# Testing a Filtering and Regeneration System on a Recuperative Stand

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***Abstract* - The paper has three main objectives: the presentation of a laboratory model of a system for active filtering and regeneration (SISFREG) developed through an applied research collaborative project in the frame of Partnerships in priority area programme during 2014-2016; the presentation of the methodology and design of recuperative testing structure and the presentation of few experimental results. SISFREG allows the conversion of the DC traction substations into "active substations". The laboratory model is composed of one configurable voltage source inverter (input voltage range 200-560 V DC; output voltage 3x400 V AC; rated power 30 kVA) adequately interfaced with the DC-line and properly controlled in closed loop. The control algorithm was implemented on the dSPACE 1103 system that allows the monitoring of the system too. The methodology and the testing structure configuration started from the actual conditions existed in a substation for DC traction. The experimental structure is based on the equipment available in the laboratory and it contains: the equivalent of the transformer-rectifier traction group; the equivalent of the DC 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 the DC line (equivalent catenary). Finally, the paper presents several experiments conducted in accordance with the testing protocol, the analysis of the experimental results and the resulted performance of the system, during both active filtering and regeneration operation modes.**

**Cuvinte cheie:** *filtrare activa, regenerare, stand de testare, substatii active, tractiune in c.c.*

**Keywords:** *active filtering, regeneration, test stand, active substation, DC Traction.*

## I. INTRODUCTION

In the DC traction systems, the traction substations (TSS) contain, usually, a specific traction transformer and an uncontrolled rectifier. The traction substations provide the current only in one direction and they have not the capacity to absorb the energy generated during the braking regime of trains. A reversible station has the capacity to allow the active power flow in the both ways. However, the connection to the same transformer, at the medium voltage side, can affect the capability of achieving the function of harmonics filtering and reactive power compensation. Indeed, it is well known that, based on the operating principle of an active power filter (APF), the DC voltage value must be higher than the AC line voltage magnitude. Moreover, the performance of the system, in terms of current distortion during recovery process after compensation, depends on the difference between the two voltages [1]-[4].

In order to implementing of "high energy efficiency", two main directions for improving energy performance were identified [5]:

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 and send it in supply line.

Though the compensation of the current harmonics and reactive power is an old concern materialized simply by passive filters, nowadays, due to the power electronics development and associated digital processing techniques, the use of active power filters represents a viable and much higher performance alternative [6], [7], [8]-[12].

The second direction has implications on increasing the energy efficiency even more significant than the first one and can be concretized through the following ways [13]: using the recovered energy by the auxiliary services of the train; sending it in the catenary line to be used by another train in the same catenary section [16]; storing it by various mobile/stationary devices [6], [14]-[16]; sending it in the TSS' power grid [17]-[22].

The paper has three main goals: designing the experimental test protocol of a filtering and regeneration system (SISFREG); the presentation of the synthesizing of structure of stand test and the presentation of the experiments conducted in accordance with the test protocol, interpretation results and determine the energy performance of the system in the active filtering and regeneration operation mode.

## II. TESTING PROTOCOL OF FILTERING AND REGENERATION SYSTEM - LABORATORY MODEL

### A. *Experimental model of the filtering and regeneration system*

The system is based on the diagram from figure 1 and was developed around of one voltage three-phase inverter (VI). Other components of power part are: ChC-the charging circuit; CAIF-interface filter on the a.c. part; SC-the separating circuit on the c.c. part. For system control and its monitoring, a lot of current and transducers are needed [18].

Supplementary, two aspects must be underlined. The first is to test the influence of parameter values of the interface filters, both with the DC side and with the AC side. For this, the coils in question were designed and manufactured with multiple sockets, as follows:

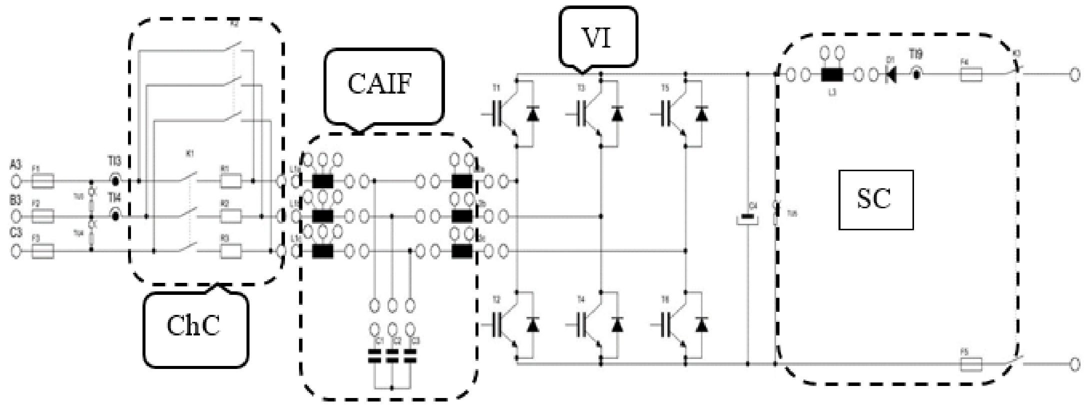


Fig. 1. Electric scheme of the power part of experimental model of SISFREG.

a) L1 coil, from the network, has 3 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 2 plugs and consequently 3 values can be used (10 μH, 20 μH, 30 μH);

c) coil L3 on the DC side has 2 plugs and consequently 3 values can be used (1 μH, 2 μH, 3 μH);

d) LCL filter capacitor on the AC side can be connected or not.

The second to refer to control part of the system. So, the control part of the system contains two closed loops, where the first one is outer and controls the DC voltage and the other is inner and controls the current. In the adopted cascaded control loops, the DC-capacitor voltage PI controller is designed according to the Modulus Optimum Criterion. In the indirect current control case, the output of voltage controller is the reference current magnitude of the grid current controller during both filtering and regeneration modes [19]. A specific PLL circuit provides the system “voltage template” of unity magnitude sinusoidal signals, having the same phase as the fundamental voltages. For obtaining the grid currents reference, these are multiply by the output of voltage controller.

### *B. Testing protocol*

The main objectives of the testing procedure have been:

1. Verifying the proper operation of the voltage controller;

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.

4. Evidencing of influence of interface filters’ parameters, in both DC and AC sides.

Equipment and materials used are: one experimental structure; Metrix OX 7042-M oscilloscope; current probe Fluke i1000s; cc/c.a. Fluke 80i-110s; three-phase analyzer for Fluke 42s energy quality; Fluke 289 digital multimeter; LM6113 galvanic isolation amplifier.

To collect the data needed to meet the objectives, the methods used are: direct measurement of currents and voltages; recording with oscilloscope and saving data; recording energy quantities at the entrance of the equipment with the Fluke analyzer and saving them; acquisition of a lot of quantities with dSPACE 1103 and their processing.

## III. RECUPERATIVE EXPERIMENTAL TESTING STAND

At the synthesis of the structure of the experimental test bench it was imposed that it contain all the components correspond to one DC traction Substation. Thus, the structure of Fig. 2 was found, in which:

1. The equipments 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) is of type Y/d, 380/130V and the inverter is connected at its secondary;

5. The possibility of connecting SISFREG, on the one hand, in the connection point of the traction transformer, and, on the other hand, with the DC line (K4 and K3).

It pointed out that:

1. The synchronous machine (MS) is connected to the three-phase network and it operates as generator for the traction regime of the system and as motor for the 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 operates as generator and resend to the grid a part of power taken by the autotransformer;

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

In addition, the test stand must operate with electric energy recovery both in traction mode (active filtering) and in braking mode (regeneration).

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

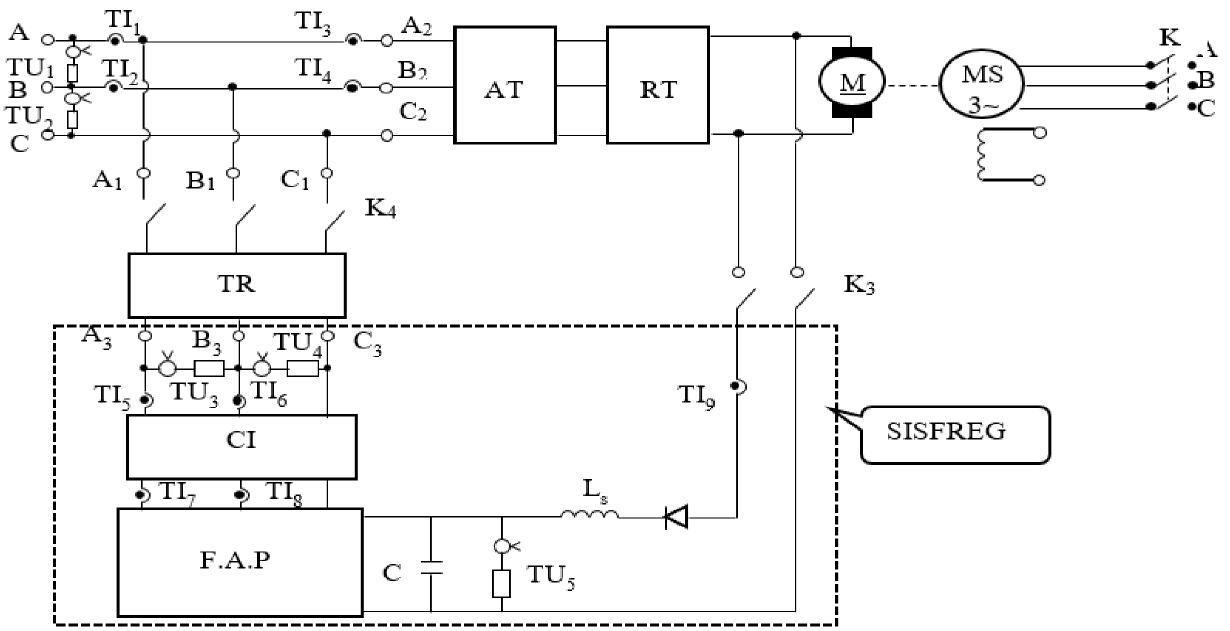


Fig. 2. Electric scheme of the experimental testing stand.

1. Connecting SISFREG to the network and charging the filtering/compensating capacitor at the prescribed value Ucp (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) by decrease or increase the current in the second excitation coils.

The physical disposition of all the components of experimental testing bench is pictured in figure 3.

In fact, if DC voltage is lower as the voltage across compensating capacitor (Ucp), the SISFREG operates in active filtering mode and when the DC voltage becomes higher than Ucp, the SISFREG passes in regeneration mode.

The SISFREG control algorithm implementation on the DS1103 platform was started 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.

A graphic user interface (GUI) was built for the experimental setup management and for recording a lot of quantities useful in the proper operation of the system

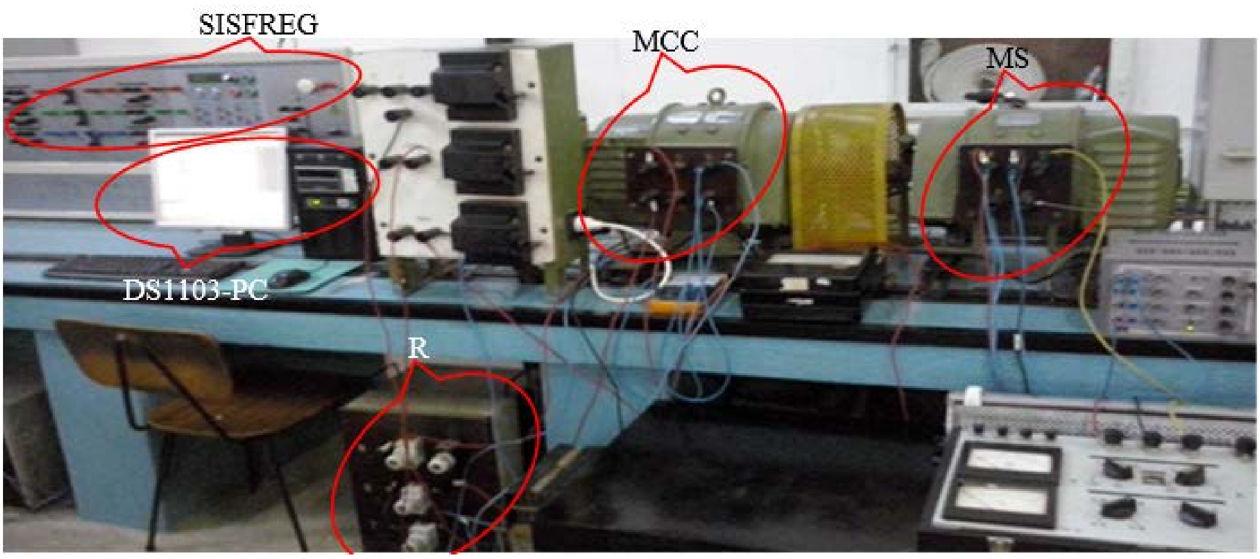


Fig. 3. Picture of the experimental testing stand.

## IV. The Performance Of The Voltage Control Loop

The proper operation of the DC-voltage control loop is determined by the parameters of the PI controller. In the indirect control case, the controller's parameters depend on the parameters of regeneration transformer [20]. The time-evolution of the voltage across the DC-capacitor (Fig. 4 and 5) highlights the following:

1. The charging process takes place in three stages (first- free charging by current limiting resistors, second- free charging by direct connection and third-active charging by prescribing a ramp voltage);

2. In the active charging mode, the voltage across capacitor accurate follows the prescribed values;

3. The voltage ripple is low (about 1%), which confirms the correct calculation of the voltage controller's parameters.

## V. The Performance In The Active Filtering Mode

The traction regime is obtained, by reducing the excitation current of the DC motor. The waveforms of the main quantities are given in three forms: on the base of numerical dates acquisitioned by DS1103 platform and their processing under Matlab (Fig. 6), measured by oscilloscope (Fig. 7) and through the conceived virtual control panel, which is a graphical user interface (GUI) in the frame of dSPACE 1103 platform (Fig. 8). Two important remarks can be drawn:

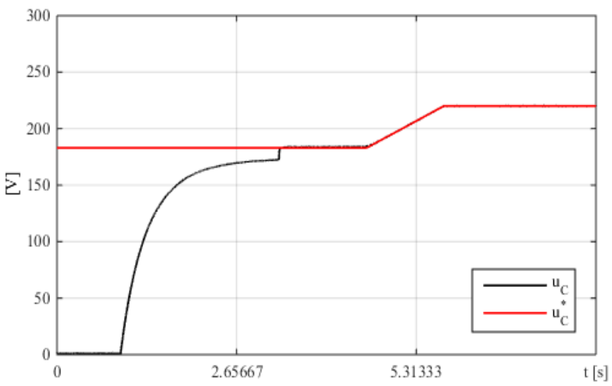


Fig. 4. Evolution of the voltage across the compensation capacitor during the charging process (prescribed-red; real-black).

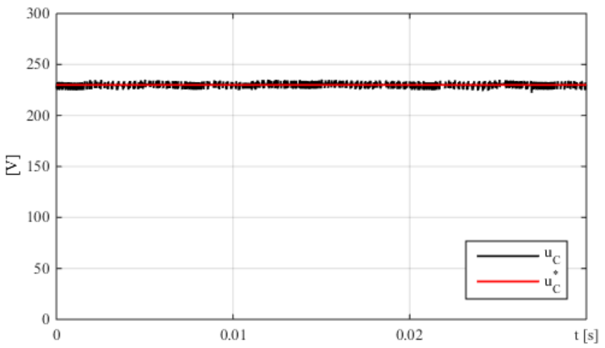


Fig. 5. Detail of evolution of the voltage across the compensation capacitor during the filtration regime.

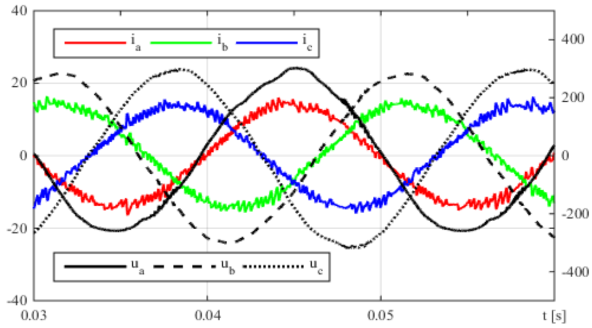


Fig. 6. The grid phase voltages and currents in traction/active filtering regime.

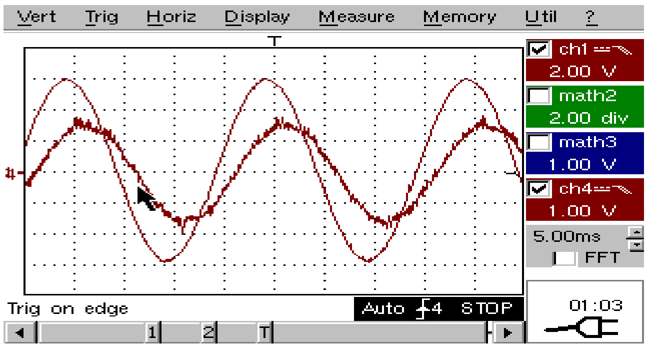


Fig. 7. The grid line voltage and current in traction/active filtering regime.

1. The phase voltages and currents are simultaneously passing through zero and consequently, the power factor is unitary;

2. The currents are practically sinusoidal because their distortion factor is about 3.5%.

The quantities in GUI (Fig. 8) are described below.

1. In the left side (from top to bottom):

- The phase power supply voltages and the associated "templates" provided by a phase-locked loop (PLL) block;

- The voltage across the compensation capacitor.

2. In the right side (from top to bottom):

- The current per phase and its prescribed wave form;

- The load phase current along with the phase voltage and current drawn from the power supply;

- The phase currents at the inverter output;

- All phase voltages and currents at the power supply side.

As it can be seen, the voltage across the compensating capacitor is almost constant (about 210 V).

Fig. 6 and Fig. 8 show that the supply voltages have a significant degree of harmonic distortion. Consequently, they can not be used as active currents templates in the control algorithm implementation. From this reason, the control scheme contains a PLL block providing three sinusoidal signals having the same zero crossing as the phase voltages [29].

It is quite clear that an incorrect reference to the current waveforms decisively affects the filtering performance of the system. To avoid this, the PI controller inside the PLL loop was tuned after a specific procedure set up by the authors.

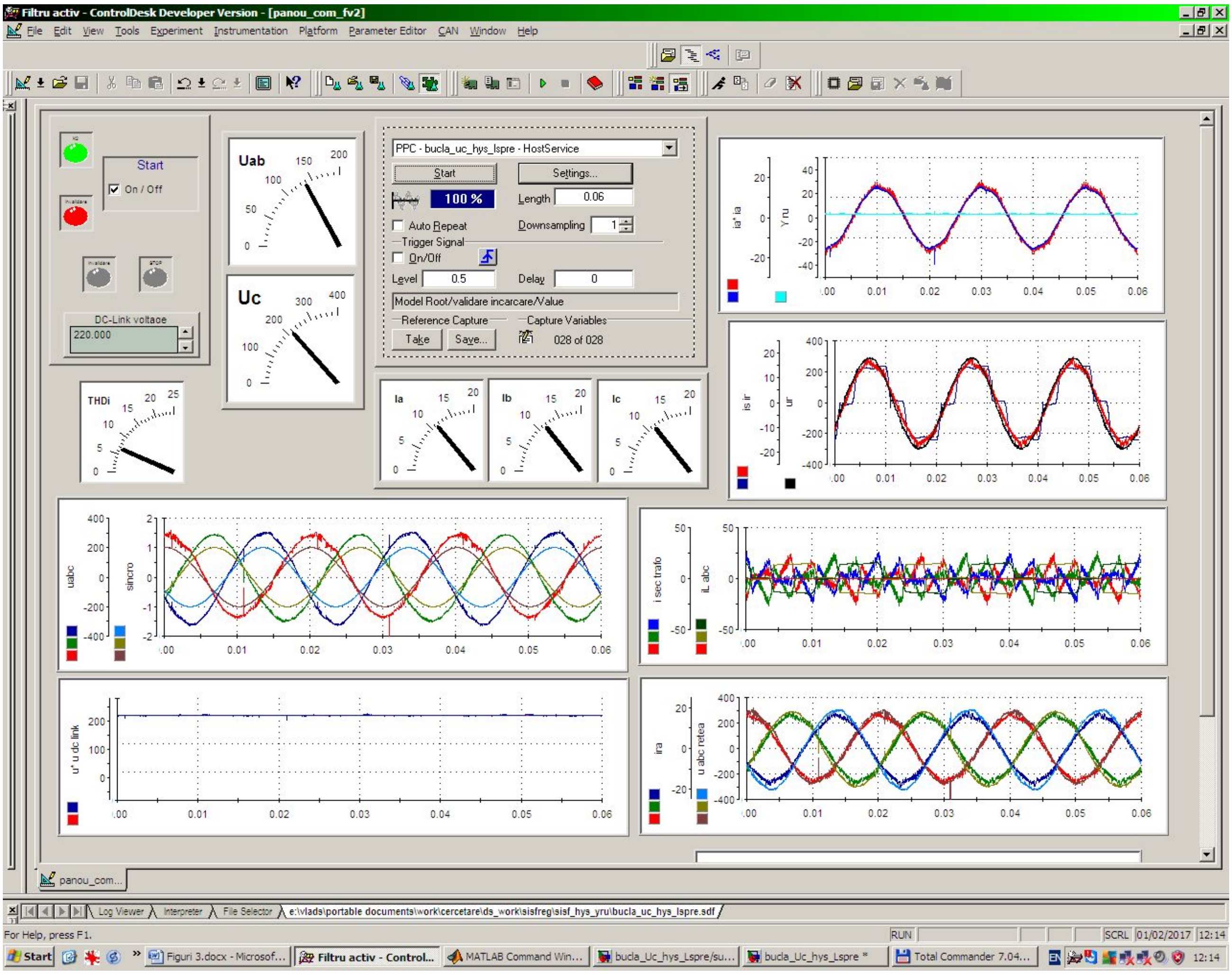


Fig. 8. Virtual control panel of the the experimental system during the traction/filtration regime.

The proper operation of PLL loop is proved by waveforms from figure 9. It can see that, although the available supply voltage has a significant degree of distortion and asymmetry, the grid current templates are sinusoidal. Must be noted that correct operation of PLL loop is critical for the stability of the system too and the experimental results prove that its design was an attempt successfully solved.

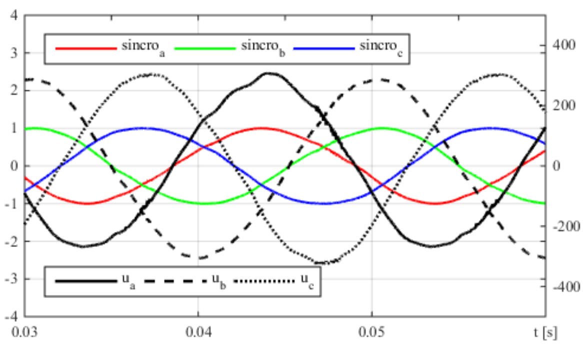


Fig. 9. The grid phase voltages and their templates obtained by PLL loop.

The energetic performances are summarized in Table I, on the base of following quantities:

PHD_S - partial harmonic distortion factor of the supply current;

PHD_L - partial harmonic distortion factor of the load current;

Eff – active filtering efficiency,

$$Eff = \frac{PHD\_L}{PHD\_S} \tag{1}$$

P_S, P_L – active powers at the power supply and load sides;

PF_S, PF_L – global power factors at the power supply and load sides.

The partial harmonic distortion factor (*PHD*) has been calculated by taking into consideration the first 51 harmonics, where $I_1$, $I_k$ are the rms value of the fundamental and k order harmonic of the current.

$$PHD = \sqrt{\left[\sum_{k=2}^{51} (I_k)^2\right]} / I_1 \tag{2}$$

TABLE I.
THE VALUES OF THE ENERGETIC INDICATORS IN ACTIVE FILTERING MODE

| *PHD_S* [%] | *PHD_L* [%] | *Eff* | *P_S* [kW] | *P_L* [kW] | *PF_S* | *PF_L* |
|---|---|---|---|---|---|---|
| 3.39 | 23.71 | 6.022 | 6.918 | 6.661 | 1 | 0.95 |

As illustrated, the value of the partial distortion factor of the supply current is low (about 3.39%), compared to the load current distortion of 23.71%.

It leads to a good filtering efficiency (over 6).

An increasing of the global power factor, from 0.95 to 1 is achieved too.

## VI. THE PERFORMANCE IN THE RECOVERING MODE

In the experimental setup, the transition from traction regeneration regime to recovery regime is obtained by increasing the excitation current of the DC motor.

First, the load current decreases to zero until the rectifier is blocked, because the DC voltage becomes higher than the line voltage on the AC side of the rectifier. Simultaneously, the synchronous machine become motor and the dc machine become generator. Also, as soon as the voltage provided by the DC generator becomes higher than the prescribed voltage across the compensating capacitor, SISFREG passes in regeneration mode and provides active power to the grid.

The waveforms of the various quantities are shown in figures 10 (obtained by GUI), 11 (obtained by acquisition) and 12 (obtained from oscilloscope).

The values of energetic indicators corresponding to breaking/regenerating operation mode are gave in Table II. The following remarks can be done:

1. The grid current is practically sinusoidal and its phase is in opposition with those of the supply voltage. In the same time, the zero crossings of the current and corresponding voltage are the same. It means that the global power factor has unitary value;

TABLE II.
THE VALUES OF THE ENERGETIC INDICATORS IN ACTIVE FILTERING MODE

| *PHD_S* [%] | *P_S* [kW] | *P_c* [kW] | *S_S* [kVA] | *PF_S* | *Eff_Reg* |
|---|---|---|---|---|---|
| 4.48 | 4.993 | 6.322 | 5.02 | 0.9942 | 0.7898 |

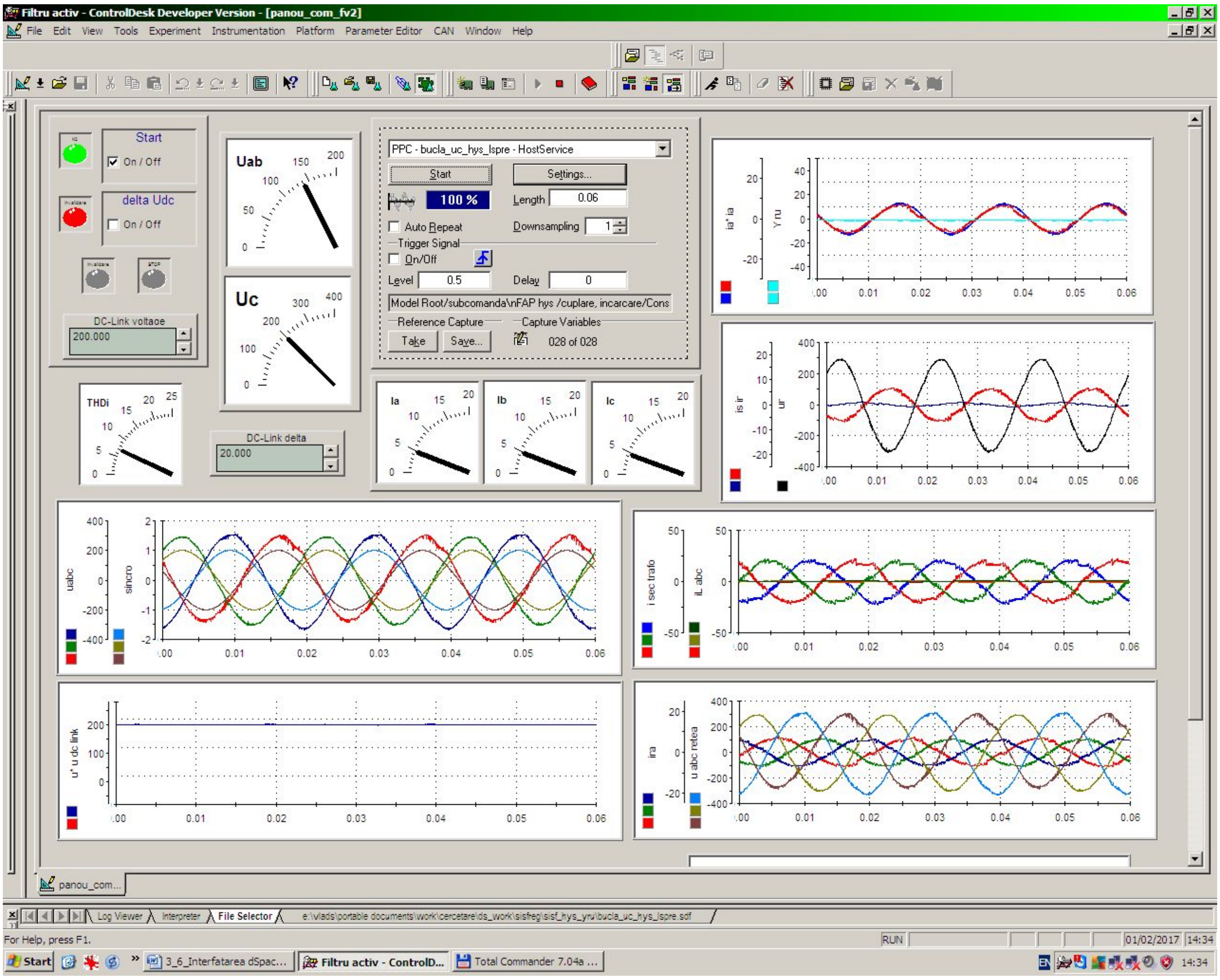


Fig. 10. Virtual control panel of the the experimental system during the traction/filtration regime.

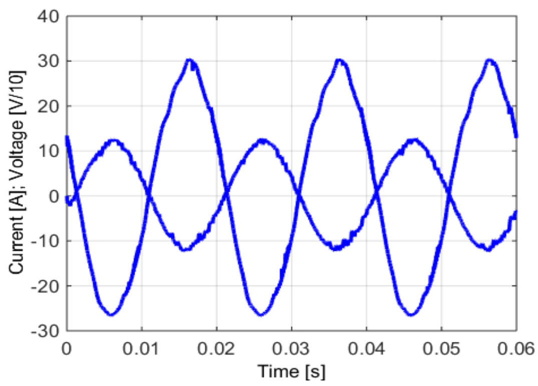


Fig. 11. The grid phase voltage and current in recovery regime.

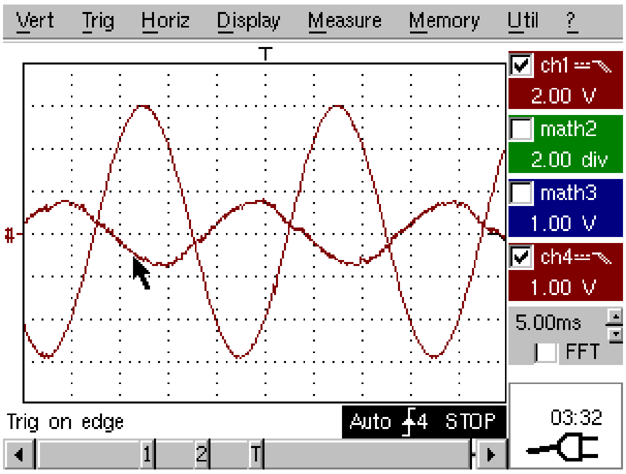


Fig. 12. The grid line voltage and current in recovery regime recorded by oscilloscope.

2. The partial harmonic distortion factor of the regenerated current, calculated by first 51 harmonics, has a value of 3.62% and falls within the limitations imposed by standards.
3. The regenerated current contains high frequency harmonics due to the inverter switching;
4. The switching frequency (about 7 kHz) depends on the switching inductance and the hysteresis band of the current controller.
5. The efficiency of the regeneration process is about 80%, according to the regenerated power (6.3 kW);

The significance of other quantities appearing in Table II is:

*P_c* – the active power at the DC-line;

*S_S* – apparent power at the power supply side;

*Eff_Reg* – the efficiency of the regeneration process calculated by relation,

$$Eff\_reg = \frac{P\_S}{P\_c} \tag{3}$$

## VII. Influence Of The Filter Coils On The Ac Side

The third order LCL filter with damping resistance leads to better performance in rejecting the switching harmonics and handling the current's dynamics. On the other hand, when SISFREG operates in recovery mode, the coupling filter is charged with the additional task to allow the passage of the compensating harmonics without modifying them. In these conditions, the design of coupling filter has high influence over performance of the system. This aspect is pictured in figure 13 and 14 that present the load current and the grid current for two values of L1 coil (1.2 mH and 0.8 mH). In the first case (Fig. 13) the grid current is nearly sinusoidal and its harmonic distortion factor is about 4% (within the limitations imposed by standards).

In the second case (Fig. 14), the harmonic distortion factor is over 6% (outside of the limitations imposed by standards).

The records made by authors sustain the mathematical and simulation results referring to AC coupling filter influence, respectively:

1. For an imposed value of capacitor voltage, exists one the best value of the L1 coil;

2. The third order LCL filter with damping resistance leads to better performance in rejecting the switching harmonics only if it is proper designed. Contrary, it can lead to poorer performance.

3. The coil on the inverter side can be missing from point of view of quality of the current, it is necessary only for limiting the variations speed of the current changed between the DC capacitor and the capacitor of coupling filter.

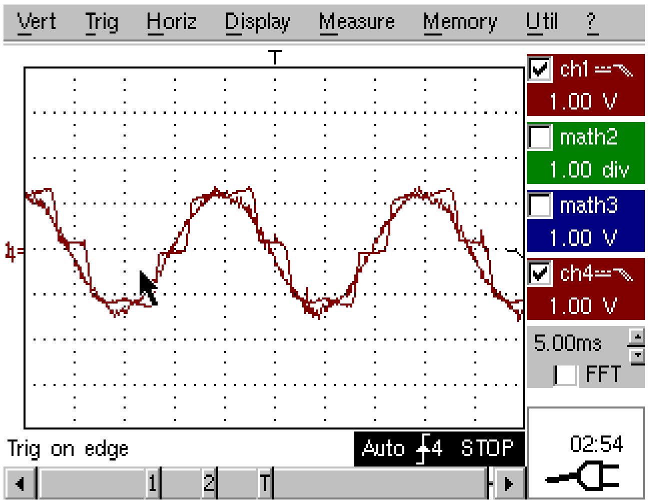


Fig. 13. The load and the grid currents for L1=1.2 mH.

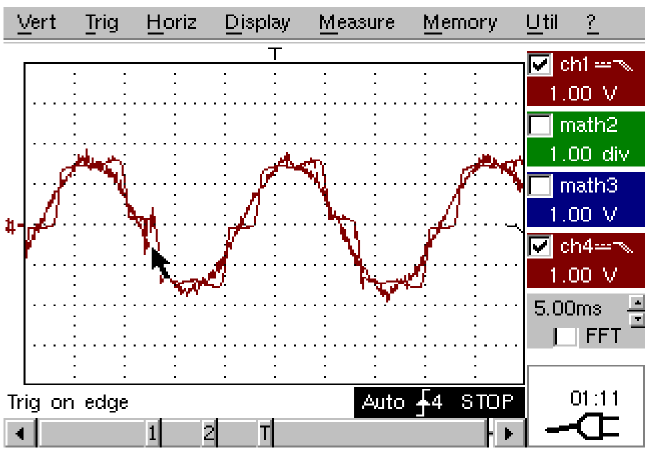


Fig. 14. The load and the grid currents for L1=0.8 mH.

## VIII. Conclusions And Remarks

The grid current, in the both traction and recovery regime, contains high frequency harmonics due to the inverter switching;

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.

The efficiency of the regeneration process is about 80%, according to the regenerated power (6.3 kW);

It is estimated that, at the power of 2 MW, the efficiency will be over 90%, as obtained on the virtual model.

## Acknowledgment

This work was performed through the program Partnerships in priority areas — PN II, conducted with the financial support of MEN – UEFISCDI, project no. PN-II-PT-PCCA-2013-4-0564 (42/01.07.2014).

Thanks our partners from INDA, especially Mr. Dr. Eng. Mihail Radulescu and Mr. Eng. Lavinius Goreci for their contributions in the laboratory model manufacturing.

Contribution of authors:
Firs author – 60%
First coauthor – 20%
Second coauthor – 20%

*Received on July 25, 2017*
*Editorial Approval on November 5, 2017*

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