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DESIGNING A FILTERING AND REGENERATION SYSTEM TESTING STAND AND THE EXPERIMENTAL EVALUATION

BY

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Abstract. The main goal of the paper is presentation the design of the testing structure and methodology for experimental evaluation of a filtering and regeneration system. The configuration of the testing structure was made based on the actual conditions prevailing in a substation for traction d.c. and given the equipment available in the Laboratory of Power Electronics and Electrical Drives of Department of Electromechanics, Environment and Applied Informatics.

The experimental structure contains: the equivalent of the transformer-rectifier traction group; the equivalent of the d.c. traction motors; the possibility of system to be connected, on the one hand in the connection point of the traction transformer, and on the other hand with line d.c. (Equivalent catenary). Consequently, can be determined the performances of the system in filtering and regeneration operation modes.

The paper presents the experiments conducted, in accordance with the test protocol, of a laboratory model of a filtering and regeneration system (SISFREG) which allows the conversion of the dc traction substations in “active substations”. The control and monitoring algorithm was implement on the 1103 dSpace system.

Keywords: active DC traction substation; experimental setup.

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1. Introduction

The railway electric transportation system (RETS) is generalized in technologic advanced countries and it there is in expansion in many other. The DC traction system has an important weight because it is used in all transport types (metro and trams in the local cities transport, in regional express and intercity transport).

The electric traction substation (TSS) is a common component of electric transportation systems (DC or AC). In DC case line, TSS contains a specific traction transformer and an uncontrolled rectifier. Consequently, the current received from the medium voltage three-phase network is distorted and contains many harmonics. The harmonic distortion of the supply current can be reduced by using twelve-pulse rectifiers supplied from a traction transformer equipped with two secondary windings (connected in star and delta).

In order to implementing of “high energy efficiency”, two main directions for improving energy performance were identified (De Jager *et al.*, 2014):

1. The compensation of the current harmonics and possibly of the reactive power, so that Recovery Transformer (TR) operates at unity power factor;
2. Recovering, partially or entirely, the braking kinetic energy as electrical energy.

The first direction is implemented by using Active Power Filters (APF) and determines increasing the efficiency especially for Traction SubStations (TSS) equipped with 6-pulse rectifiers.

The second direction has implications on increasing the energy efficiency even more significant than the first one. It can be concretized through the following ways (Raveendran *et al.*, 2016): supplying the auxiliary services of the train; sending the remained energy in the catenary line and using it by other trains (Yang *et al.*, 2013); storing it by various mobile/stationary devices; sending it in the TSS’ power grid (Tamai, 2014).

The recovering the braking kinetic energy is an old concern of the specialists. In the last years, new solving perspectives have been open by the recent developments in the field of power electronics. The economic importance of regeneration is given first by the need to increase the efficiency and reduce the energy consumption, but on other hand, also by the amount of energy that can be regenerated (Tian *et al.*, 2016).

The braking energy remained after using by the auxiliary services can be recovered two main methods: by various mobile/stationary energy storage devices or the direct return to the AC-power utility.

The many specialists agree the idea that implementing the “active station” concept represents a very good solution in order to increase energy efficiency by recover the surplus of braking energy and increase power quality (Warin *et al.*, 2011).

Ingeteam Traction Company developed a power electronics system that includes a DC-DC converter between the vehicle DC-line and inverter in order to

DC voltage elevation. In this mode, the system can operates as both recovery system and APF, by using the existing transformer (Ortega, 2011).

The paper is organized on seven sections: the presentation of a filtering and regeneration system (SISFREG) and its control developed by authors and their team (Section **2** and **3**); the presentation of the synthesizing of structure of the stand test and the presentation of the experiments conducted in accordance with the test protocol (Section **4** and **5**). In addition, the results interpretation and determine the energy performance of the system in the active filtering and regeneration operation mode are showed in Section 6. Finally, few conclusions were drawn.

2. Experimental Model of Filtering and Regeneration System

The system was design in modular construction and the connection between the modules are made with jump connectors (Fig. 1). It was develop around of shunt active power filter (APF), by adding two blocks (CC and CS) (Fig. 2). It can be identified the power part and the sensors need for control implementation.

1. The connection circuit (CC) that contains the terminals for grid connection (A, B, C), the terminals for load connection (A2, B2, C2), the terminals for charging circuit connection (A1, B1, C1), the grid current sensors (TI1, TI2), the load current sensors (TI5, TI6) and the line voltage sensors (TU1, TU2);

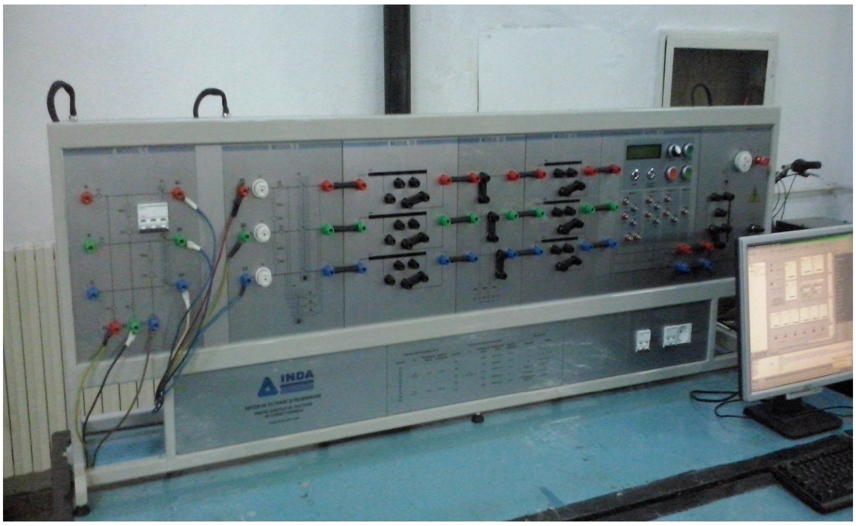


Fig. 1 – The frontal view of SISFREG experimental model.

2. Charging circuit (CHC) that contains the input terminals (A3, B3, C3), the fusible plug (F1, F2, F3), the charging resistors (R1, R2, R3), the connecting contactors (K1, K2) and the SISFREG current sensors (TI3, TI4);

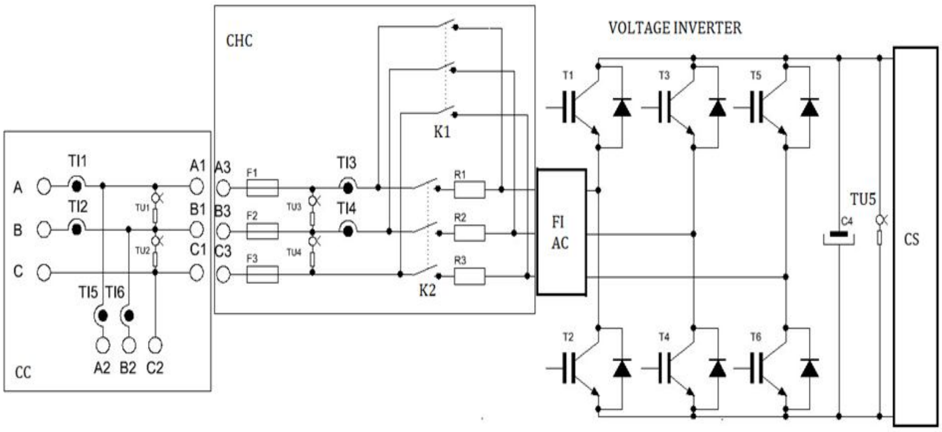


Fig. 2 – Electric scheme of the power part of experimental model.

3. AC interface filter (Fig. 3);

4. Inverter and DC link that contains six IGBT (T1-T6), compensating capacitor (C4) and DC voltage sensor (TU5);

5. Separating circuit (CS) (Fig. 4).

The AC interface filter (LCL type) has the structure from Fig. 3 (Popescu M. *et al.*, 2018; Busarello *et al.*, 2016). In order to test the influence of parameter values the coils were design and manufactured with multiple sockets, as follows:

a) L1 coil, from the network, has three plugs and consequently can be used four values (0.6 mH, 1.2 mH, 1.8 mH, 2.4 mH);

b) L2 coil, from the inverter, has two plugs and consequently three values can be used (10 μH, 20 μH, 30 μH).

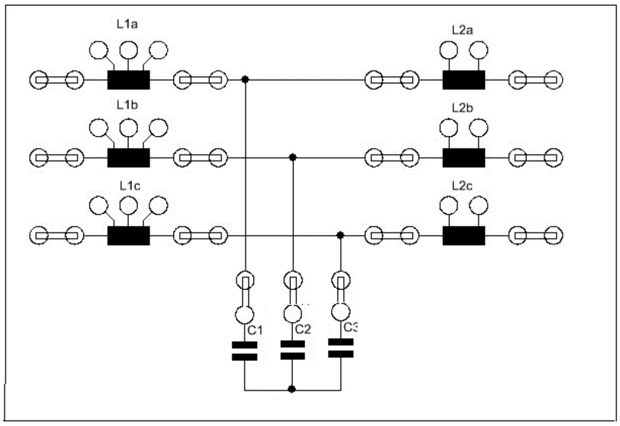


Fig. 3 – Electric scheme of the interface AC circuit (CI AC).

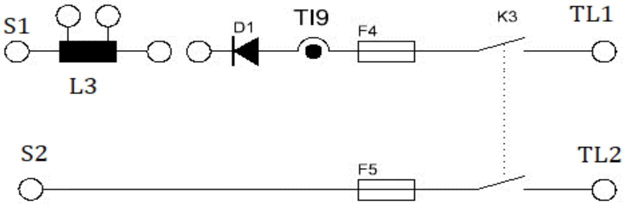


Fig. 4 – Electric scheme of the DC separating circuit (CS).

In addition, the interface filter capacitor can be connect or not.

The separating circuit (CS) must satisfy the following three requirements:

– to prevent very fast variation of the current between the DC-line and APF;

– to ensure the existence of the recovery current during the braking regime;

– the decoupling of APF from the DC-line during traction regime, in order to achieve the function of harmonics filtering and, eventually, the reactive power compensation.

The first requirement can be satisfied using of a properly designed inductance.

To fulfill the second requirement, a diode connected properly was adopt.

In this mode, the system can to operate in filtering and regeneration modes if the corresponding conditions are met.

Thus, as long as the DC-line voltage is below the compensating capacitor’s voltage, the separating diode is reverse-biased, the DC-line is practically disconnect from APF and the control block prescribes a compensating current to APF in accordance with the adopted algorithm.

If it suppose that the system operates in filtering mode, the transition to regenerative regime doing in following stages:

– when the vehicle passes in braking regime, the traction motors became generators and the DC-line voltage increases because the rectifier does not allow the existence of a reverse current;

– the DC voltage regulation controller maintains the voltage of the across the compensation capacitor at the prescribed value, with deviations not exceeding 5%;

– when DC-line voltage exceeds compensating capacitor’s voltage, the separating diode is forward-biased allowing the existence of the recovering current and the control block prescribes the current to be recover, which is an active current in phase opposition with the transformer voltage at which APF is connected.

3. Control of the System

The control part of the system must fulfill two roles: controlling the current by an inner loop and controlling the DC voltage by an outer loop. From point of view of current control, the indirect current control (ICC) method has a lot of advantageous and it was adopt (Fig. 5) (Bitoleanu *et al.*, 2017; He *et al.*, 2011; Popescu M. *et al.*, 2015).

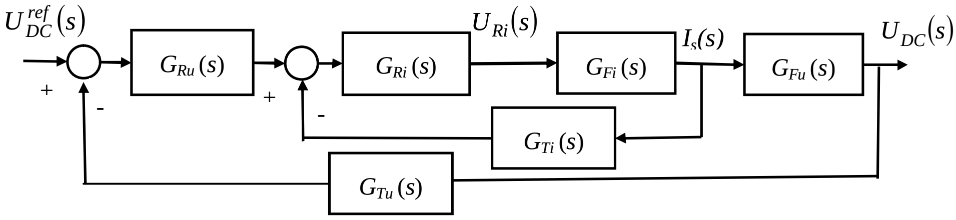


Fig. 5 − Block diagram of closed-loop control system based on ICC.

The magnitude of the reference supply currents is obtained as output of the voltage controller of proportional-integral (PI) type. Three sinusoidal signals of unity magnitude, synchronized with the supply phase voltages need for generating of the reference currents, are given by a specific circuit. They represent the shapes of the reference line currents. The operation of the adopted circuit of phase-locked loop (PLL) is based on the cancellation of an internal fictitious power (Bitoleanu *et al.*, 2016). It is very important that the output signals are in phase with the fundamental components of the input voltages. Consequently, the system operates correctly even under nonideal voltages, as happens in the case of the DC traction substations.

The current controller was adopt as hysteresis type, which leads to good performances. Since the transfer function of the direct path of the voltage loop has a simple pole in origin, the voltage controller was tune through the Symmetrical Optimum criterion (Bitoleanu *et al.*, 2016).

The SISFREG control algorithm implementation on the DS1103 platform was start from the complete Simulink model of the active traction substation. The model contains all the virtual versions of the physical system components, on one hand, and the control block contains exactly the functional implementation of the control algorithm, on the other hand.

The processed signals are taken from the physical system by means of the A/D converters and digital I/O ports. Concretely, all the outputs of current and voltage transducers are connect to the inputs of the A/D converters. The control signals of the system (six signals for the IGBTs' control and two signals for contactors' control) are applied back to the physical system by means of the digital I/O channels. A graphic user interface was build for the experimental setup management and for recording many quantities useful in the proper operation of the system (Popescu M. *et al.*, 2013).

4. Design of the Experimental Testing Stand

The synthesis of the test stand structure is based on the functions it has to perform:

1. Reproduce the traction regime conditions, respectively, to be a variable load of the same type as traction rectifier;
2. Reproduce the recuperative braking regime conditions in the same mode as traction vehicle;
3. Allow the transition of SISFREG from filtering to recovery operating mode and vice-versa;
4. Connecting SISFREG, on the one hand, in the connection point of the traction transformer, and, on the other hand, with the DC line.

Starting from these requirements, the experimental testing stand contains (Fig. 6 and 7):

1. The equipment equivalent of the transformer-rectifier traction group (the autotransformer AT and the six pulse uncontrolled rectifier R);
2. The equivalent of DC traction motors (the DC motor M);
3. The equivalent of the vehicle (synchronous machine MS);
4. The regeneration transformer (TR); its type is Y/d, 380/130V and the inverter is connected at its secondary;
5. The K4 and K3 contactors for connecting SISFREG in the connection point of the traction transformer and with the DC line.

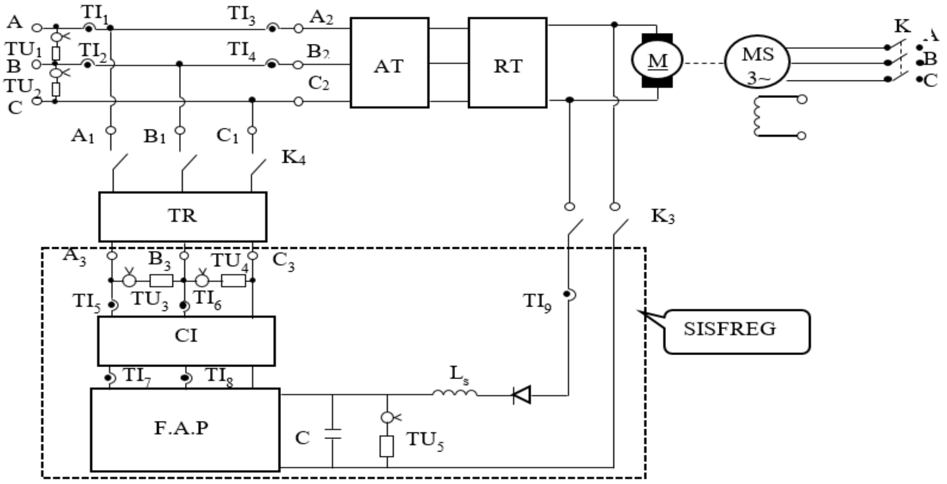


Fig. 6 – Structure of the experimental testing stand.

It pointed out that:

1. The synchronous machine (MS) operates as generator in traction regime and as motor in braking regime;

2. The DC motor M is provided with two excitation coils, both fed separately; the second is supplied by 20% in traction regime and until 100% in braking regime;

3. In the traction regime, the synchronous machine sends to the grid a part of power taken by the autotransformer;

4. In the braking regime, the DC machine operates as generator and SISFREG sends to the grid a part of power taken by the synchronous machine that operates as motor.

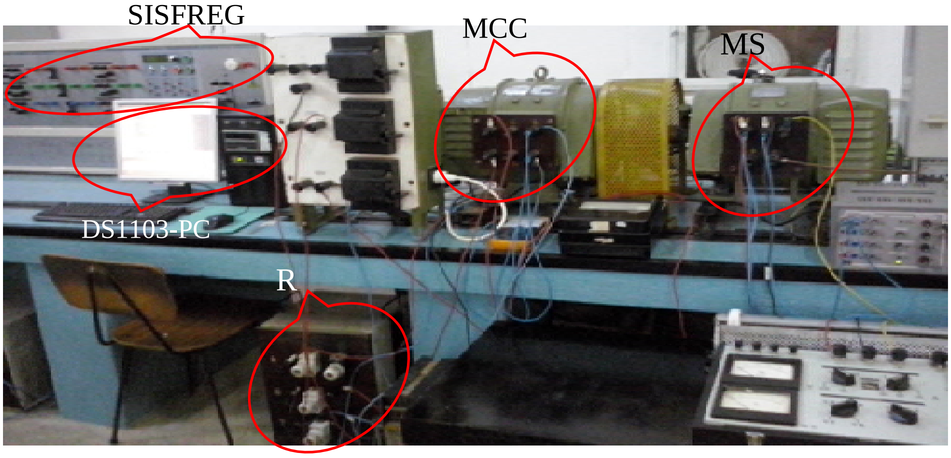


Fig. 7 – Picture of the experimental setup.

5. Testing Procedure

The testing procedure should ensure that the correct operation of the system is check at all stages of operation and, at the same time, be aimed at determining the energetic and dynamic performance of SISFREG.

Thus, the goals of the testing procedure are followings:

1. Verifying the proper operation of SISFREG in start-up of the system and determining the associated dynamic performances;

2. Verifying the proper operation of SISFREG in active filtering mode and determining the associated energy performances;

3. Verifying the proper operation of SISFREG in regeneration mode and determining the associated energy performances.

The start-up of the system involves the following key sequences:

1. Connecting SISFREG to the network and charging the filtering/compensating capacitor at the prescribed value U_{cp} (finally, K3 is closed);

2. Starting the DC motor by supplying it with increasing voltage (control by autotransformer);

3. Synchronization of the synchronous machine with the network (control by autotransformer, by excitation of the DC motor, so that the voltage

in the DC line is about 95%Ucp and the excitation current has nominal value and by excitation of the synchronous machine);

4. Obtaining the required operating mode of the system (active filtering or regeneration).

Further, achieving the operation in traction or regeneration mode is accomplish by modifying the excitation current of the DC machine as was showed in preview section. In fact, if DC voltage is lower as *Ucp* the SISFREG operates in active filtering mode and when the DC voltage becomes higher than *Ucp*, the SISFREG passes in regeneration mode.

6. Results of Tests and Experiments

In order to obtain an interactive communication with the system, a friendly graphic user interface (GUI) under the dSPACE Control Desk environment was conceive. In addition, GUI is an useful tool in the experimentation management, data recording and waveforms display.

6.1. Verifying the Proper Operation of SISFREG in Start-Up of the System and Determining the Associated Dynamic Performances

The proper operation of the DC-voltage control loop is shown of the time evolution of voltage across the compensating capacitor during charging (Figs. 8 and 9).

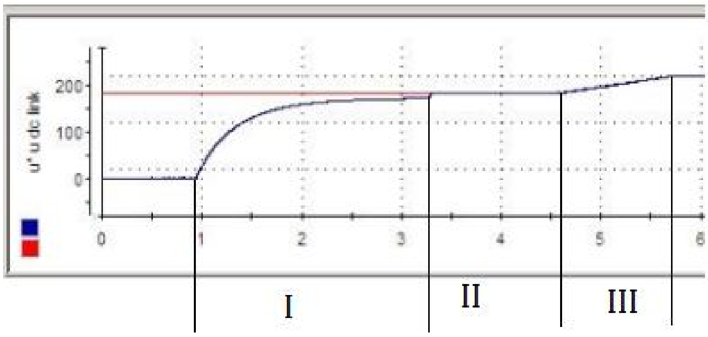


Fig. 8 – Evolution of the voltage across the compensation capacitor during the charging process (detail from GUI).

The Fig. 8 highlights that the charging process contains three stages:

I. Free charging by current limiting resistors;

II. Free charging by direct connection;

III. Active charging by prescribing a ramp voltage.

It can see that in the third stage the capacitor voltage follows exactly the prescribed values, as proof of very good dynamic performance.

In the same time, the voltage ripple in steady-state regime is low (about 1%) (Fig. 9), which confirms the correct calculation of the voltage controller's parameters.

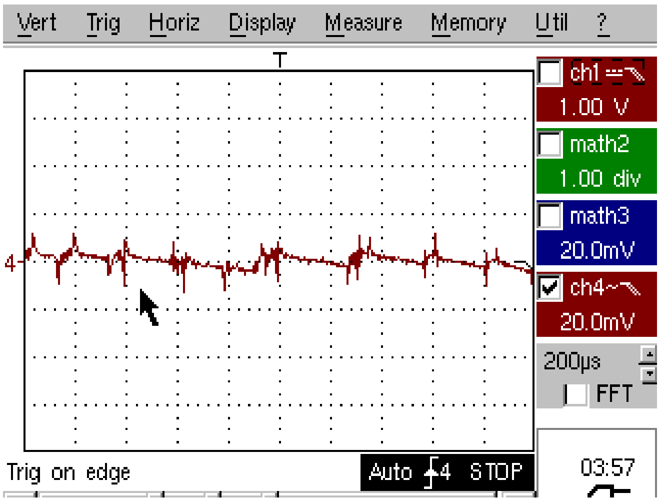


Fig. 9 – Detail of the voltage across the compensation capacitor in steady-state regime.

6.2. Verifying the Proper Operation of SISFREG in Active Filtering Mode and Determining the Associated Energy Performances

After the capacitor charging stage is finished, the system is prepared for operating in active filtering or regeneration regime depending of relation between voltages on DC capacitor and DC traction line. By reducing the excitation current of the DC motor, the SISFREG passes in active filtering operating mode. Waveforms of the main quantities are given in three forms: by graphical user interface (Fig. 10), graphical representation under Matlab using the acquisitioned dates (Fig. 11) and obtained by oscilloscope (Fig. 12).

The quantities on the graphic interface are defined below.

1. On the left (top to bottom):

– the phase voltages to the network and templates of active current provided by the PLL block;

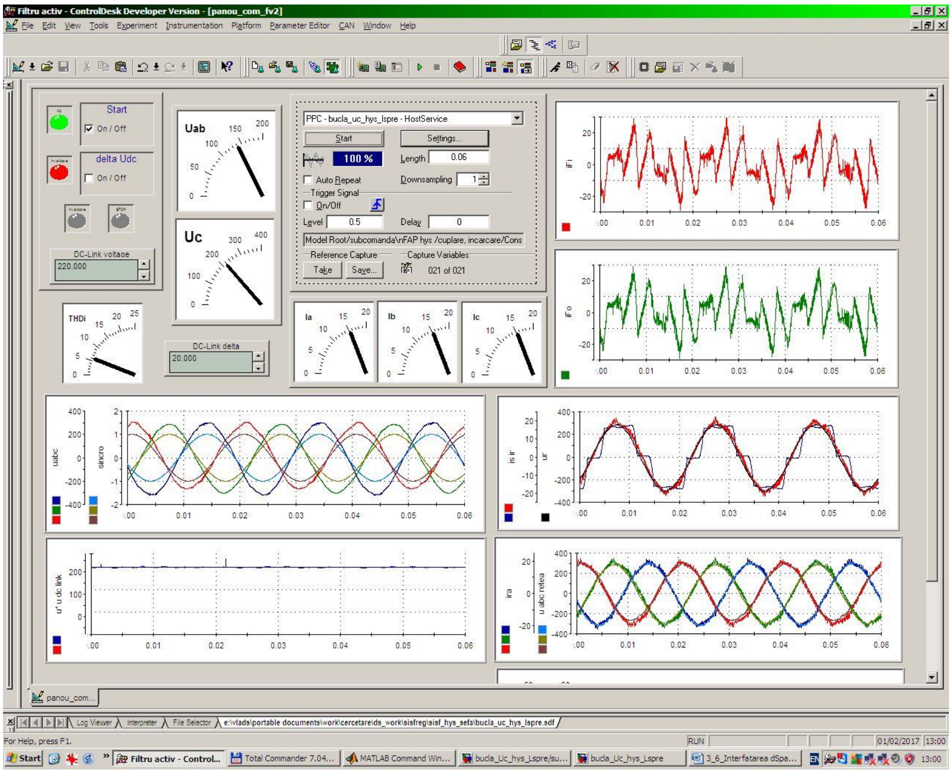
– the voltage on the compensation capacitor.

2. On the right (top to bottom):

– the active filter current before and after interface filter;

– the load and grid currents per phase;

– the network line current.



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Downsampling 1
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Level 0.5
Delay 0
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Fig. 10 − Virtual control panel of the experimental setup during the traction/filtering regime.

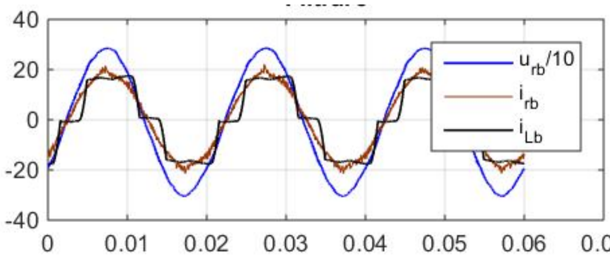

Fig. 11 – The waveforms of voltage, supply current and load current during the filtering/traction.

Next, the main good performances are highlighted.

1. The voltage across the compensating capacitor is almost constant (about 210V).

2. The current of the power supply is practically sinusoidal; it means that a very good active filtering is achieved.

3. The phases of the supply voltage and the supply current are the same, which means that unity power factor is obtained.

4. The partial harmonic distortion factor (PHD) of the current is about 3.4% (has been calculated by taking into consideration the first 51 harmonics).

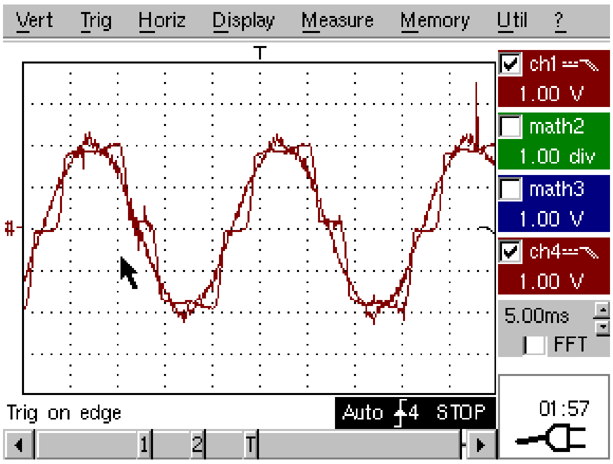

Fig. 12 – The waveforms of supply current and load current during the filtering/traction, recorded by a digital oscilloscope Metrix OX 7042-M.

Also, few specifically aspects must be underlined.

1. The supply current contains high frequency harmonics due to the inverter switching (f_{sw} of about 7 kHz).

2. As illustrated in Fig. 10, the supply voltages have a certain degree of distortion and cannot be use as active currents templates in the control algorithm implementation. Consequently, the control scheme contains a PLL block providing three sinusoidal signals having the same zero crossing as the phase voltages.

3. It is very clear that the active filtering performance is determined by the correctness of generation the phase currents templates. For this purpose, the PI controller of the PLL was tune through a specific procedure by authors.

The energetic performances are synthesized in Table 1 and the significance of quantities are presented next.

Eff – the efficiency of active filtering defined as,

$$Eff = \frac{HDI\_L}{HDI\_R}, \tag{1}$$

PHD – partial harmonic distortion factor of the current,

$$PHD = \sqrt{\sum_{k=1}^{51} I_{sk}^2} \Big/ I_{s1} \cdot 100 , \tag{2}$$

I_{s1}, I_{sk} – fundamental and *k* order harmonics of the current;
HDI_R – partial harmonic distortion factor of the grid current;
HDI_L – partial harmonic distortion factor of the load current;
P_L – active power of the load;
P_R – active power of the grid;
PF_R, *PF_L* – power factors of the grid and of the load.

Table 1
The Values of the Energetic Indicators in the Filtering Mode

HDI_R [%]	HDI_L [%]	Eff	P_R [kW]	P_L [kW]	PF_R	PF_L
3.39	23.71	6.022	6.918	6.661	1	0.95

6.3. Verifying the Proper Operation of SISFREG in Regeneration Mode and Determining the Associated Energy Performances

In the experimental setup, transition to the regeneration regime is perform by increasing the excitation current of the DC motor.

Consequently, the DC voltage becomes higher than the line voltage on the AC side of the rectifier, until the load current decreases and the rectifier is blocked. Thus, the voltage provided by the DC generator becomes higher than the prescribed voltage across the compensating capacitor and SISFREG passes in regeneration mode and provides active power to the grid.

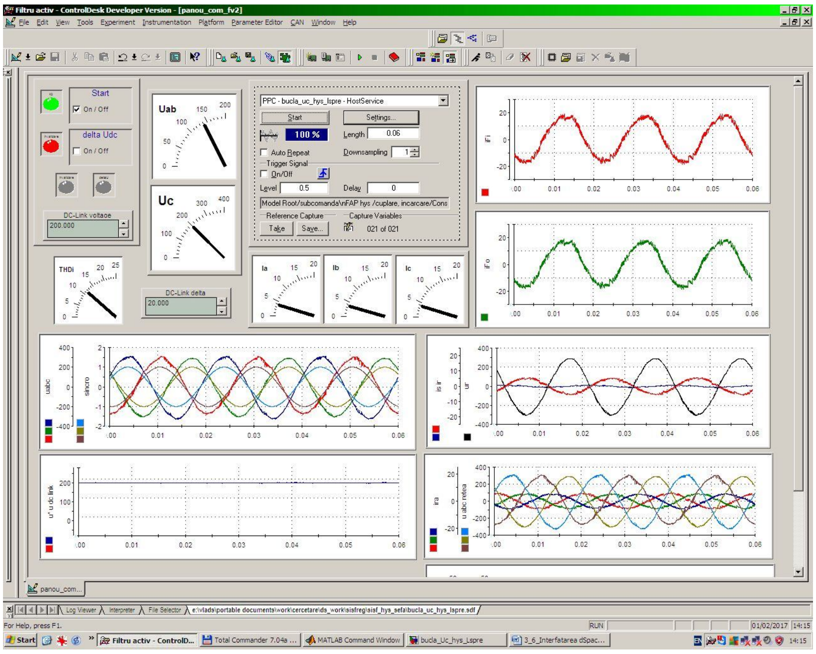

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Fig. 13 − Virtual control panel of the experimental setup during the breaking/regeneration regime.

The waveforms of the main quantities (Figs. 13,…,15) show the following:

1. The current is practically sinusoidal, its phase and of the supply voltage are opposite and the zero crossings are the same; it means that the global power factor has unity value (Figs. 13 and 14);
2. Fig. 15 shows the waveforms of line voltage and current recorded by a digital oscilloscope; because the phase of line voltage is π/6 in advance, it denotes, again, that the global power factor has unity value;
3. The partial harmonic distortion factor of the regenerated current, calculated by first 51 harmonics, has a value of 4.48% and falls within the limitations imposed by standards;
4. The regenerated current contains high frequency harmonics due to the inverter switching;
5. The average value of the switching frequency is the same as in active filtering regime (fsw ≈ 7 kHz), since it depends on the switching inductance and the hysteresis band of the current controller;
6. The efficiency of the regeneration process is about 80%, according to the regenerated power (6.3 kW).

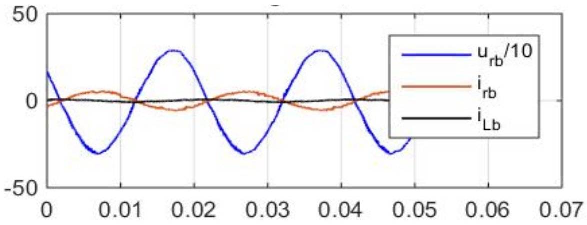
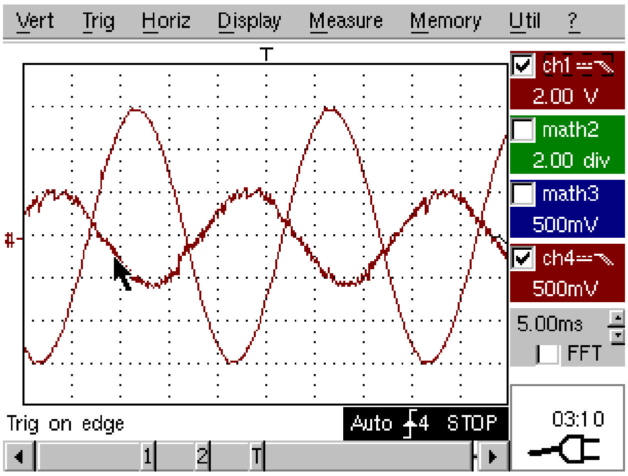


Fig. 14 – The waveforms of voltage, supply current and load current during the breaking/regeneration regime.



☑ ch1 2.00 V
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☐ math3 500mV
☑ ch4 500mV
5.00ms
☐ FFT
Trig on edge
Auto 4 STOP
03:10

Fig. 15 – The waveforms of supply current and line voltage during the breaking/regeneration, recorded by a digital oscilloscope Metrix OX 7042-M.

7. Conclusions

The results of the complex experimental investigations on the conceived laboratory model for an active DC-traction substation lead to useful and important findings that fully validate the proposed solution and the theoretical background.

1. It was theoretically and experimentally proved that the indirect current control method can be applied in both active filtering and regeneration modes operation and leads to high performance in terms of power quality at the grid side (harmonic distortion and power factor).
2. It was experimentally prove that the transition of the system from the active filtering mode in regeneration-mode and vice versa occurs naturally.
3. The experimental results show the very good behavior of the voltage control loop with PI voltage controller designed by applying the Symmetrical Optimum criterion in accordance with the system's parameters.
4. Even under the existing nonideal supply voltages of the laboratory (harmonic distortion and asymmetry), a balanced and almost sinusoidal system of supply currents is obtained. It is the effect of the correct design of the voltage controller and the correct operation of the conceived PLL circuit charged to provide the sinusoidal "template" signals in the reference current generation.

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PROIECTAREA UNUI STAND DE TESTARE A SISTEMULUI DE FILTRARE ŞI REGENERARE ŞI EVALUAREA EXPERIMENTALĂ

(Rezumat)

Lucrarea este dedicată prezentării proiectării structurii de testare şi a metodologiei de evaluare experimentală a unui sistem de filtrare şi regenerare. Configuraţia structurii de testare a fost realizată pe baza condiţiilor reale existente într-o staţie de tracţiune în c.c. şi având în vedere echipamentele disponibile în Laboratorul de Electronică de Putere şi Acţionare electrică a Departamentului de Electromecanică, Mediu şi Informatică Aplicată. Structura experimentală conţine: echivalentul grupului de tracţiune transformator - redresor; echivalentul motoarelor de tracţiune (c.c.); posibilitatea conectării sistemului, pe de o parte, în punctul de conectare al transformatorului de tracţiune şi, pe de altă parte, cu linia de c.c. (echivalentul catenarei). Astfel, pot fi determinate performanţele sistemului la funcţionarea în regim de filtrare şi de regenerare. Lucrarea prezintă experimentele efectuate, în conformitate cu protocolul de testare, a unui model de laborator al unui sistem de filtrare şi regenerare (SISFREG) care permite conversia staţiilor de tracţiune în c.c. în "staţii active". Algoritmul de control şi monitorizare a fost implementat pe sistemul dSpace 1103.

Lucrarea este organizată pe şapte secţiuni: prezentarea unui sistem de filtrare şi regenerare (SISFREG) şi controlul său elaborat de autori şi echipa lor (secţiunile 2 şi 3); prezentarea sintetizării structurii testului de stand şi prezentarea experimentelor efectuate în conformitate cu protocolul de testare (secţiunile 4 şi 5). În plus, interpretarea rezultatelor şi determinarea performanţei energetice a sistemului în modul de filtrare şi de regenerare funcţionare activă sunt prezentate în secţiunea 6. În cele din urmă, a fost tras câteva concluzii.