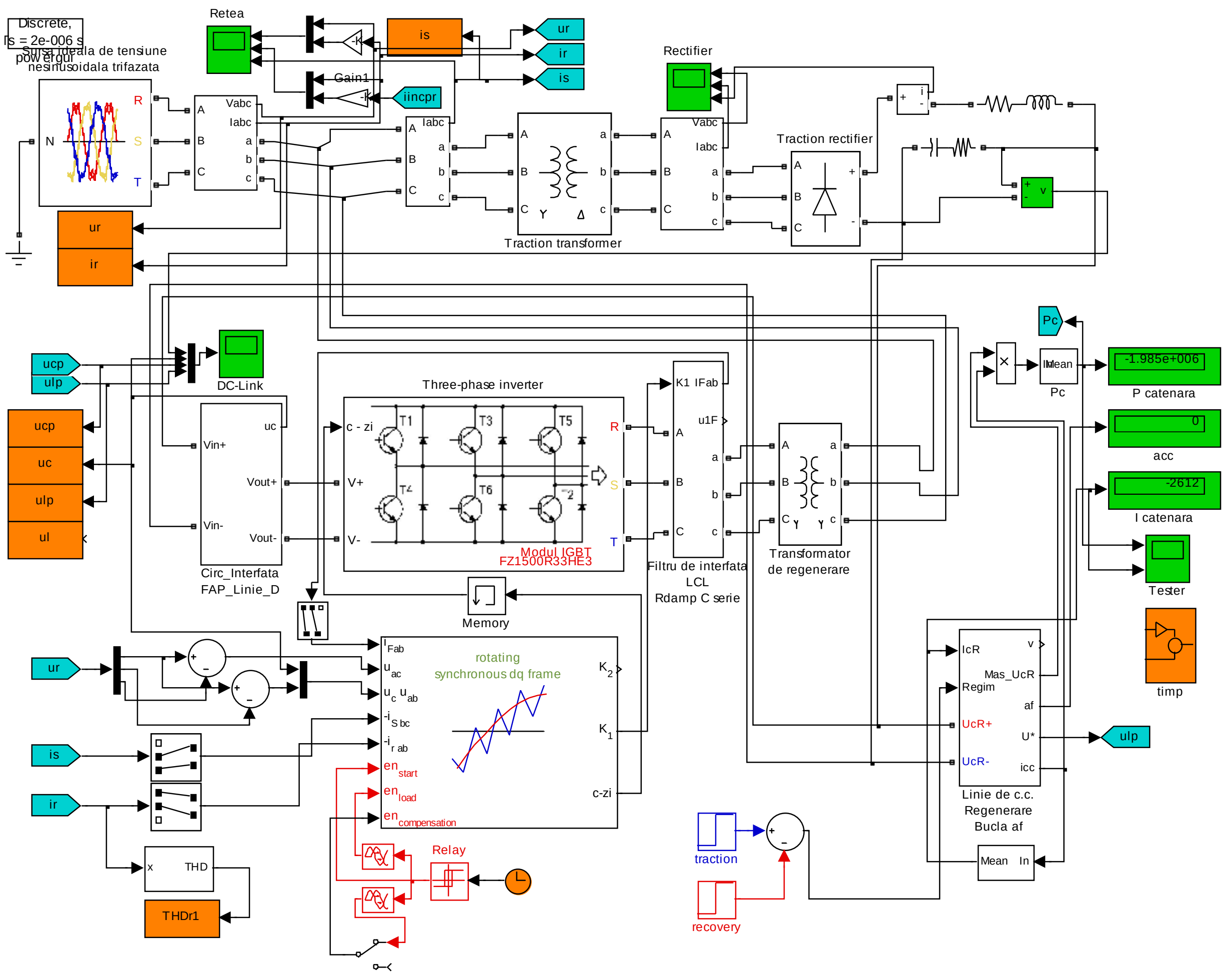

Fig. 3. The Simulink model of the active urban traction dc substation

- Traction / compensation –the *Catenary/Vehicle* block simulates the train accelerating regime, so the three-phase traction rectifier is functional consuming power from the power grid and supplying the catenary. As a result, the active compensator is filtering the current distortion and reactive power absorbed by the traction rectifier. The grid current is the active current, in phase with the grid voltage and with the same shape.
- Braking / recovery - the *Catenary/Vehicle* block simulates the train electrical braking regime, so the three-phase traction rectifier is blocked, the voltage on the catenary increases, connecting the compensating capacitor to the catenary through the interface circuit. Now, the power flow is from the catenary to the compensating capacitor and further to the power grid via the compensator power inverter and transformer. The grid current is also an active current with the same shape as the voltage, but with reversed phase because the power is transferred from the catenary (train) to the power grid.

The traction and braking mode of the DC line is controlled to simulate the sequence traction – braking – traction using *Step* blocks and, the *Catenary/Vehicle* block.

IV. Simulation Results

The current absorbed by the traction substation, without the compensation is illustrated in Fig. 4

It can be seen that the traction substation current absorbed from the power grid is the typical current absorbed by a three-phase diode rectifier using a Y-Δ transformer, having a total harmonic distortion factor of 21%. The total harmonic distortion factor and the partial harmonic distortion factor were calculated using:

$$THD = \sqrt{\frac{\sum_{k=2}^{\infty} I_k^2}{I_1^2}} = \sqrt{\frac{I^2}{I_1^2} - 1} \tag{3}$$

$$PHD_n = \sqrt{\frac{\sum_{k=2}^{n} I_k^2}{I_1^2}} \tag{4}$$

Where n is the highest harmonic order taken into consideration.

When the system is fully functional (the compensator is functioning) the total active power absorbed from the grid is about 1.985 MW, close to the nominal power of the traction substation.

A. Desired grid current computation based on the distorted load current (synchronus rotating dq frame)

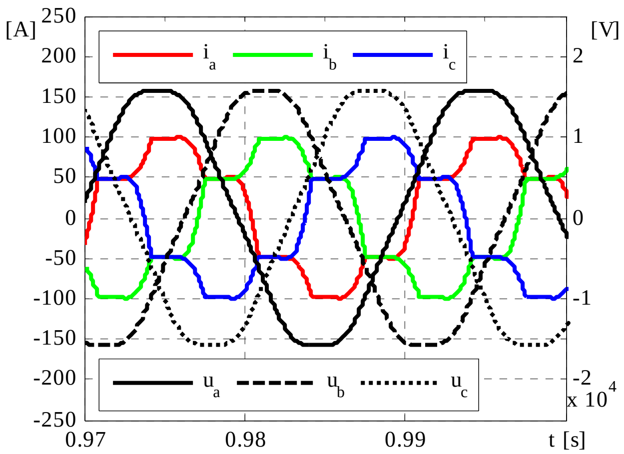

Fig. 4. The nonlinear load current

The current absorbed from the power grid in traction operation is illustrated in Fig. 5.

Because the voltages on all phases are distorted (THDU = 3.04%) and the compensated current took the voltage shape, the better the compensation is, the closer are the THD values. So, the total harmonic distortion of the current absorbed by the active substation had been reduced from 21% without compensation, to 3.73%, with compensation.

This gives a filtering efficiency of 5.62, but also, a supplementary distortion of the current of 22% compared to the voltage distortion. This distortion is due to the switching operation of the active filter but also due to the performance of the control algorithm. The last component will be visible when the results of this algorithm will be compared to the results of the other algorithm.

Another important aspect is the current distortion of the recovered current which again, it ideally takes the voltage distortion. The recovered current shape is illustrated in Fig. 6, and its total harmonic distortion factor is 2.90%. Because the voltage regulator output in static regime is constant, the recovered current shape is identical (in theory) to the voltage shape, so the slightly lower recovered current THD compared to the grid voltage THD can be explained by the passive current filtering done by the compensator power transformer (the generated recovered current harmonics are reduced by the transformer giving a less flattened waveform).

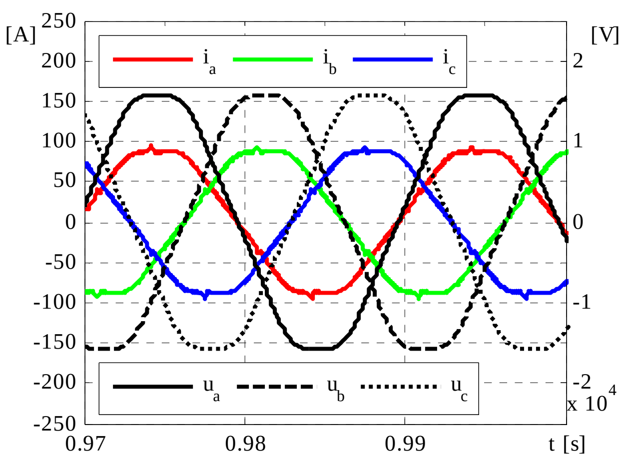

Fig. 5. The current absorbed from the power grid in traction operation when the desired grid current computation is based on the distorted load current

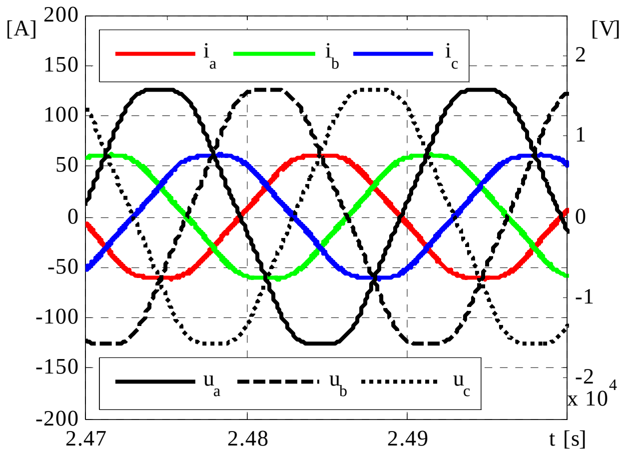

Fig. 6. The current generated to the power grid in recovery operation when the desired grid current computation is based on the distorted load current

Obviously, the current generation in recovery mode does not depend whatsoever by the synchronous rotating d-q frame current decomposition method, but it depends on the voltage regulator performance, which in turn is dependant by the proportionality and integration constants (different for the two algorithms, as expected).

B. *Desired grid current computation based on the DC-Link voltage controller*

In this case, the current absorbed by the active substation, from the power grid in traction operation, is illustrated in Fig. 7. For this control algorithm the total harmonic distortion factor of the grid current is 3.15% which gives a filtering efficiency of 6.66, with the supplementary distortion of the current of 3.51% compared to the voltage distortion. Though, this low distortion is not due to the similarity between the grid current and voltage shapes, as it can be seen in Fig. 8, because the supplementary distortion due to the switching operation of the active compensator is compensated (in terms of total harmonic distortion factor) by the waveform shape which is less flattened.

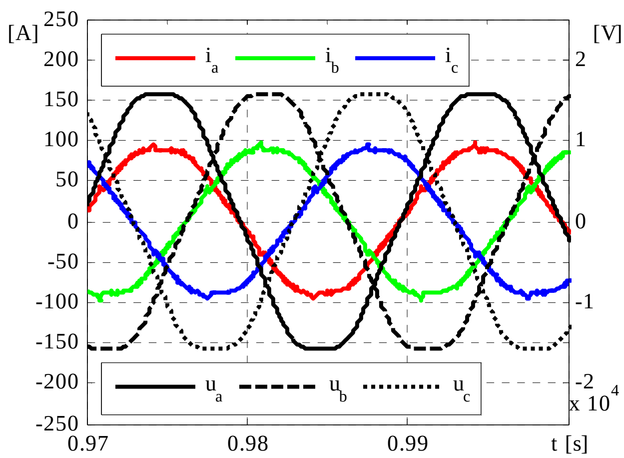

Fig. 7. The current absorbed from the power grid in traction operation when the desired grid current computation is based on the DC-Link voltage controller

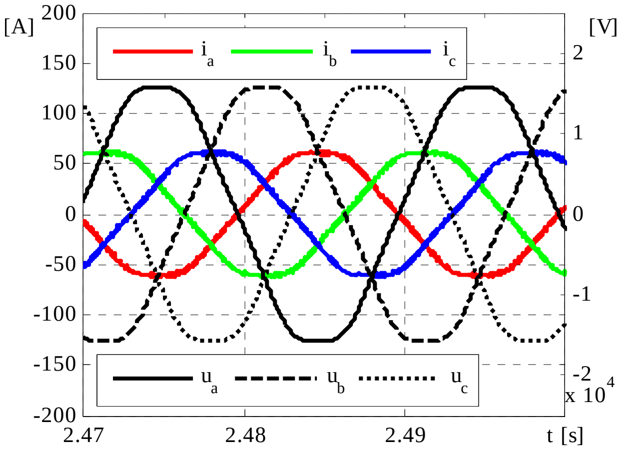

Fig. 8. The current generated to the power grid in recovery operation when the desired grid current computation is based on the DC-Link voltage controller

Yet again, this less flatten shape is not the result of the voltage regulating loop (which prescribes to the current regulating loop a current with the same shape as the voltage), but the result of a shortcoming of the compensation – close to the current amplitude is a current overshoot due to the incapacity of the active compensator to filter the steep load current switching.

The recovered current shape, illustrated in Fig. 8, and its total harmonic distortion factor is 2.90%.

It can be observed that besides the passive filtering of the compensating current done by the compensator grid transformer (whose effect is reflected in the compensated grid current), which appears again as expected, is can be graphically observed that addition switching distortion is present in the recovered current waveform. This additional distortion is present in the current total harmonic distortion factor.

V. EXPERIMENTAL RESULTS

Some of the simulation results were experimentally validated on a scale model of the active substation. The experimental setup includes:

- The traction substation formed by:
  - Traction transformer;
  - Traction rectifier;
  - Passive DC load.
- The active filtering system formed by:
  - 1st order interface filter;
  - Power inverter;
  - Compensating capacitor;
  - Industrial computer;
  - dSpace DS1103 control system.

As stated, the control algorithm of the active filter was implemented on the dSpace DS1103 control and acquisition board. The grid desired current computation and the two control loops (the compensating capacitor voltage control and the power grid current control) were implemented through a Matlab Simulink model, which was compiled and loaded to the DS1103 program memory.

The filtering system was controlled using a virtual control panel, implemented on the control board specific software (Fig. 9). All the controls on the virtual control panel were linked to the Simulink model appropriate variables, so not only the system functions can be controlled by means of Simulink blocks and model variables, but the time evolution of model variables can be viewed on virtual oscilloscopes placed on the control panel.

Likewise, the evolution of the control board inputs (system transducers outputs) can be viewed real time on control panel virtual oscilloscopes, because the signals applied to the DS1103 DAC inputs are converted to Simulink model signals by means of the DS1103ADC_Cx and DS1103MUX_ADC_CONx Simulink blocks.

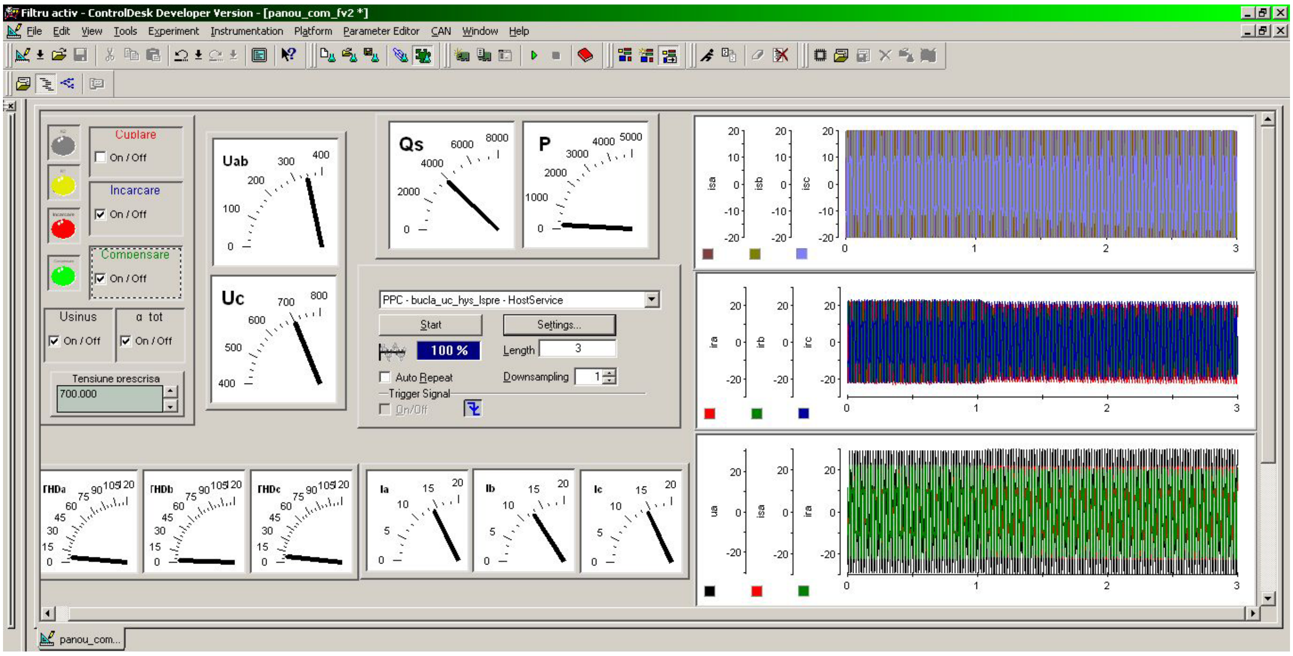

Fig. 9. The virtual control panel of the filtering system

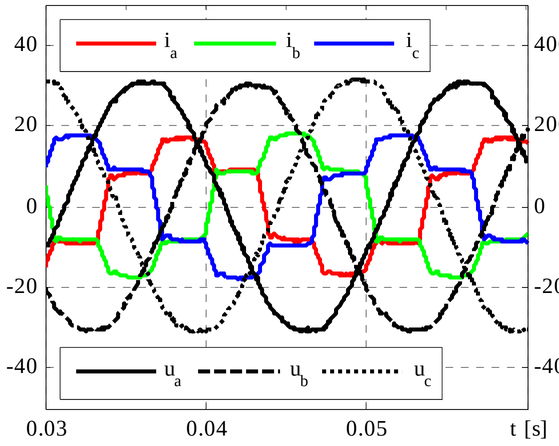

Fig. 10. The current absorbed from the power grid by the experimental rectifier

The current absorbed from the power grid by the traction rectifier (Fig. 10) is about 12 A per phase with a total harmonic distortion factor of 24.15%. When the filtering system is activated, the current drawn from the power grid is illustrated in Fig. 11. The computation method for the desired grid current is based on the load current; in other words, the synchronous rotating d-q frame is used for extracting the active component of the load current which is further imposed to the current regulator.

It can be seen that the grid resulted current is almost taking the voltage shape, with a total harmonic distortion factor of 8.67%, giving a filtering efficiency of 2.78. The grid current partial harmonic distortion factor, PHD_{51}, (calculated for the first 51 harmonics) is 4.72%, which is almost half of the total harmonic distortion factor.

Regarding the grid voltage THD, it is 3.81%, with the most important harmonics being the 5^{th}, 7^{th}, and 13^{th}. The PHD of the voltage (calculated for the first 51 harmonics) is 2.28%, while the PHD (calculated only for the 5^{th}, 7^{th}, and 13^{th} harmonics) is 2.18%. This leads to the conclusion that the active filter switching operation is noticeably affecting the voltage although the laboratory power grid is a relatively strong grid.

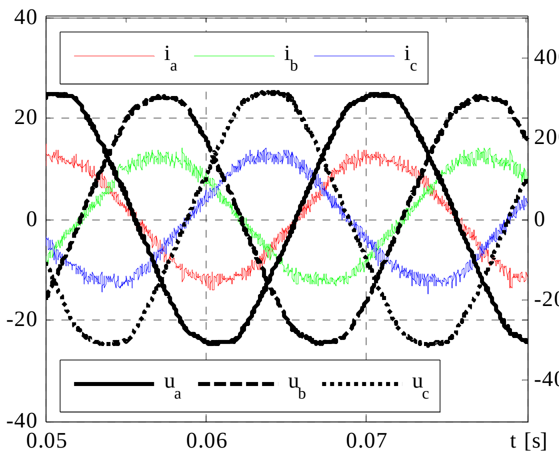

Fig. 11 The current absorbed from the power grid in traction operation when the desired grid current computation is based on the distorted load current

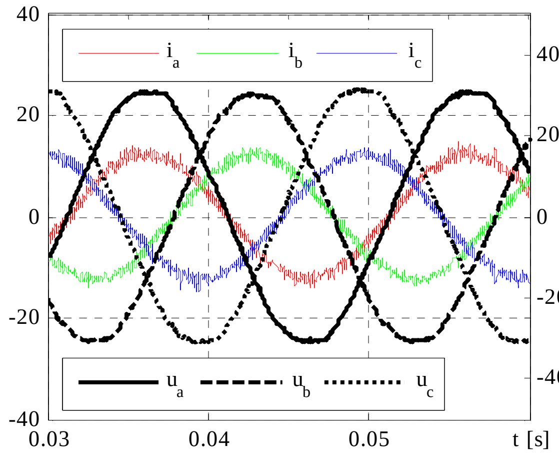

Fig. 12. The current absorbed from the power grid in traction operation when the desired grid current computation is based on the DC-Link voltage controller

Likewise, the difference between the power grid current THD and PHD_{51} is showing that a great amount of the compensated current distortion is due to the switching operating of the active filter – This is explicable by the relatively low power rating of the experimental active filter, for which the current hysteresis band of about 1.85A is quite high related to the compensated grid current RMS of 8.8 A.

However, the compensated grid current PHD (calculated only for the 5^{th}, 7^{th}, and 13^{th} harmonics) is 2.03, which if compared to the voltage corresponding PHD of 2.18 shows that the neglecting the switching harmonics, the compensation goal of making the grid current to take the voltage shape after the compensation was achieved.

When the grid current computation is based only on the voltage regulator, which is the second approach (Fig. 12), the grid current THD is 8.79%, which is insignificantly higher than in the previous case. What differs, however, is the grid voltage THD, which in this case is 2.52%, this difference being obviously determined by the active filter change in operation. The voltage PHD_{51} is 1.93 is and the PHD (calculated only for the 5^{th}, 7^{th}, and 13^{th} harmonics) is 1.79. At the same time, the grid current PHD (calculated only for the 5^{th}, 7^{th}, and 13^{th} harmonics) is 2.16, which is not that similar to the grid corresponding voltage PHD. Also, the fact that the current PHD is higher means that the current is less sinusoidal than the voltage, which means that this control method also reached the compensation goal but with a slightly lower performance.

The numerical simulation results as well as the corresponding numerical experimental results are synthesized in Table 1, where:

- THDI - the grid compensated current total harmonic distortion factor;
- $PHDI_{51}$ - the grid compensated current partial harmonic distortion factor (calculated for the first 51th harmonics;
- $PHDI_{5,7,13}$ - the grid compensated current partial harmonic distortion factor (calculated only for the 5^{th}, 7^{th}, and 13^{th} harmonics);
- THDU, $THDU_{51}$, $THDU_{5,7,13}$ – the corresponding total and partial harmonic distortion factor calculated for the grid voltage.

TABLE I.
NUMERICAL RESULTS

	THDI	$PHDI_{51}$	$PHDI_{5,7,13}$	THDU	$PHDU_{51}$	$PHDU_{5,7,13}$
Desired grid current computation based on the distorted load current – traction / filtering mode						
Simulation	3.73	3.67	3.35	3.04	3.04	3.04
Experimental	8.67	4.72	2.03	3.81	2.28	2.18
Desired grid current computation based on the DC-Link voltage controller						
Simulation	3.15	2.80	2.17	3.04	3.04	3.04
Experimental	8.79	4.29	2.07	2.52	1.93	1.79

CONCLUSIONS

In this paper is a comparative study was done between two control methods for an active filtering and energy recovery system for high power DC traction substations. These indirect current control methods, refers to the closed loop control of the current absorbed from the power grid, for which the compensator controls the grid current, and for a given load current, the compensator injected current results from the first two. The both methods achieved good results with very small performance differences, yet, slightly higher performance being obtained by the first studied control algorithm, particularly regarding the reduction of the power grid voltage distortion.

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