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Abstract

This paper analyzes a control method for a filtering and regenerative system which can be attached to a classical DC traction substation. This allows the conversion of the classical traction substation in an active traction substation. The latter absorbs, from the power grid, only the active component of the substation current, which is computed using the Conservative Power Theory. On the other hand, the active traction substation can inject to the power grid the braking energy recovery current, which is also an active current. For this purpose, an indirect current control method had been implemented on a virtual system and validated on a scale experimental model.

Keywords: Active Filtering, Conservative Power Theory, Indirect Control, Railway DC Traction Substations

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Introduction

In the paper a control method for a filtering and regenerative system is analyzed.

This allows the conversion of the classical dc traction substations in active traction substations [1], [2]. The main properties of the active traction substations are that they absorb, from the power grid, only the active current, in the same time they can inject active current to the power grid. This means that the harmonic current of the traction rectifier is compensated by the active compensator and the braking energy can be recovered to the power grid.

After a brief introduction in this section, the next section presents the filtering and recovery component of the active substation. This system contains a shunt active compensator with IGBTs and a unidirectional circuit for the interface between the compensator and the catenary. The active compensator is connected on one side to the catenary through the separating circuit, and on the other side, to the power grid through the step up recovery transformer.

The description of each block is followed by the control block structure substantiation based on the indirect current control and the active load current computation, in the “The Control Block Structure Substantiation based on the Indirect Current Control and the Grid Desired Current Control and the Grid Desired Current Computation” section. The control part is a cascade structure that contains two loops, one very fast for control of the grid current and other for DC voltage control. The desired grid current is computed by adding two currents. First is the active current absorbed by the traction rectifier, using the Conservative Power Theory (CPT), the newest theory about non-sinusoidal regime, developed by Paolo Tenti. The second component is the active current required to cover the losses into the active power filter and to keep constant the compensating capacitor voltage. This current is obtained from the DC voltage controller (PI controller). The desired grid current is compared to the real grid current and the error is applied to the current controller (hysteresis controller).

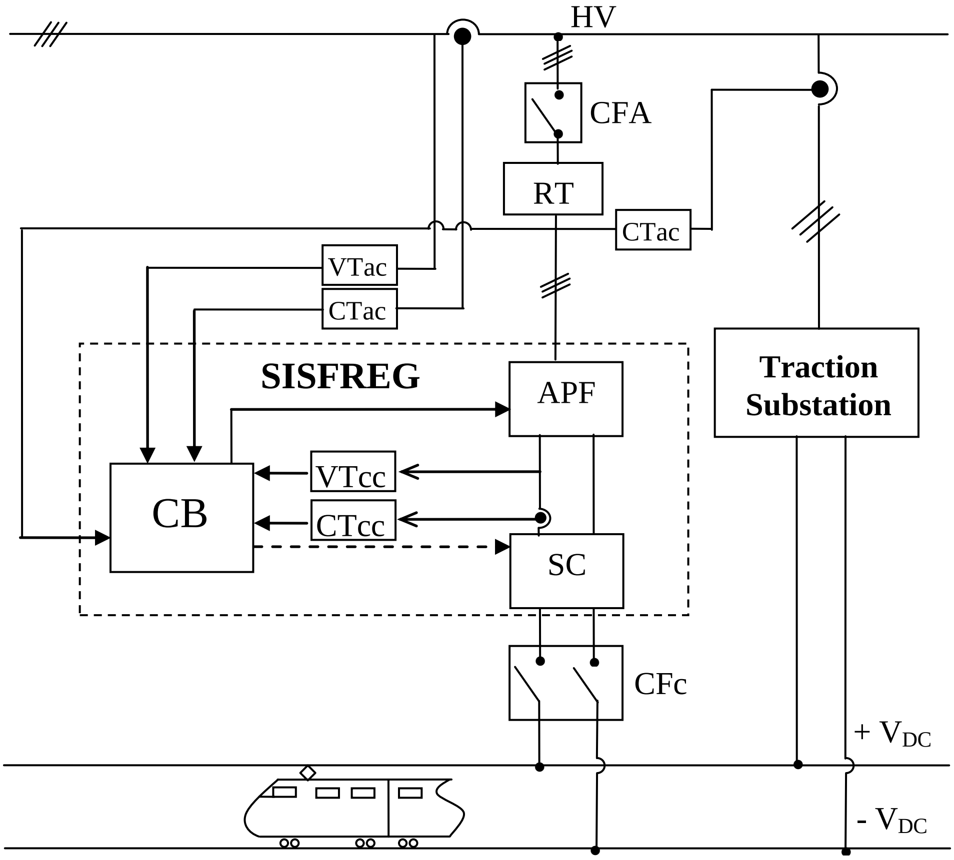
Thus, the “The Active Current Definitions in Three-Phase System based on the CPT under Non-sinusoidal Voltage” section, the main part of the paper, presents the active current definitions based on the CPT under non-sinusoidal voltage. Further, in the “The Simulink Model of the Regenerating and Compensating System for DC Traction Substations with 12-pulse Bridge Parallel Rectifier” section the paper describes the complete Simulink model of the regenerating and compensating system for dc traction substations with 12-pulse bridge parallel rectifier. The obtained simulation results are illustrated in the “The Simulation Results for the Filtering and the Recovery Mode” section. The model is analyzed for the filtering mode, as well as, for the recovery mode.

The last section emphasizes the experimental results, for the filtering mode, obtained by implementing the proposed control method, this time, on a scale model of the regenerating and compensating system for dc traction substations with a six-pulse bridge rectifier. The conclusions, concerning the performances and advantages of the analyzed system, are drawn at the end of the paper.

The Filtering and Recovery System Structure

The main element of the regeneration and filtering system added to the traction substation is a shunt active power filter (with IGBTs). The IGBT bridge of the active filter is connected on one side to the high voltage power grid through a dedicated transformer, and on the other side, the DC-Link containing the compensating capacitor is connected to the traction line, through a unidirectional separating circuit (Figure 1). The unidirectional separating circuit is necessary to allow the regeneration mode operation, in other words to allow the energy flow only from the catenary to the active filter compensating capacitor. Consequently, the main functions of the separating circuit are: energy buffer between the dc line and the active filter when the braking energy is recovered to the power grid, it allows the recovery current flow when the traction motors of the vehicle request it and disconnects the active filter from the dc line if the recovery current does not exist.

Figure 1. *The Block Schematic of the Regenerating and Compensating System for DC Traction Substations with 12-Pulse Bridge Rectifier*



The transition from filtering to energy recovery occurs naturally as well as the transition from energy recovery to filtering. This means that when the train is braking, the catenary voltage increases naturally ceasing the traction rectifier operation. At the same time, the separating diode turns on increasing the compensating capacitor voltage. The voltage regulator response is a current prescribed to the active filter with opposite phase to the grid voltage, to discharge the capacitor and reduce the DC-Link voltage back to the operating value. In a similar manner, when the train stops braking and accelerates, the catenary voltage decreases and the traction rectifier enters normal operation. Because the DC-Link voltage was kept at the operating value during recovery, the capacitor voltage is now greater than the catenary voltage and the separating diode turns off naturally. Because the traction rectifier is again functional, its current is again compensated by the active filter. As seen, there is no additional control needed to make the active filter switch from the filtering mode to the energy recovery mode and back to the filtering mode. All the transitions are accomplished naturally by the traction rectifier and separating diode on one hand, and by the DC-Link voltage regulator on the other hand which adapts at the DC-Link voltage change.

The Control Block Structure Substantiation based on the Indirect Current Control and the Grid Desired Current Control and the Grid Desired Current Computation

Direct Current Control vs. Indirect Current Control

Regarding the active power filter current regulating loop, in the literature two directions are covered:

- Direct current control – which is the classical approach [3]-[5] and it assumes that the current loop controls the current injected by the active filter to the power grid, i.e. the current through the interface filter inductors. As a result, the grid compensated current is the sum of the load current and the filter compensating current. For this approach, the active filter control block must compute the nonlinear load non-active current (the compensating current) and the active current needed by the active filter to charge the DC-Link capacitor and to cover the losses. Regarding the conventional current flows, 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 looses covering current is negative because it is absorbed from the power grid by the active filter;
- Indirect current control – it is a new approach [6]-[8] and it assumes that the active filter current loop controls not the generated current but the grid current at the PCC side. This way, the current loop reference current is the sum of the grid desired current (typically the nonlinear load active current) and the active filter losses covering

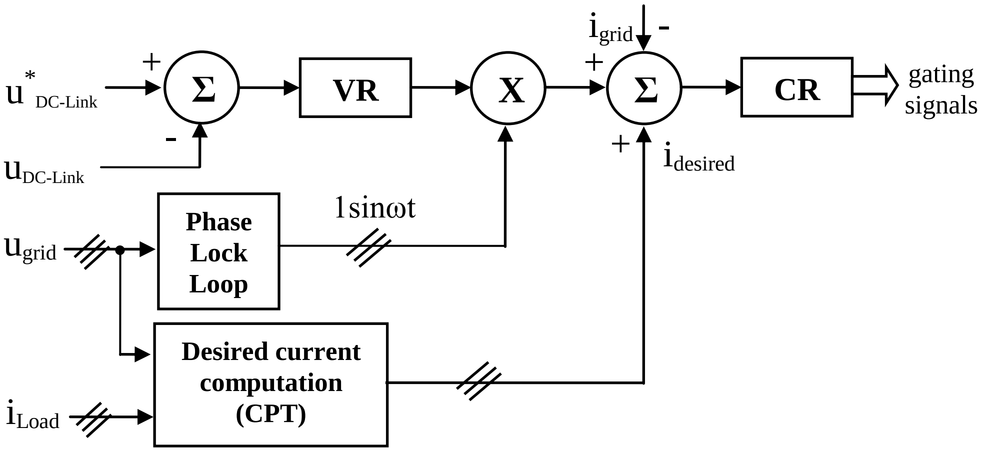
current. The losses covering current is the same as the previous case and is obtained in the same way. The grid desired current is obtained using any current decomposition method [9]-[14]. Regarding the conventional current flows, the grid desired current is positive (because being an active current, is absorbed from the power grid and thus is in phase with the grid voltage) and the losses covering current is also positive (also absorbed from the power grid) but with opposite sign as in the previous case. This is because the current transducer is oriented from the grid to the active filter while previously its orientation was from the filter towards the power grid.

The Active Filter Control Block for the Indirect Current Control with the Grid Desired Current Computation

The block control schematic of the active filter for the indirect control is illustrated in Figure 2.

The control structure was created starting from the classical control structure of a shunt active power filter. Consequently, it contains two regulating loops, an internal fast response regulating loop for the grid current control and an external low response regulating loop for the compensating capacitor voltage control.

Figure 2. *The Active Filter Control Structure for the Indirect Current Control with the Grid Desired Current Computation*



For simplicity, the internal loop uses three simple and reliable hysteresis current regulators (CR), one for each phase, with their known advantages and disadvantages (they are very simple, robust and with no tuning required, but the switching frequency of the power inverter is variable).

The voltage regulating loop, on the other hand is using a single PI regulator (VR). The regulator output is the amplitude of the current needed to charge the compensating capacitor and to cover the system losses. Accordingly, the regulator output is multiplied with three unitary sinusoidal signals (in phase with the power grid voltages) giving the three prescribed losses covering grid currents.

The losses covering current is added to the grid desired current and the result is applied to the hysteresis current regulator. At the current regulator reaction input the instantaneous grid current is applied (from the Current measurement Simulink block for the virtual system and from the DS1103MUX_ADC_CON3 Simulink block for the experimental system – which is the block giving the virtualized signal from the DS1103 board multiplexed analog to digital converter – the signal at the ADC input is received from the corresponding experimental system current transducer).

At the three-phase hysteresis current controller output the gating signals for the power transistors are available. In the virtual system this signals are applied to the virtual IGBTs gates and for the experimental system, these signals are applied to the DS1103_BIT_OUT_G0 Simulink output port, which is the port corresponding to the board digital outputs. The digital outputs are applied to the power IGBTs through a specialized amplification and protection circuitry.

The Active Current Definitions in Three-Phase System based on the CPT under Non-sinusoidal Voltage

As it was mentioned in the previous section, the reference current is the sum of the grid desired current (i^*_{grid}) and the active filter losses covering current (i_{aF}). The grid desired current is obtained using the CPT current decomposition method [12]-[14]. It will be calculated from the load current depending on the compensation goals. Thus, if partial compensation is needed, the grid desired current will be computed using relation (1):

$$\underline{i}^*_{grid} = \underline{i}_{aL} + \underline{i}_{rL} + \underline{i}_{aF} \tag{1}$$

In this case the active filter will compensate only the distortion component.

On the other hand, for the total compensation, the active filter will compensate the entire non-active current components and the grid desired current will be expressed as follows:

$$\underline{i}^*_{grid} = \underline{i}_{aL} + \underline{i}_{aF} \tag{2}$$

The CPT current components (the active and reactive terms) are defined as follows:

$$\underline{i}_{aL} = \frac{\mathbf{P}}{\mathbf{U}^2}\underline{u} \tag{3}$$

$$\underline{i}_{rL} = \frac{W}{\widehat{\mathbf{U}}^2}\underline{\widehat{u}} = B^b\underline{\widehat{u}} \tag{4}$$

where,

- $\underline{i}$ means the column vector containing the components of i on each phase (i_R, i_S, i_T);

- **P** and W are the three-phase active power respective the reactive energy of the load.

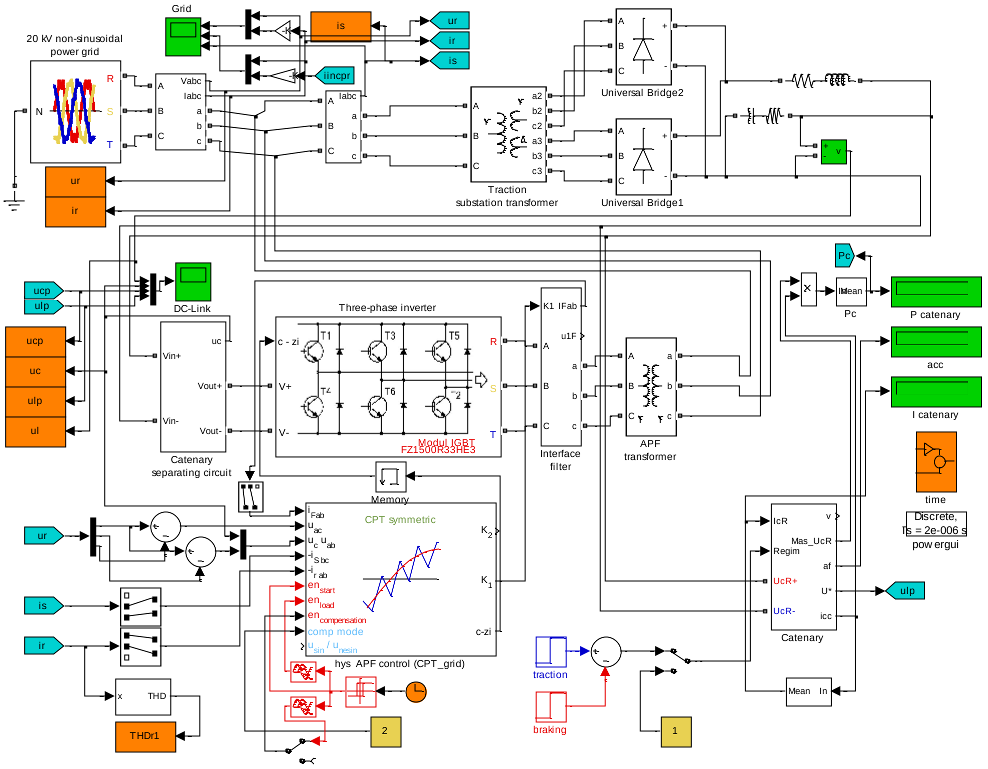
The Simulink Model of the Regenerating and Compensating System for DC Traction Substations with 12-pulse Bridge Parallel Rectifier

The Simulink model of the active filtering and energy recovery system added to the traction substation in Figure 3 contains all the mentioned components modeled using SymPowerSystems blocks. It must be mentioned that for creating the virtual model, a specific Simulink library was developed. This way, a common structure with modular blocks was obtained, adding or replacing specific blocks depending on the conducted study. The virtual system is therefore complex with lots of variables taken into account.

The main components of the model are:

- The catenary block – which models the DC traction feeder and the passing train; one of the block input signals is controlling the catenary behavior – the train is accelerating so it is absorbing power from the traction substation or the train is decelerating so it is producing power increasing the catenary voltage;

Figure 3. *The Simulink Model of the Regenerating and Compensating System for DC Traction Substations with 12-pulse Bridge Rectifier*



- The traction substation – composed of:

    - Traction substation transformer (two secondary windings);
    - Traction rectifiers (one for each winding);
    - DC line smoothing filter (LC);
- The active power filter composed of:
    - Three phase IGBT power inverter;
    - 1st order interface filter;
    - Adapting power transformer;
    - Catenary separating circuit block (containing the compensating capacitor and the separating diode);
    - APF control block;

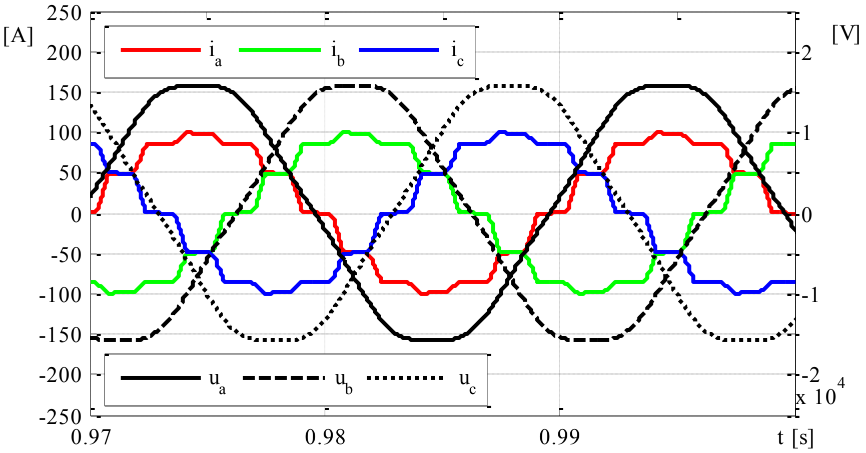
The active power filter must accomplish two individual tasks:

- Compensating the traction substation current absorbed from the grid when power is transferred to the catenary (the trains are accelerating). As a result, the active traction substation is absorbing a sinusoidal current from the power grid minimizing the losses and the distortion produced to the grid;
- Recovering the braking energy when the trains are decelerating and the power is produced from the catenary towards the active substation. As a result, the active traction substation is injecting to the power grid a sinusoidal current with opposite phase to the voltage.

The Simulation Results for the Filtering and the Recovery Mode

Considering the system is working in traction mode close to the nominal working point (the train is consuming from the traction substation about 2.2 MW, thus the 12-pulse rectifier is functional and absorbing active and non-active power from the grid) the active filtering system added to the traction substation has to compensate the non-sinusoidal current in Figure 4. Because the 12-pulse rectifier is uncontrolled the absorbed reactive power is low and only due to the diodes natural switching point. Also, because of the 12-pulse rectifier typical low harmonic distortion factor, the distortion power to be compensated is again relatively reduced, but considering the high power of the system, the compensation of these non-active powers leads to a significant losses reduction.

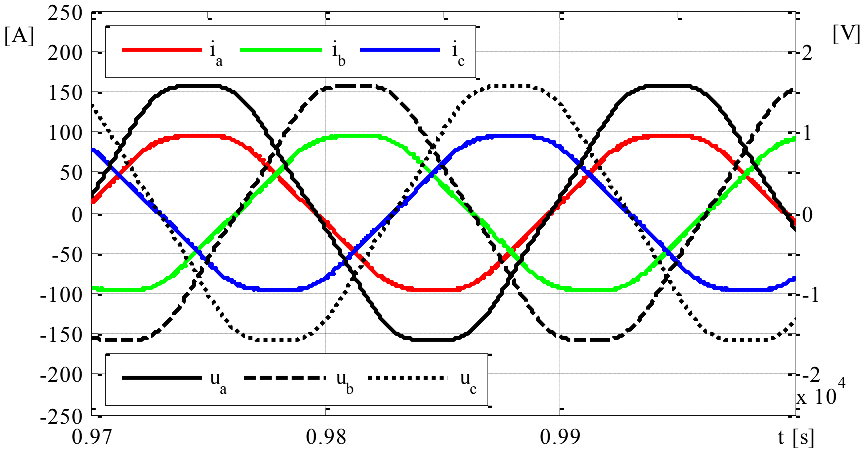
Figure 4. *The Waveforms of the Grid Voltage and Current Absorbed from the Power Grid by the Traction Substation without Current Compensation*



So, after the compensation, the grid current takes the shape in Figure 5. It can be seen that the current is not yet sinusoidal, but the reactive current component and the typical rectifier current shape had been eliminated. The compensated current is not sinusoidal because of the active current definition which according to the CPT, the active current is proportional to the grid voltage. So, after the compensation the grid current has the same shape as the grid voltage, with a small distortion added due to the active compensator switching operation.

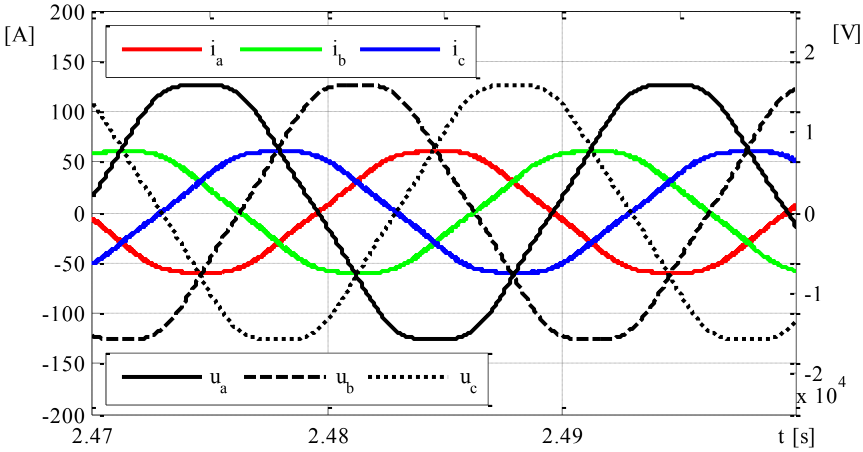
Regarding the numerical data, the total harmonic distortion of the current absorbed by the active substation depends on the active filter performance. The current total harmonic distortion factor was reduced from 10.46% before the compensation, to 3.07%, after the compensation, obtaining a filtering efficiency of 3.39. For the obtained result one important fact must be considered: the voltage total harmonic distortion which is 3.04%. So, on one hand, the compensated current THD cannot be reduced less than the voltage THD of 3.04%. On the other hand, the partial harmonic distortion factor of the compensated current is again 3.04%, meaning that the distortion introduced by the active filter itself (by its switching operation and by the voltage regulator response, respectively) is negligible.

Figure 5. *The Waveforms of the Grid Voltage and Current Absorbed from the Power Grid by the Active Substation in Traction Operating Mode*



The recovery current waveform in steady state is presented in Figure 6. This operating point is obtained when the virtual train is braking, and the recovered power is about 1.66 MW.

Figure 6. *The Current Injected to the Power Grid by the Active Substation in Energy Recovery Mode*

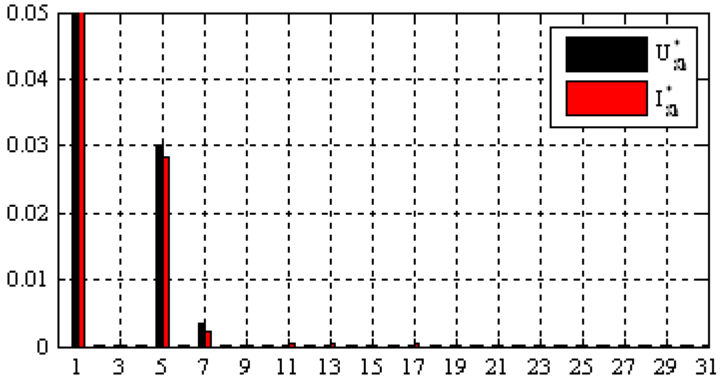


The total harmonic distortion of the current generated by the active filtering system to the power grid is 2.91%. The small difference between the grid voltage THD and the grid current THD is given by the harmonic spectra. Thus, while the voltage contains only the 5^{th} and the 7^{th} harmonics, the current spectrum contains more harmonics beside these. The 5^{th} and the 7^{th} are generated by the active filter because the recovery current is obtained by multiplying the voltage regulator output with a unitary three-phase signal (obtained in turn directly from the grid voltage, taking its shape). On the other hand, as seen in Figure 7, the 5th and the 7th current harmonics amplitudes are slightly lower than the corresponding voltage harmonics. This is because of the small variations in the voltage regulator output over a period, altering the current shape.

In addition, the current spectra contains other low order harmonics (11, 13, 17, etc) which are also produced as stated above.

The high order harmonics produced by the active filter switching operation (not illustrated because their order is between 200 and 250) are negligible, fact proven by the partial harmonic distortion factor (for the first 51th harmonics) which is 2.83%.

Figure 7. *The Recovery Current and Grid Voltage Normalized Harmonic Spectra (Detailed View)*



Experimental Results for the Filtering Mode

The simulation results were experimentally validated using a scale model of the active filtering system which can be added to the active substation. Because the scale model does not implement the energy regeneration component of the system, but only the active filter and traction rectifier, the energy recovery could not been experimentally verified, but for the filtering mode, the control algorithm of the active filter was experimentally validated.

Because a 12-pulse diode rectifier was unavailable, for the given purpose, a classic three-phase six pulse rectifier was used instead, connected to the 380 V power grid and absorbing a current of about 11.5 A (Figure 8). The grid voltage and current were captured for analysis using the Metrix OX 7042-M digital oscilloscope.

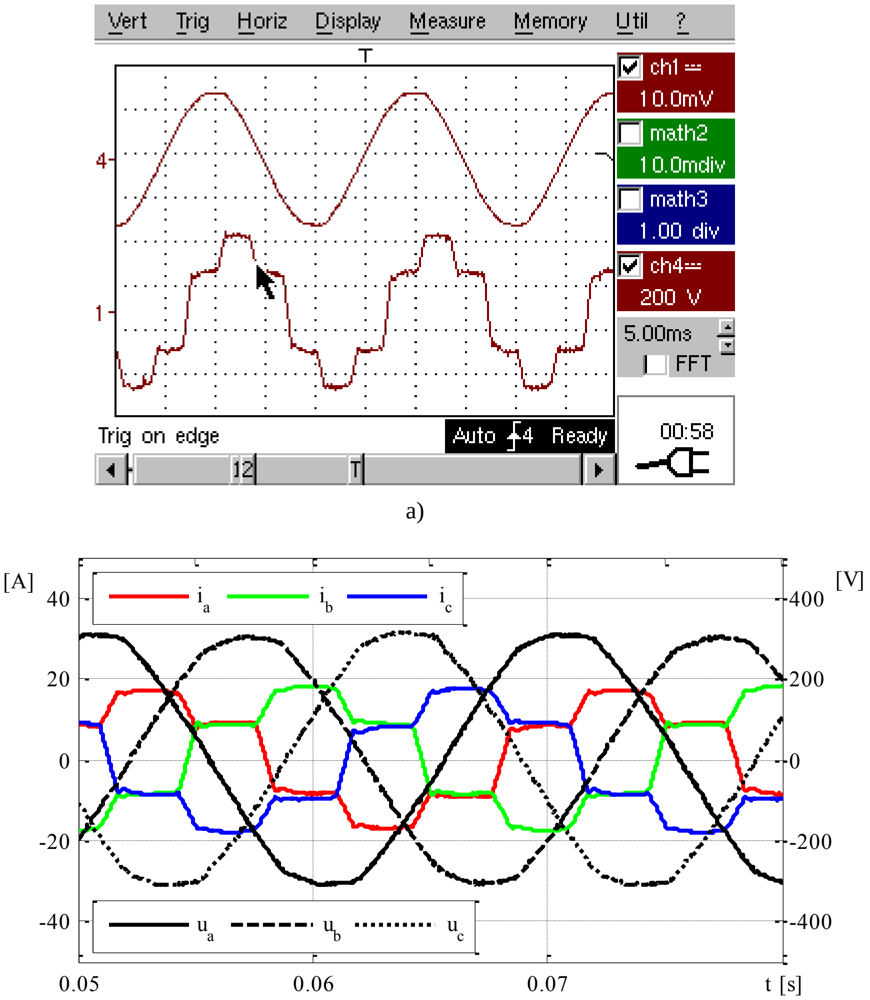
The active filter which was used for this experiment has the rated power of 9.5 kVA. No adapting transformer between the power grid and the active filter was necessary, because its nominal AC voltage rating is 380 V. The active filter main parameters are [15]:

- 1st order interface filter (4.4 mH);
- 1100 μF DC-Link capacitor;

- 700 V DC-Link prescribed voltage.

The active filter was controlled using a dSpace DS1103 control board. The Simulink model compiled by the board specific software and loaded to the program memory contained the same control block of the active filter used for the virtual system.

Figure 8. *The Current Absorbed from the Power Grid by the Traction Rectifier without Current Compensation: a) Captured with Metrix OX 7042-M; b) Captured with DS1103 board and Plotted in Matlab*



☑ ch1 ⎓ 10.0mV
☐ math2 10.0mdiv
☐ math3 1.00 div
☑ ch4⎓ 200 V
5.00ms
☐ FFT
Trig on edge
Auto 4 Ready
00:58

a)

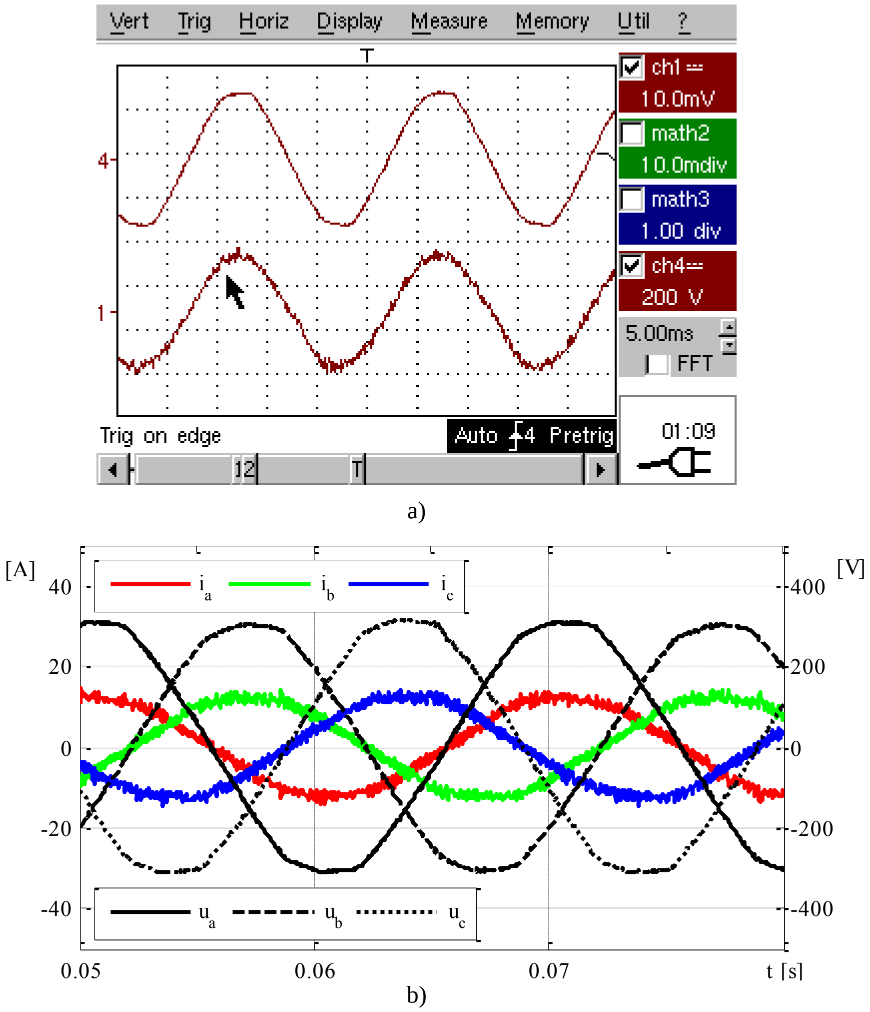
b)

After the active filter was started and the compensating capacitor charged to the operating value of 700 V, the grid current could be compensated (Figure 9). The total harmonic distortion of the grid current was reduced this way, from 24.08% to 8.27%. It must be noted that the grid voltage THD, at the compensation time, was 2.42%.

It results that, the harmonic content produced by the active filter switching operation is not negligible this time. This is because the experimental results are dependant by the DS1103 board time step which cannot be lowered below

20µs. This implies important current regulators overshoot so the hysteresis band cannot be maintained at the imposed value. Moreover, the experimental filtering system is relatively low power so the hysteresis band of about 1.5 A weights a lot in the total harmonic distortion factor (the compensated current fundamental RMS value is 8.77 A). For an industrial system which absorbs a much higher current this hysteresis band will give less distortion. This is confirmed by the compensated current partial harmonic distortion factor (for the first 51th harmonics) which is 4.61%.

Figure 9. *The Current Absorbed from the Power Grid after the Current Compensation: a) Captured with Metrix OX 7042-M; b) Captured with DS1103 Board and Plotted in Matlab*



a)

b)

Conclusions

Considering the simulation results, the proposed algorithm was validated both for the filtering mode and for the energy recovery mode. Also, the simulation results, for the filtering mode, were experimentally validated using a scale model of the active filtering system. The scale model does not implement the energy regeneration component of the system, so the energy recovery could not been experimentally verified (being verified only by simulation). Although, considering the similitude between the simulation and the experimental results, for the filtering mode, the correctness of the proposed algorithm is proved both for filtering and energy recovery.

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