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PhD THESIS

ACTIVE FILTERING AND ENERGY RECOVERY SYSTEMS FOR SUBWAY TRACTION SUBSTATIONS

SUMMARY

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Summary

The problem of kinetic energy recovery related to the braking process of power-driven trains has long been posed, and recent developments in the field of power electronics are creating new perspectives for solving. Its importance is given by the need for efficiency and reduction of energy consumption, as well as the share of energy that can be regenerated.

Electric drive motors can transform this kinetic energy into electricity. Currently only a small part of the resulting energy is reused for auxiliary services. The remaining energy can be sent back to the grid and therefore recovered only if an acceleration vehicle is nearby on the same line section.

If there is no other train in the vicinity to absorb this energy, the mains voltage increases and this extra energy has to be dissipated in braking resistors. Three methods of recovering this energy have been identified: storage in mobile equipment; storage in fixed equipment and recovery of traction substations in the supply network.

The expert's opinion is unanimous, that the best solution is to recover the energy surplus at the traction stations and to compensate the harmonics of the current and reactive power, by generating the concept of "active station" [42]. The DC traction stations are only one direction power provider and do not have the ability to absorb the energy generated by the vehicle that brakes.

A reversible station allow active power to circulate in both directions, but connecting to the same medium-voltage transformer affects the harmonic filtering function and reactive power compensation. It is known that the working principle of an active filter requires that the DC voltage must be greater than the amplitude of the AC line voltage and the performance is depending on the difference between the two voltages. Also the quality of the injected current on the power grid depending on the difference of the two voltages. To obtain a harmonic current distortion (THD) factor less than 5%, impose that the DC voltage must be greater than the amplitude of the AC line voltage, making it difficult to fit the current harmonic distortion factor values into existing norms.

Unlike reversible stations, the new system, called "active station", uses the new generation of high-performance electronic components (in particular insulated gate bipolar transistor – IGBT) and not only allows for energy recovery, but also complementary functions such as: power grid harmonics compensation by operating as active power filter; active compensation of reactive power; dynamic compensation of voltage fluctuations on the high-voltage line and limitation of voltage drops on the power grid [9], [11], [13].

Considering that active filtering domain has a great development potential, determined the main reason for selecting the PhD thesis theme, divided on six chapters and one chapter for conclusions.

The first chapter describes the concept and technologies of electric energy recovery and their implementation in the public system.

Also there are proposed contributions made to a system that allows the current harmonics and reactive power compensation, as well as the recovery of the resulting surplus power in the DC line due to the braking process of the vehicles, to the DC traction substation supply network. This system allows the DC traction substations upgrade into "active substations".

Further there are presented the filtering and energy recovery systems for “active substations” along with the methods of calculating the current to be absorbed from the grid as a result of active filtering. Here are used the p-q and the synchronous rotating orthogonal reference system theory methods. Also here is presented a synthesis of power definitions and compensation in single-phase and three-phase circuits with non-sinusoidal currents and voltages.

The power section design for the active filtering and energy recovery system for subway traction substations is addressed in the third chapter, starting from the premise that a properly designed IGBT power filter is the main structure of the system.

Chapter four is addressed to the control section of active filtering and energy recovery systems for subway traction substations, taking into consideration the reference currents computation and the closed loop control algorithm. There are also considered the methods for direct respectively indirect current control methods for active traction substations.

Chapter five presents the design and analysis of the active filtering and energy recovery systems and performance determination by numerical simulation in Matlab Simulink, using SimPowerSystems blocks, for traction substations with three-phase/12 pulse rectifier with sinusoidal/non-sinusoidal grid voltage.

In the sixth chapter, the experimental results had been presented, obtained using a dedicated experimental stand for the study of the filtering and energy recovery systems for the DC traction substations. The filtering and energy recovery systems control is performed by the industrial computer / dSpace DS1103 control board. It describes the physical and virtual used equipments, as well as the results validation obtained by simulation for both the traction and the regeneration regime.

The conclusions chapter summarizes the significant results from the thesis and the original contributions.

Chapter one

The concept of braking energy recovery, together with related technologies and application types for their implementation in the public system, are the subject of the first chapter.

Although most recent railway vehicles have the ability to brake electrically, using regenerative braking techniques, a small portion of this kinetic energy can be reused to power vehicles auxiliaries, the remaining energy can be sent back to the network and hence recovered only if a vehicle is accelerating nearby. In this case, the accelerating vehicle takes advantage of this energy transfer. If that is not the case, the network voltage increases due to the energy surplus and this extra energy has to be dissipated in braking resistors. The amount of energy that a public transport network is able to absorb is mainly conditioned by the probability of braking and simultaneous acceleration of rail vehicles.

Considering this, a reversible DC traction substation has the ability to improve power in the contact line, to regenerate almost the entire amount of braking energy. The main aplications for reversible substations has been designed by HESOP system and SIEMENS SITRAS – TCI.

Also, the INGEBER active filtering and energy recovery system for DC substations, it's able to compensate the current harmonics and reactive power. The system also allows the recovery of the resulting surplus electricity in the DC line due to the vehicle braking process to the power supply. The system allow to recover the energy surplus from the DC line, which can be sent back to the grid.

Chapter two

Next, there are presented the structure of active filtering and energy recovery systems for DC traction substations together with the calculation methods of the current to be absorbed from the grid due to filtering.

Considering the calculated compensating current, the active filter must provide to the load the necessary harmonic and reactive current, or at least, a part of it. Using the space vectors of these currents:

$$\underline{i}_F = \underline{i}_r - \underline{i}_S \tag{2.1}$$

where, $\underline{i}_F$ is the space vector of the filter current, $\underline{i}_r$ is the reactive current vector and $\underline{i}_S$ is the load current vector.

Among the most used method to calculate the compensating current, were discussed the p-q theory and the synchronous rotating dq frame theory.

According to the first theory, the instantaneous complex apparent power is defined as the product between the grid phase voltage space vector and the complex conjugate of the current space vector:

$$\underline{s} = \frac{3}{2}\underline{u} \cdot \underline{i^*} \tag{2.2}$$

Considering the real and imaginary parts of voltage and current space vectors, the apparent power space vector real and imaginary parts are:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{3}{2} \cdot \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2.3}$$

Because for the active filtering, is necessary to determine the active and non-active parts of the load current, from (2.3) one can obtain the real and imaginary components of these currents as a function of the real and imaginary components of the grid voltage and the load power space vectors:

- active current real and imaginary components:

$$i_{ad} = \frac{2}{3}\frac{u_d}{|\underline{u}|^2}p$$

$$i_{aq} = \frac{2}{3}\frac{u_q}{|\underline{u}|^2}p \tag{2.4}$$

- reactive current real and imaginary components:

$$i_{rd} = \frac{2}{3}\frac{u_q}{|\underline{u}|^2}Q$$

$$i_{rq} = -\frac{2}{3}\frac{u_d}{|\underline{u}|^2}Q \tag{2.5}$$

- additional current due to the fluctuating part of the apparent power:

$$\underline{i}_s = \frac{2}{3}\frac{u_d p_\sim + u_q q_\sim}{|\underline{u}|^2} + j\frac{2}{3}\frac{u_q p_\sim - u_d q_\sim}{|\underline{u}|^2} \tag{2.6}$$

According to *the synchronous rotating dq frame theory*, the Park transform is used for the calculation of the compensating currents, which makes the transition from the three-phase coordinate system of current obtained from the current transducers, to a two-phase orthogonal coordinate system rotating at imposed speed.

Following this transformation, the current projections on the two axes will be:

- a DC component due to the current harmonic of angular frequency equal to the dq frame rotating speed.

- an AC component, due to the current harmonics of angular frequencies different from the dq frame rotating speed.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \cdot \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.7}$$

For the extraction of the DC component, low-pass filters are commonly used, and for the extraction of the AC components, high-pass filters are used. The three-phase prescribed currents are obtained from the selected dq component by means of a inverse Park transform. The advantages of this method consists on one hand in the reduced volume of calculations, and on the other hand, in the independence of the obtained results on the grid voltage distortion. Consequently, the resulted reference currents will not be affected by a distorted and a unbalanced grid voltage, therefore, the filtration efficiency will increase.

Chapter three

The power section design for the active filtering and energy recovery system for subway traction substations is starting from the premise that a properly designed IGBT power filter is the main structure of the system.

In this case, the active filter is has the capacity to provide the increased DC voltage, on a required value.

Nominal data of the traction substation:

Medium voltage: 20 kV;
Catenary voltage: 750 V;
Traction transformer: 2 transformers Δ/ Δ; S_N=1200kVA each ; 20kV/650V;
Rectifier: 2 three-phase bridge rectifers with diodes;
Maximum voltage at the 950 V on DC current collector;
Rated current 6000 A DC.

On the grid there may be internal switching voltages whose maximum amplitude will not exceed the value of 1400V with a maximum width of 0.1 seconds and a frequency rate of 1 pulse per minute;

Regenerative brake on the following voltage range 600 – 950 V;
The rated power recovered from the DC line: 2.2 MW;
The maximum rated power recovered from the DC line for 1 sec: 3.3 MW.

For selecting the semiconductor elements there were calculated their values which are depending to the static converter.

The secondary winding voltage of the recovery transformer (U_{SR}) it's equal with the primary winding voltage of the traction transformer (U_{1t}),

$$U_{SR} = U_{1t} = 20\ KV \tag{3.1}$$

The apparent power (S_{R2}) can be calculated with reactive power which needs to be recovered (P_{CR}), considering that the transformer works with a unitary power factor.

$$S_{R2} = \eta_{Rt} \cdot P_{CR} \tag{3.2}$$

$$P_{CR} = 2.2\ MW \tag{3.3}$$

The average value of the current through the transistor is calculated by considering the load current, having a sinusoidal shape and the phase voltage (the worst case for the inverter because it works at its rated power).

$$I_{TAV} = f(I_{T\,RMS}) = f(I_{RMS\,iesire}) \tag{3.4}$$

The voltage which strain the blocked transistor depends on the compensation capacitor voltage ($U_{DC\ Link}$) having the same value:

$$U_b = U_{DC\ Link} \tag{3.5}$$

Because the voltage in the primary winding of the recovery transformer has the value of:

$$U_{1R} = 480\ V \tag{3.6}$$

It results that the DC voltage of the inverter is:

$$U_{CR} = U_{DC\ Link} = U_b = 950\ V \tag{3.7}$$

The current absorbed by the DC line is calculated according to the recovered power and line voltage:

$$I_{CR} = \frac{P_{CR}}{U_{CR}} = \frac{2.2 \cdot 10^6}{950} = 2.315 \cdot 10^3 [A] \tag{3.8}$$

Considering that the relationship between the DC current of the inverter and the AC current side is:

$$I_{CR} = I_d = \frac{3\sqrt{2}}{\pi} \cdot I_N \tag{3.9}$$

$$I_N = 1714\ [A] \tag{3.10}$$

It result the average current through transducer

$$I_{TAV} = \frac{\sqrt{2}}{\pi} \cdot I_N = 770\ [\mathrm{A}] \tag{3.11}$$

The average current through the diode is calculated from the relationship

$$I_{FAV} = \frac{1 - cos\Phi_{max}}{\sqrt{2}\pi} \cdot I_N \tag{3.12}$$

Considering the relationship (3.9) it results:

$$I_{FAV} = \frac{1 - 0.85}{\sqrt{2}\pi} \cdot I_N \cong 58\ A \tag{3.13}$$

The IGBT module is selected considering the below relationship [7], [21]:

$$I_{TAV\ N} \cdot k_{si} \le I_{TAV\ cat} \tag{3.14}$$

$$\Rightarrow I_{TAV\ N} \cdot 2 \le 1600\ A$$

$$U_b \cdot k_{su} \le V_{CES\ cat} \tag{3.15}$$

$$\Rightarrow 950 \cdot 2 \le 1900\ V$$

where:

$I_{TAV\ N}$ - the average current through transducer;

$I_{TAV\ cat}$ - the maximum average current through a transistor;

k_{si} - current safety factor;
U_b - the voltage strain for the locked transistor;
$V_{CES\ cat}$ - the maximum admissible voltage strain for the locked transistor;
k_{su} - voltage safety factor.

For a nominal current of 780 A through transistor and a current safety factor of 2, it results an average current of at least 1600 A supported by a transistor. Similarly, for a voltage with a value of 950 V, which strain the locked transistor and a safety factor of 2, is obtained the minimum catalog value of 1900 V for V_{CES} parameter.

In this case is selected the insulated gate bipolar transistor module manufactured by EUPEC, type CM1600HC-34H, with the following main catalog data [14]:

I_{CM} = 1600 A - the average rated current of the device;
I_{CRM} = 3200 A - the maximum (shock) current repeatedly supported;
P_t = 2850 W - the maximum dissipated power;
V_{CES} = 1700 V - the maximum supported voltage in the locked state;
$V_{CE\ sat}$ = 3,10 V - voltage drop in conduction;
E_{oncat} = 540 mJ - turn-on energy;
E_{offcat} = 580 mJ - turn-off energy;
t_{on} = 1,6 μs - turn-on time;
t_{off} = 2,7 μs - turn-off time;
$R_{th\ JC} = 0{,}010\,\frac{K}{W}$ - thermal junction-capsule resistance;
$R_{th\ CR} = 0{,}008\,\frac{K}{W}$ - thermal cooler-capsule resistance.

In order to design the cooler which be installed on the transistor module, it is necessary to perform the heater check of the radiator transistor assembly. The total losses on the semiconductor device are calculated with the relationship [21]:

$$P_t = P_{on} + P_c + P_{off} \tag{3.16}$$

where:

P_{on} - the losses at the transistor input;
P_c - the transistor conduction losses;
P_{off} - the losses at the locked transistor.

Also, for sizing the protection circuit due to the inductance from the primary winding of the transformer, there are overvoltage switching which strain the IGBT modules and the rectifier diodes. The Simulink model is illustrated in fig. 3.1.

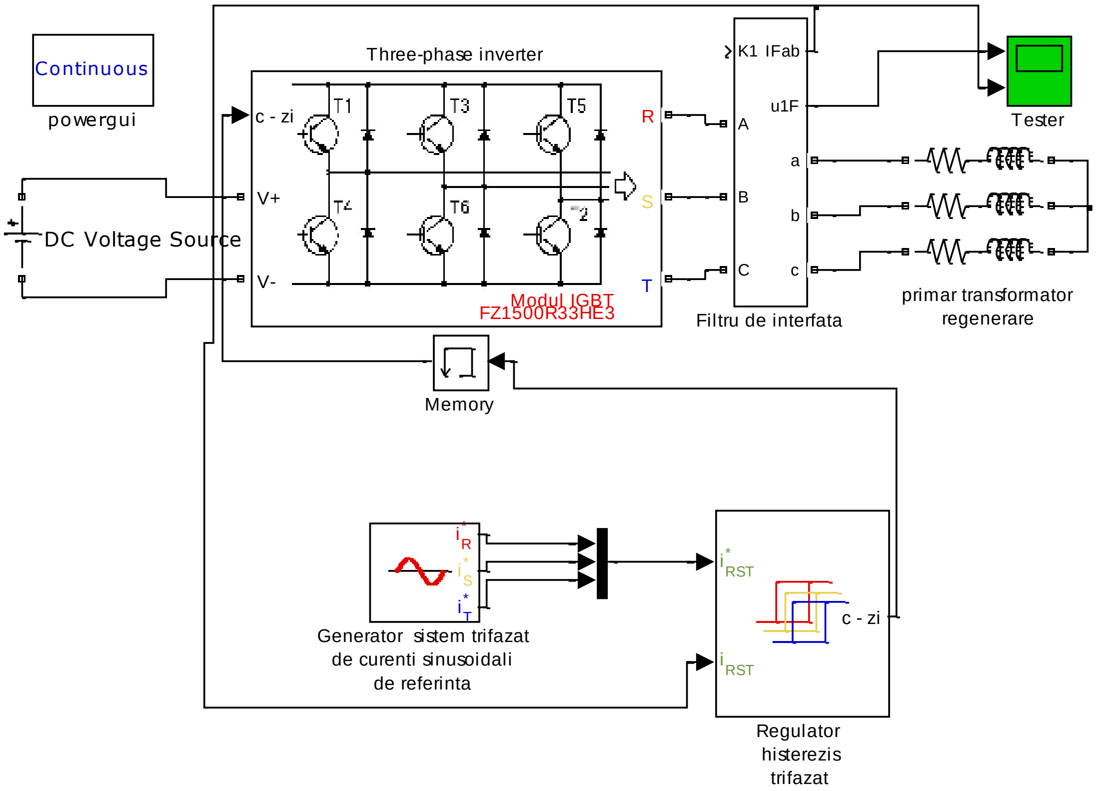


Fig. 3.1. The Simulink model to verify the protection circuit operation on overvoltage switching

The Simulink model contains only the simplified component of the active filter as part of the DC active substation, namely the three-phase inverter block with insulated gate bipolar transistors, the first order interface filter, the reference current generator, the intermediate circuit DC current, hysteresis current regulator and inverter load.

The worst case scenario was simulated, in which the substation is running in regeneration mode, the most demanding for the inverter.

The inverter is controlled by a three-phase hysteresis current regulator, whose band was selected for about 5% of the rated current of 1714 A.

The inverter load which is the regeneration transformer has been replaced by a passive RL consumer in a star connection with similar parameters. The voltage and current waveforms which are corresponding to inverter output are illustrated in fig. 3.2.

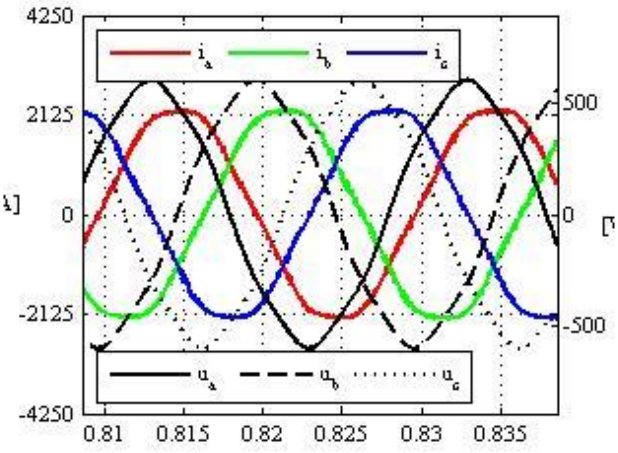


Fig. 3.2. Tensiunea și curentul la ieșirea invertorului

Se constată că funcționarea invertorului pe baza parametrilor stabiliți prin proiectare este corectă, după cum rezultă din analiza formelor de undă, atât la ieșirea invertorului cât și a căderii de tensiune pe tranzistoarele din componența invertorului ilustrat în fig. 3.3.

It is noted that the inverter running is correct based on the design parameters, as it results from the waveforms analysis, both at the inverter output and the voltage drop on the inverter transistors from fig. 3.3.

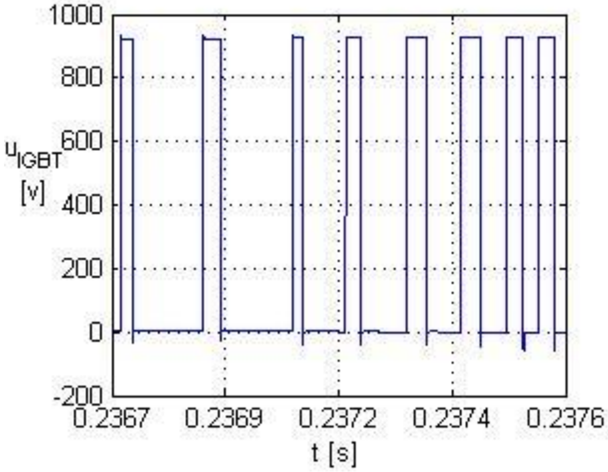


Fig. 3.3. The voltage drop on one of the inverter transistors

The equivalent diagram of the separation circuit is used to analyze the mathematical model running.

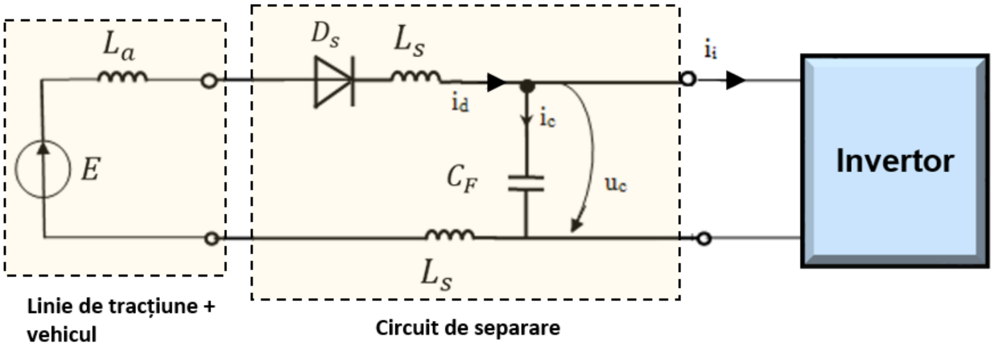


Fig. 3.4. Schema echivalentă a circuitului de separare
și locul său în fluxul energetic

For compensation capacity calculation, the separation circuit have a direct implication in the sizing relationships determination. The lower the current pulses are, the less DC line-vehicle assembly is qualitatively influenced.

Chapter four

The role of the active filter control sections to obtain the gating signals for the power transistors, receiving at the input, the reference currents to be generated by the active filter, and, respectively, the actual generated current measured by transducers, the command being implemented as a closed loop regulating system. The filtration efficiency is equally affected by the compensating current determination method and by the control algorithm.

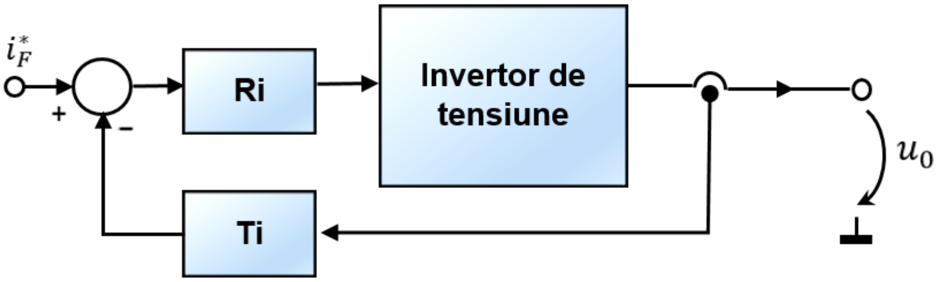


Fig. 4.1. Closed loop current control system

where:

- Ri - current regulator;
- Ti - current transducer

Usually, for the active filters the current regulator is a hysteresis regulator or a PI regulator followed by a PWM modulator.

There are two approaches to current control methods:

- direct current control is the active filtering classic approach, according to which the current control loop controls the output current of the active filter at the common switching point, so the loop input is the required compensating current;
- indirect current control is a new approach, according to which the current control loop controls the current absorbed from the grid by the entire active filtering system, so the loop input is the desired grid current.

For direct current control, in the below figure can be found two control loops, the control loop of the active filter current and the voltage regulating loop on the compensation capacitor.

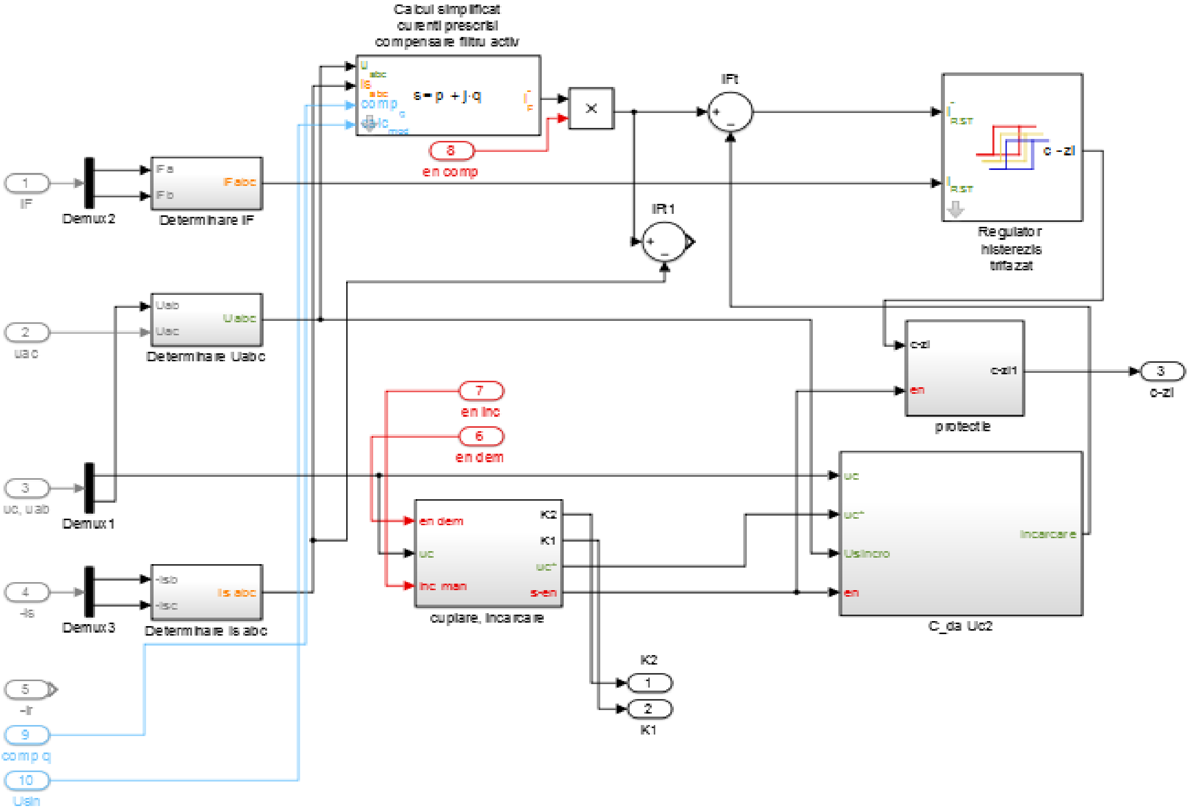


Fig. 4.2. Active filter control block for direct current control

The model can run in two ways:

- Traction / Compensation - when the DC Machine works in electric motor mode

In this case, the three-phase traction rectifier is functional by consuming energy from the grid and supplying the catenary. The active compensator work in the filtering mode, compensating for the distortion and reactive power absorbed by the traction rectifier. The grid current is almost sinusoidal in phase with the voltage.

- Braking / Recovery - when the DC Machine block acts as if the train decelerates.

In this case, the three-phase traction rectifier is blocked, the voltage on the catenary increases, opening the compensating interface circuit. The energy is transmitted from the catenary to the compensation capacitor and then to the power grid through the power inverter and the compensation transformer. Also, the mains current is sinusoidal, but in antiphase, so the power is transferred from the catenary to the grid.

For indirect current control, similar to the model from fig. 4.2 was modified the active filter structure by replacing the control block.

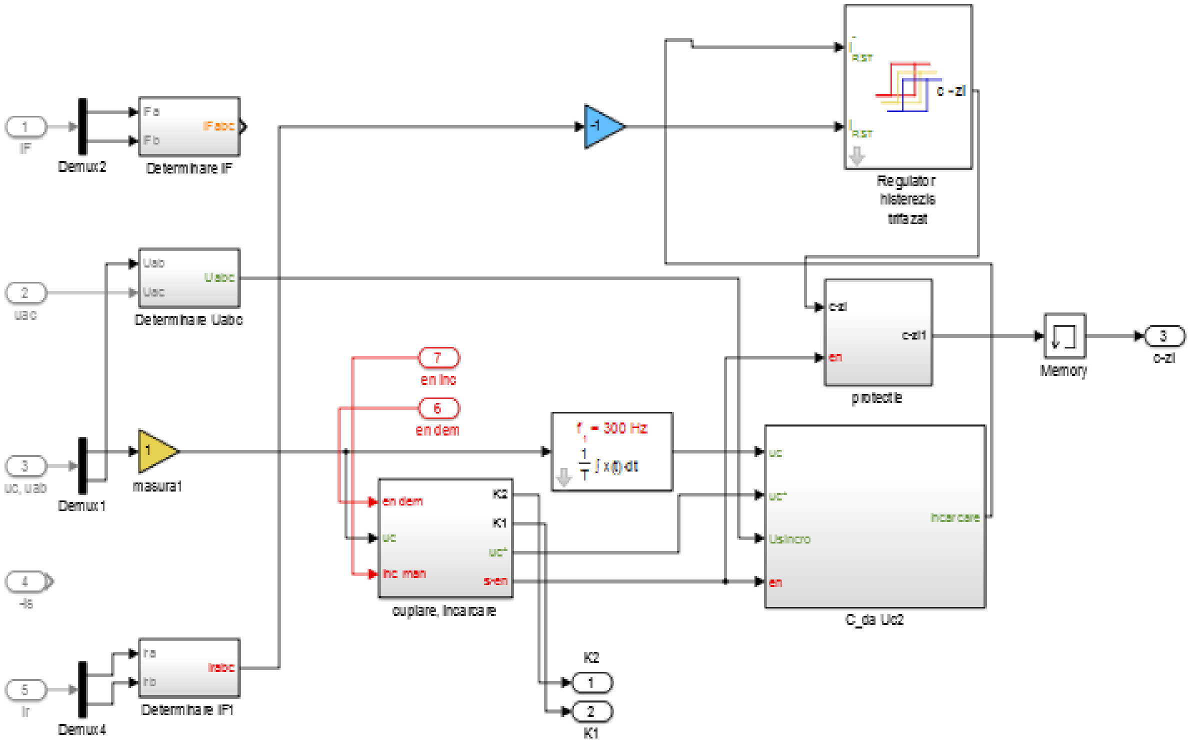


Fig. 4.3. Active filter control block for indirect current control

The control loop structure is similar to direct control current with two main differences:

- on the current regulator input the desired grid current is applied instead of the injected current on common connection point;
- in this case it was calculated the current prescribed by the voltage regulator.

Chapter five

The filtering and energy recovery sistem which was presented in the previous chapters was analyzed by numerical simulation in Matlab Simulink programming environment. In this case was created the model from below figure using SimPowerSystems blocks that allow a detailed design of system components.

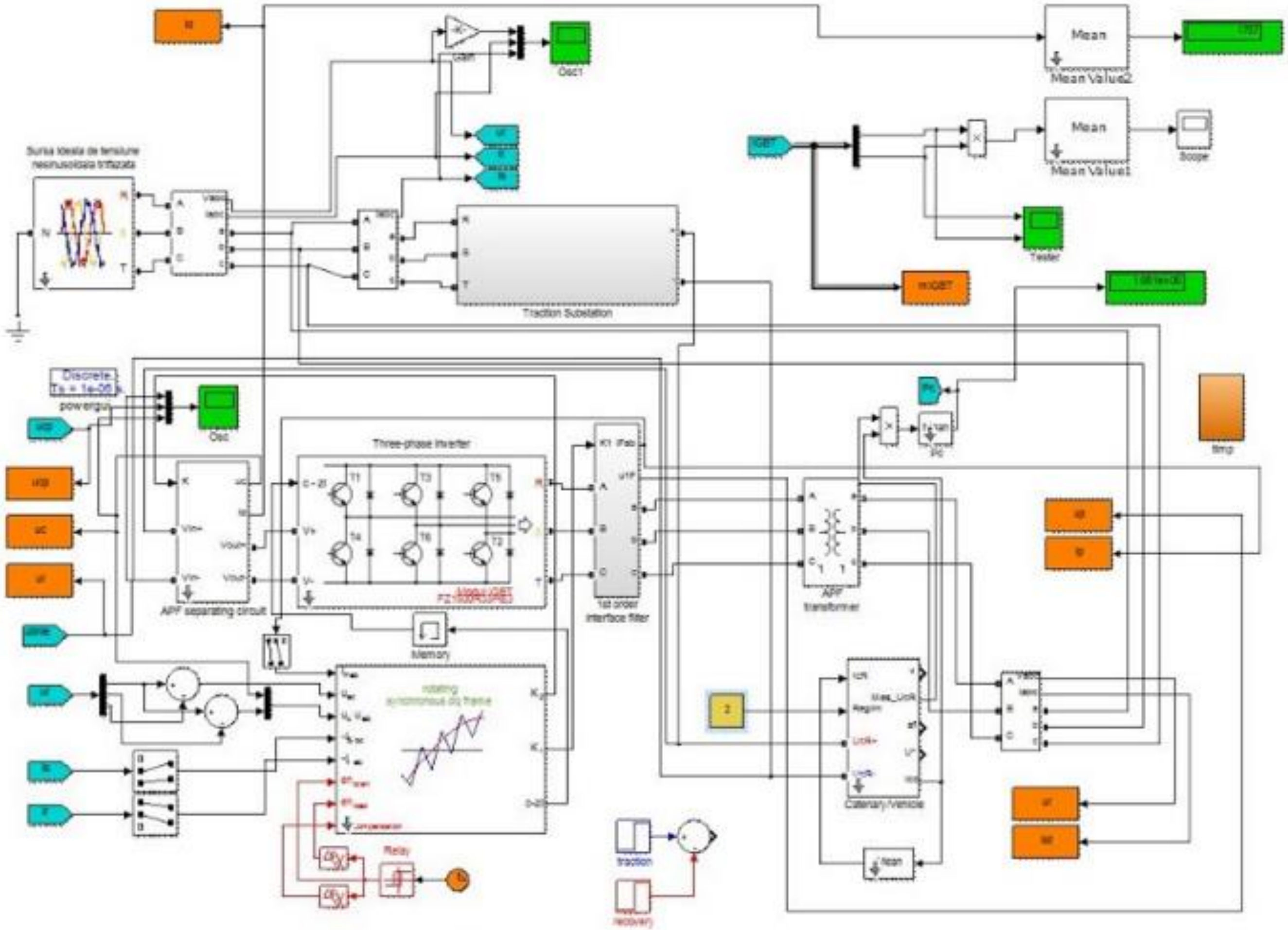


Fig. 5.1. The complete model for filtering and energy recovery sistem for DC traction substations

The model include the following components:

- Three phase medium voltage grid, 20 kV;
- DC traction substation with three-phase bridge rectifier;
- Recovery transformer in star connection;
- Interface filter;
- Three-phase bridge inverter with IGBT, with adapted parameters for CM1600HC-34H transistor;

- Separation circuit between inverter and DC line which includes the compensating capacitor, buffer inductivity, separation diode (with adapted parameters RA20064816);

The model analysis has been done in stationary regime and presume the following aspects:

- the traction substation is in regeneration mode, which means that the train brakes with an imposed acceleration, resulting in an voltage increase in the DC line;
- The filtering and energy recovey system for DC traction substations is in normal operating mode, it is connected to grid via the recovery transformer and to the DC line through the separation circuit; also the compensation capacitor is loaded at the normal working voltage of approx. 925 V;
- if the train is in maximum braking regime causes a voltage increased to 950 V, on the DC line, opening the separation diode and loading the compensation capacitor in DC line at a voltage similar to the line voltage;
- the voltage regulator loop on the compensation capacitor will reduce the prescribed voltage value of approx. 925 V, resulting a sinusoidal current and in antiphase with the grid voltage; in other words, in order to discharge the compensation capacitor and return the voltage to the prescribed value, the voltage regulating loop will inject an active current to the grid, so the mechanical braking power transferred to the compensating capacitor as electrical energy is finally recovered following its transfer to the grid;
- the model has been dimensioned so that all of the mechanical braking energy is recovered, so the filtering and energy recovery system for the DC traction substations works at nominal capacity; because in practice it is unlikely that this operating point will be reached, there are two situations:
  - the mechanical power transferred to the DC line is less than the nominal power of the filtering and energy recovery system for DC traction substations, in which case the grid current is also smaller than the rated current;
  - the mechanical power transferred to the DC line is greater than the nominal power of the filtering and energy recovery system for DC traction substations, in which case the grid current is limited to the nominal value of the system that will flow into the grid for as long as the DC line voltage is greater than the tension in the traction mode; in this situation, since only a part of the mechanical energy is recovered, the filtering and energy recovery system will only produce a partial voltage drop across the DC line; in order to avoid uncontrolled voltage increase for short periods of time when the mechanical braking energy is very high (two or more trains brake simultaneously), additional measures such as: timing of the train traffic so that the braking energy does not exceed the rated loading capacity of the filtering and energy recovery system for DC traction substrates or this extra energy has to be dissipated in braking resistors.

Study synthesis of numerical model simulation for the filtering and energy recovery system control based on direct/indirect current control.

The filtering and energy recovery system performance has been studied by comparison for both direct and indirect current control methods. For three phase three-phase rectifier traction substation with a rated power of 2.2 MVA, the obtained results are shown below.

The active power absorbed from the grid is about 2.2 MW, close to the rated power. When the station uses the active filtering system, the current absorbed from the grid to the traction regime is illustrated in fig. 5.2.

Considering a strong grid, the voltages across all phases are sinusoidal. The harmonic distortion of the current absorbed by the active station depends on the active filter performance, the total harmonic distortion factor of the current being reduced from 25.23% before the compensation to 8.84% after the compensation. This provides a filtering efficiency of 2.85.

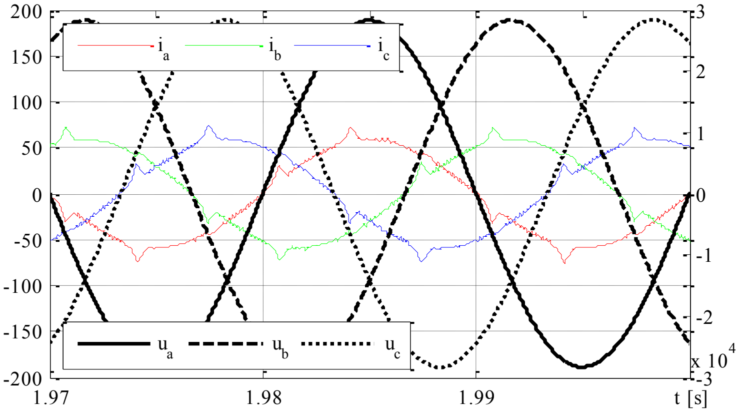


Fig. 5.2. Current and voltage absorbed from the grid for sinusoidal voltage

On the same traction substation but for indirect current control, the results obtained by simulation are illustrated in fig. 5.3.

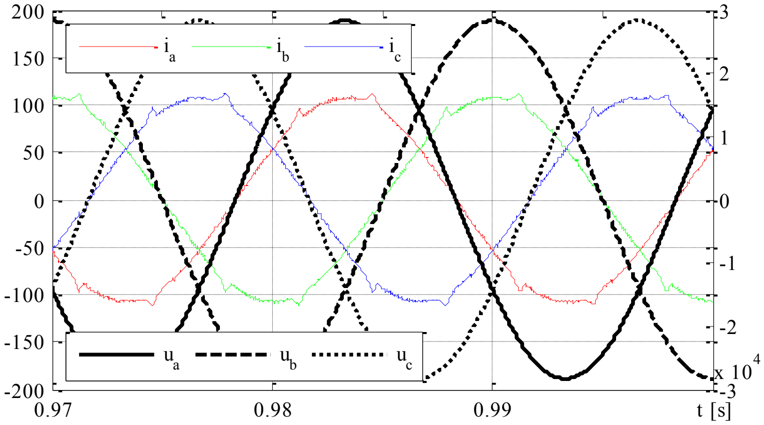


Fig. 5.3. Current and voltage absorbed from the grid for sinusoidal voltage

Qualitatively based on waveforms, it is noted that filtering is more efficient than in the previous case. This can be quantified based on the energy quality indicator:

- The total harmonic distortion factor reduced from 21.15% to 3.31%
- It results in a filtering efficiency of 6.42.

The obtained results for all studied cases can be found in the below table.

Table 5.1:

	Direct control U_{sin} 6p	Direct control U_{nesin} 6p	Direct control U_{sin} 12p	Direct control U_{nesin} 12p	Indirect control U_{sin} 6p	Indirect control U_{nesin} 6p	Indirect control U_{sin} 12p	Indirect control U_{nesin} 12p
THD_{ir}	8,84%	7,29 %	3,92 %	4,47 %	3,31 %	3,76 %	1,17 %	3,26 %
THD_{ist}	25,23%	24,86 %	11,46 %	11,19%	21,15%	21 %	10,45 %	10,45 %
THD_{ur}	0	3,06 %	0	3,06 %	0	3,06 %	0	3,06 %
FE	2,85	3,41	2,92	2,49	6,42	5,5	8,22	3,14

Chapter six

In this last chapter were presented the experimental determinations performed on a specialized stand for the study of active filtering and energy recovery system for DC traction substations, which is illustrated in fig. 6.1 containing the following parts:

- Grid connection module;
- Traction substation:
  - Adjustable three-phase autotransformer ;
  - Three-phase rectifier;
- Active power filter:
  - Recovery transformer in Δ-Y connection;
  - Module for passive load for the active filter;
  - Three-phase inverter;
  - DC line interface module;
- Digital osciloscopes (Tektronix MSO 4104 and Metrix OX7042M);
- Industrial computer/dSpace DS1103 control board
- DC machine (the vehicle connected to catenary);
- Three-phase synchronous excitation electromagnetic machine (mechanical load of DC machine);
- Measuring devices for monitoring the static operating points of the used electric machines.

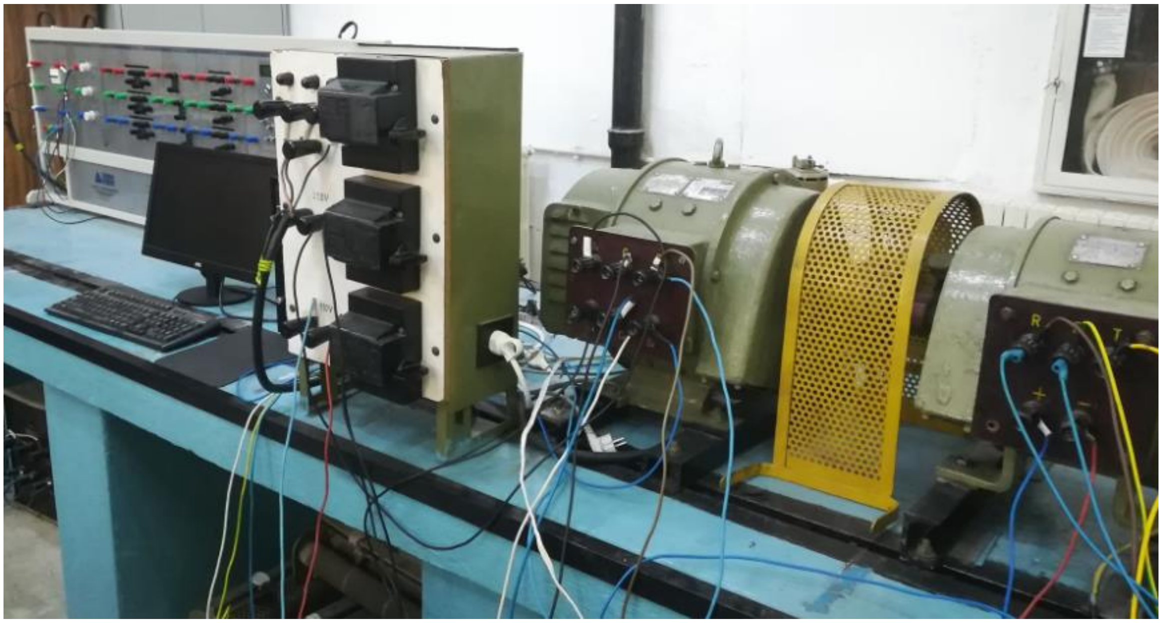


Fig. 6.1. The experimental stand for the active filtering and energy recovery systems for DC traction substations

The control and command for the active filtering and energy recovery systems is performed by the industrial computer / dSpace DS1103 control board, based on the algorithm implemented via a virtual control panel. This panel is implemented in dedicated dSpace (control desk) software and enables control of the system by controlling the values assigned to Simulink variables.

System status monitoring is done in two ways:

- by viewing the time-varying instantaneous signals on virtual osciloscopes (plotters) palced on virtual panel and related to Simulink signals, calculated in the control algorithm or received from the system transducers.
- based on virtual measuring and numerical control devices or pointer devices arranged on the virtual panel. They will display average or actual valuues of the monitored signals (it must be noted that the displayed values are not calculated by the virtual instruments, but in the Simulink model using the appropriate averaging or actual value blocks).

For the experimental checks if the control algorithms are correct and the validation results obtained by the simulation, two experiments were performed:

- experimental checks when the substation is in traction regime;
- experimental checks when the substation is in regeneration regime;

In the case of experimental checks for substation traction regime, has been adopted the method for indirect current control at the compensation capacitor loading was adopted. The active filter automatically generated the filtering of the current absorbed by the traction autotransformer.

As a result of the acquisition made with the dSpace control board, results a Workspace Matlab file type that contains all the virtual signals in the form of Matlab vectors. They were used for graphical representation using Matlab facilities, but also for numerical analysis of the studied signals, using a Simulink model for this purpose.

The voltage and current absorbed by the traction autotransformer in this operating mode are illustrated in fig. 6.2.

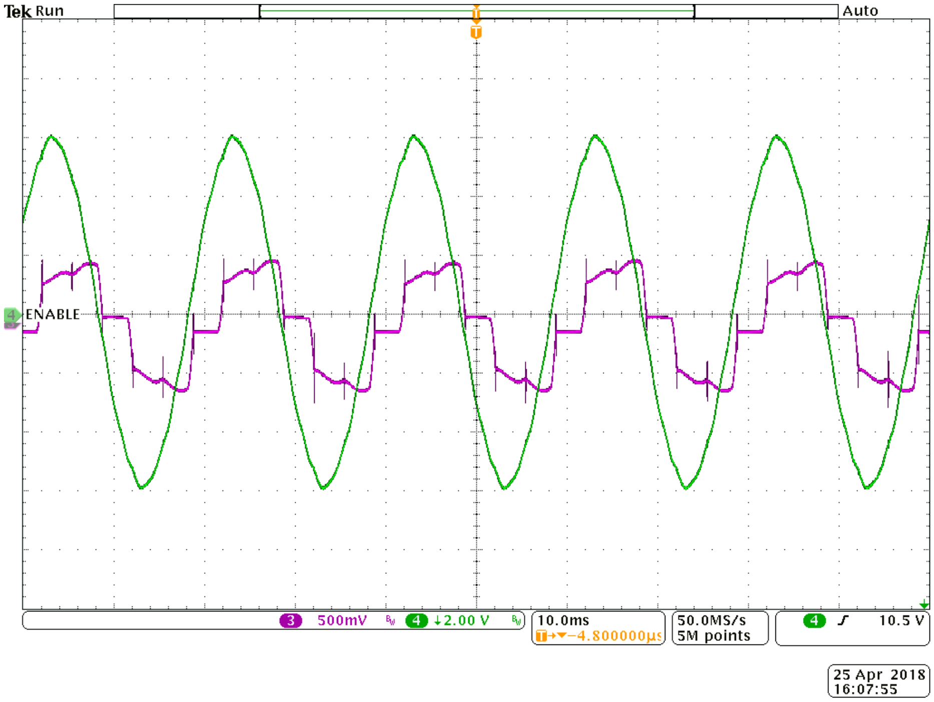
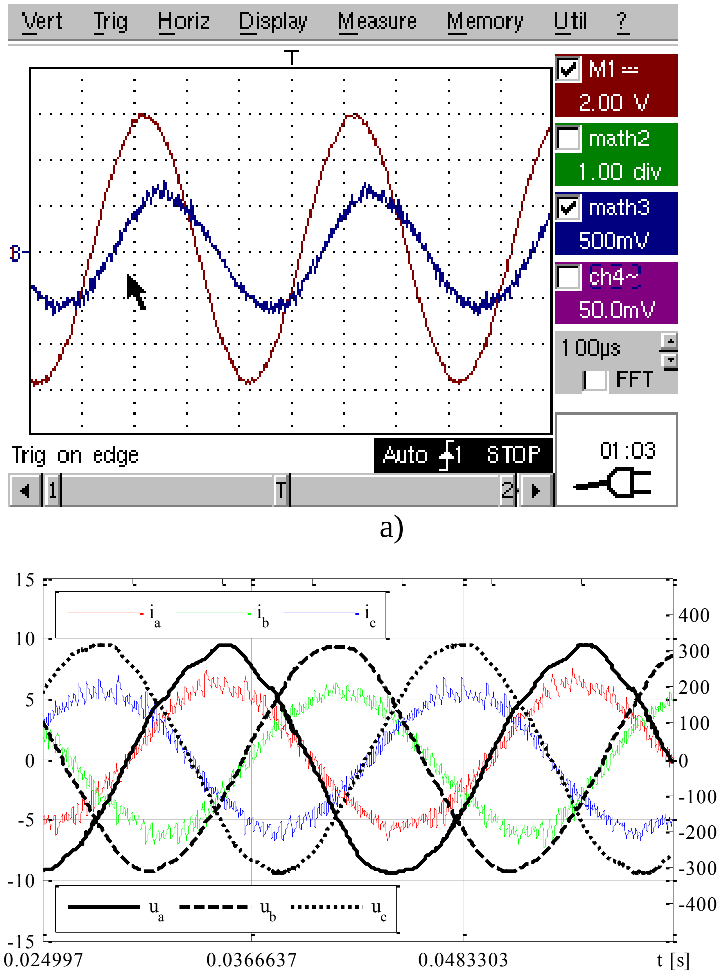


Fig.6.2. Voltage and current waveforms at the traction autotransformer terminals obtained with Tektronix MSO 4104 oscilloscope

The waveforms of the voltage and current absorbed from the grid are illustrated in fig. 6.3. It can be observed that they can be tracked in real-time on the oscilloscope screen, on the plotters in the virtual panel, or plotted later in Matlab.



a)

b)

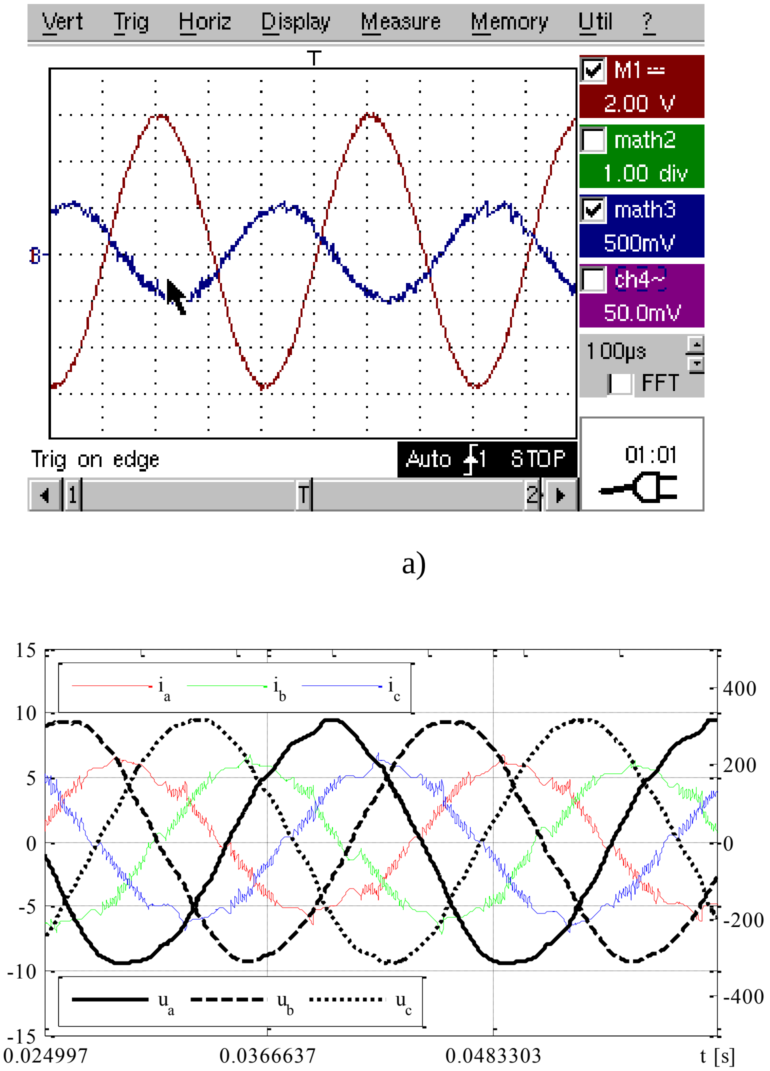
Fig. 6.3. Voltage and current waveforms at the grid in traction/filtering regime:

a) obtained on Metrix OX70442-M oscilloscope

b) obtained with dSpace DS1103 control board

The second experiment performed corresponding to energy recovery mode. To switch from traction to the energy recovery mode, the DC supply voltage has been reduced and the motor EMF has been increased, to simulate the bracke mode for the vehicle connected to the DC line.

Once the DC machine run in the regenerative brake mode, the mechanical energy absorbed from the grid by the synchronous machine and transferred to the DC machine is transferred to the compensation capacitor, generating the voltage increase at its terminals. The waveforms of the grid voltage and current in this operating mode are illustrated in fig. 6.4.



a)

b)

Fig. 6.4. Voltage and current waveforms at the grid in regenerative mode:
a) obtained with Metrix OX70442-M oscilloscope
b) obtained with dSpace DS1103 control board

In the thesis, personal contributions can be synthesized in two plans.

A. Theoretical contributions:

1. *A synthetic study has been done on the current state of the existing solutions as well as the research directions in the field of DC traction substations.*
2. *Study of specific methods of current decomposing for calculating the required compensating current, when the active substation is operating in traction mode (p-q theory, the synchronous rotating orthogonal reference system, the theory of the physical components of the current) and the elaboration of the Simulink models corresponding to*

the calculation of the compensating current for the p-q theory and the synchronous rotating orthogonal reference system theory.

3. *Design an active filtering and energy recovery system control section for a specific situation (for active subway traction substation).*
4. *The elaboration of the Simulink models corresponding to the current control loops generated by the active filter, respectively the voltage on the compensation capacitor, for direct current control.*
5. *The elaboration of the complete Simulink models (SimPowerSystems) of classical traction substations with three-phase / 12 pulse rectifiers.*
6. *The elaboration of the Simulink models for active filtering systems for each case study, including the complete active filter models (control loops and the control section) and non-linear loads used (classic traction substations).*

B. Experimental contributions:

1. *Using the dSpace DS1103 platform for controlling a laboratory model of the filtering and energy recovery system*
2. *Completing the virtual control panel of the filtering and energy recovery system for dSpace DS1103 platform and interconnecting it with the input/output variables of the corresponding Simulink models.*
3. *Performing a comparative analysis by simulation and experimental data between the active filtering performances obtained for indirect current control for substation in traction operation mode.*
4. *Performing a comparative analysis by simulation and experimental data, between the braking energy recovery obtained for indirect control for substation in regenerative operation mode.*