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Abstract

The paper is concerned with the possibilities of transformation the DC traction substations with uncontrolled rectifiers into active substation, being able to ensure both the braking energy recovery and active filtering function. The main objective is to analyze the possibilities of integrating a three-phase active power filter based on voltage source inverter topology in the power structure of a DC traction substation in order to obtain a system for active filtering and regeneration (SISFREG). Based on correlation between the DC-line and AC-line voltages, it is shown that the active power filter can be connected directly in the secondary of the existing traction transformer only in the case of 12-pulse series rectifier. Modeling of the whole system and vehicle – DC line assembly was achieved in Matlab-Simulink and, on this basis, the performances were determined, in both filtering and regeneration modes. The outlined performances are related to the most important quantities: the recovered active powers in the dc circuit, at the SISFREG output (in the secondary winding of the traction transformer) and at the power grid; efficiencies in the secondary winding and also at the grid side; the total harmonic distortion factor of the recovered current in the secondary winding and at the grid side.

Keywords: Breaking Energy Recovery, Railway Active DC Traction Substations, Traction Transformer

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Introduction

In the DC traction systems, the traction substations are fed by the high voltage three-phase network and usually contain a specific traction transformer and an uncontrolled rectifier. In order to reduce the harmonic distortion of the supply current, a structure of twelve-pulse rectifier is often adopted, consisting of two diode bridges connected in series or in parallel and supplied from two secondary windings of the transformer, one in star connection and the other in delta connection [1], [2]. The common rated DC voltages provided by the rectifier are: 750 V (most trams and metro rail); 1500 V (regional express trains and Intercity) and 3 kV [1], [2]. For low and medium DC voltages (750V and 1500V), the most used rectifier schemes are three phase bridge (6 pulses) and two three phase bridges connected in parallel (12 pulses) because of its higher efficiency. In the case of the DC voltage of 3000V, the use of the series 12-pulse rectifiers can be more advantageous, especially from reliability point of view, because the voltage class of the rectifiers is halved. Although the 12-pulse rectifiers have lower distortion factor of the current (about 15%), because of high power, the DC traction substations are important harmonic polluters. Consequently, other equipment must be used to reduce the harmonic distortion and increase the degree of compliance with the limits set. Another way to increase the energy efficiency of traction substations and reduce the energy consumption is the recovery of braking kinetic energy [3], [4]. The electric traction motors are able to transform the kinetic energy into electrical energy, but only a small amount of the resulted energy is usually reused for the auxiliary services. The remaining energy can be sent back to the grid only if other train, which accelerates, is close to the same line section and takes advantages of this energy conveyance. If there is no other train nearby to absorb this energy, the grid voltage increases and this supplementary energy must be scattered in braking resistances. The methods identified so far for braking energy recovery involve either the use of various mobile/stationary energy storage devices or the direct return to the AC-power utility [2], [3], [5]-[9]. The most advantageous solution is to recover the surplus energy in the traction substations and to compensate the current harmonics and reactive power by materializing thee “active station” concept [3]. The traction substations have not the capability to absorb the energy generated during the braking phases of trains because they provide the current only in one direction. A reversible station has the ability to allow the active power flow in the both ways. But, the connection to the same transformer, at the medium voltage side, can affect the capability of achieving the function of regeneration in terms of current distortion, because the performances of the system depend on the difference between the two voltages [7]-[9]. Compared to the reversible stations, the new system called “active substation” allows not only the energy recovery, but also complementary functions, such as: the grid harmonics compensation by operating like an APF; the active compensation of the reactive power; the dynamic compensation of the voltage variations in the high voltage line; voltage drop limitation in the supply line. Moreover, the adoption of advanced solutions, such as power active compensators, is a present concern, reflected by several achievements in the power structure and control system [10]-[13]. The proposed system in this paper is intended to ensure both the total compensation of the DC traction substation load and the braking energy recovery by sending it back to the power supply using the traction transformer of the DC traction substations with 12-pulse rectifier (two 6-pulse bridges connected in series). In this way, the existing DC traction substation with uncontrolled 12-pulse rectifier becomes “active substation”.

After demonstrating that the DC traction substations with 12-pulse rectifier allow the direct coupling of SISFREG in the traction transformer secondary, Section *“Regeneration and Filtering System Configuration”* is devoted to presenting the system structure. Next, the Simulink model of the entire system (SISFREG and vehicle – DC line assembly) is presented. Then, the performances in filtering regime, as well as in energy recovery regime are determined when the system operates in open loop mode. Finally, some concluding remarks related to the system performance are drawn.

Can be Traction Transformer used for Braking Energy Recovery?

The quality of the current injected into the AC-line depends of the difference between the voltage at the DC-side and the magnitude of the line-to-line voltage. The transformer secondary voltage is established provided that the no-load average output voltage of the rectifier (U_{DC0}) ensures the rated catenary’s voltage (U_{DCN}) and the voltage drop in the power supply circuit (ΔU), i.e.

$$U_{DC0} = U_{DCN} + \Delta U \,. \tag{1}$$

The voltage drop is expressed as a percentage of U_{DCN}, (about 5÷10 %),

$$\delta U[\%] = \Delta U / U_{DCN} \cdot 100 \,. \tag{2}$$

Thus, U_{DC0} can be expressed as:

$$U_{DC0} = (1 + \delta U) \cdot U_{DCN} \,. \tag{3}$$

U_{DC0} depends linearly on the magnitude of the line-to-line voltage in the transformer secondary,

$$U_{DC0} = k_R \sqrt{2} U_{st} \,, \tag{4}$$

where U_{st} is the rms value of the line-to-line voltage and k_R is a coefficient depending of the type of rectifier, respectively, for the 12-pulse series rectifier, $k_R = 6/\pi = 1.91$.

The capability of the scheme to allow the regeneration is showed by the ratio k_p of U_{DCN} and the magnitude of the line-to-line voltage in the transformer secondary. Thus, as a principle, if k_p is over unity, the scheme is capable of recovery. From (3) and (4), the ratio k_p can be expressed as:

$$k_p = U_{DCN} / \left(\sqrt{2} U_{st} \right) = k_R / (1 + \delta U) \,. \tag{5}$$

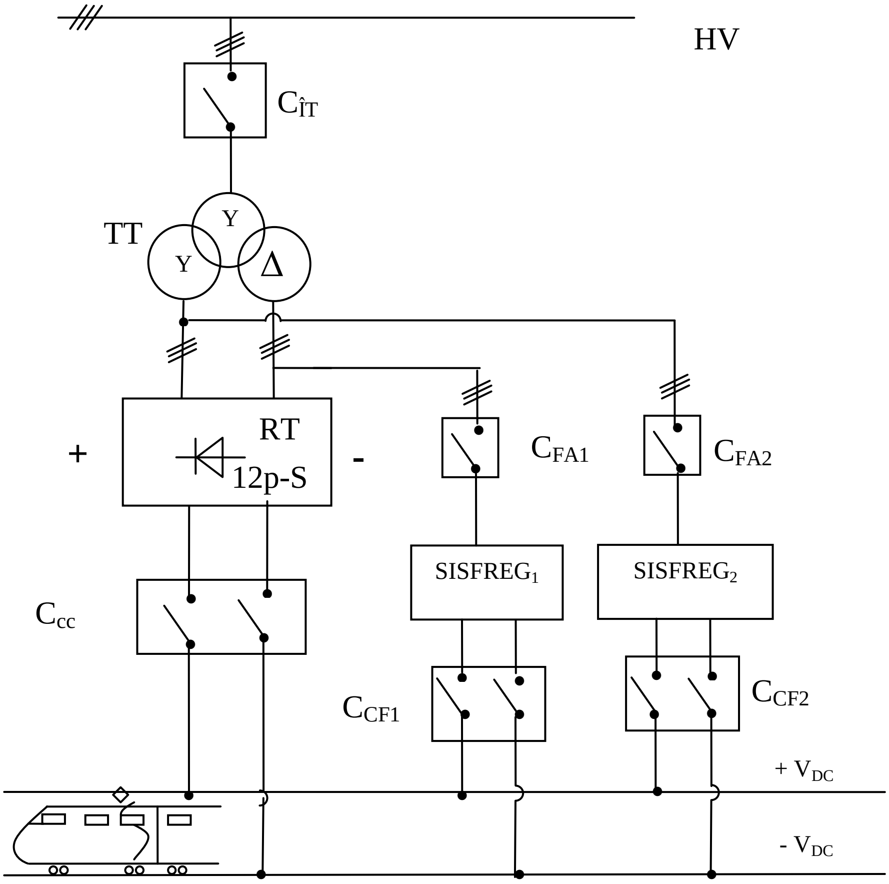
By particularizing (5) for δU = 0.1 is obtained that $k_p = 1.74$.

This result shows that the traction substations with 12-pulse series rectifiers allow the regeneration and compensation by using the traction transformer. In the case of the other schemes of rectifiers, the regeneration and compensation are possible only by using a dedicated transformer.

Regeneration and Filtering System Configuration

Two filtering and regeneration systems (SISFREG) are needed to be connected between the traction DC line and the both secondary windings of the traction transformer -TT (Figure 1). Certainly, several contactors are required for: the connection of the traction transformer to the high voltage line (C_{IT}); the connection of the traction rectifier (RT) to the DC line (C_{cc}); the connection of SISFREG to the secondary windings ($C_{FA1,2}$) and to the DC line ($C_{CF1,2}$). The detailed structure of filtering and regeneration system contains two parts: the control part and the power part. In the power part, the main component is the shunt active power filter (SAPF) which is connected to the traction line, through a unidirectional separating circuit (CS). The AC side of SAPF is coupled to one of

Figure 1. *The Block Diagram of Connection the Regenerating and Compensating System to the DC Traction Substations*



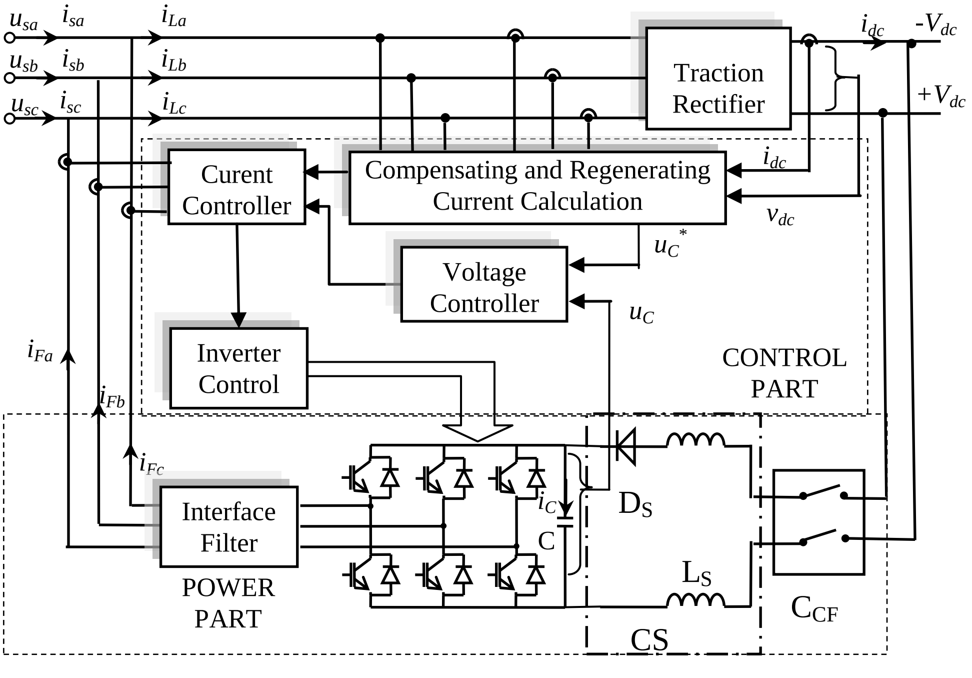
the secondary windings of the traction transformer by means of an interface passive filter (Figure 2).

In order to obtain a very good filtering of high order current harmonics (due to the inverter switching frequency of about 10 kHz), a complex structure of the passive filter was adopted (Figure 3).

The separating circuit (CS) is the supplementary part added to the shunt active power filter in order to obtain the regeneration function. It contains a diode with cathode toward DC side of SAPF and one inductivity. In this way, it can accomplish the following three functions: to work as an energy buffer between the DC-line and the SAPF’s DC-link; to provide the recovery current flow when the traction motors of the vehicle request it; to disconnect SAPF from the DC-line when the recovery current does not exist.

By adopting the prescribed voltage on the compensating capacitor to be greater than the maximum rectified voltage, the SFAP is practically disconnected from the DC-line in traction regime. Therefore, the system works in active filtering mode and the control block provides the compensating current computed using the adopted algorithm to SAPF [14], [15].

Figure 2. *Structure of SISFREG*

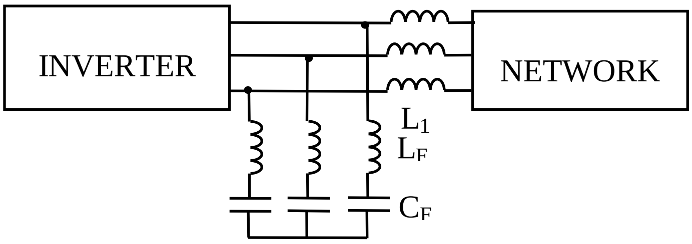


When the vehicle traction motors tend to pass into the braking energy recovery mode, the rectifier does not allow the reverse current, so the DC-line voltage increases and becomes higher than the voltage across the compensating capacitor of the active filter (U_{cF}). Therefore, the diode is forward biased and allows the existence of the recovery current. It must be noted that SISFREG does not work simultaneously in filtering and regenerating modes.

Thus, when the DC-line voltage is higher than the maximum rectified voltage, the rectifier is blocked and the load current is zero.

Finally, the control block provides the control signals for IGBTs on the basis of the current controller output. The current controller operates based on the SAPF's current (prescribed and measured values).This method is named direct control. The prescribed current has two components: the former is the active current corresponding to the losses in SAPF (i^{*}_{loss}) and the latter is the active current corresponding to the load (ia^{*}_{L}). There are two variants for the prescribed current calculation. The first variant is simpler and supposes that the whole active current is calculated by multiplying the output of the voltage controller by three sinusoidal signals synchronized with the corresponding voltages.

Figure 3. *Structure of the Interface Filter*



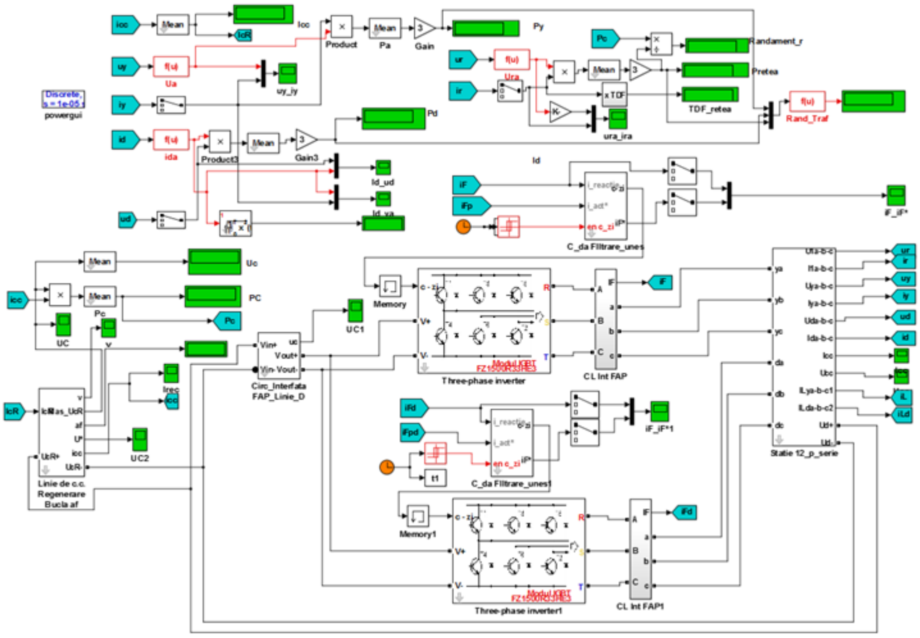
In the second variant, only i^*_{loss} is calculated by multiplying the output of the voltage controller by three sinusoidal signals synchronized with corresponding voltages, and the other component of the active current is drawn from the load current by using different methods [14]-[16].

In regeneration regime, as the prescribed capacitor voltage is maintained constant and the DC-line voltage becomes higher, the voltage controller operates in saturation mode, with negative output signal. Thus, the prescribed current is an active current with opposite phase to the primary winding voltage.

System Modeling under Simulink Environment

The Simulink model of the filtering and regeneration system is necessary in order to analyze the system performances (Figure 4). It has been obtained by connecting the subsystems models, i.e.: vehicle - catenary line assembly; traction substation; separating circuit between the active filter and the catenary line; the recovery transformer; the IGBTs voltage inverter; the interface passive filter; the reference current computation block for the filtering mode (using the p-q theory for nonsinusoidal voltage) and also the generation of the recovery current in the recovery mode together with the hysteresis current controller [14]-[16]. The model of the vehicle-catenary line assembly in braking energy recovery mode includes a braking acceleration control loop having at its input the reference acceleration and the measured acceleration calculated to be proportional to the DC current generated by the vehicle (Figure 5). The output of the acceleration controller means the e.m.f. equivalent to the traction motors in the braking energy recovery mode (modeled as a controlled voltage source) and the reference current is

Figure 4. *The Simulink Model of the SISFREG, Traction Substation and DC Traction Line Assembly*



computed to be proportional to the difference between the catenary line voltage and the compensating capacitor voltage.

Since the voltage in the traction transformer secondary has a significant degree of distortion (its shape reflects the commutations of both rectifier and SAPF), the active load current is calculated according to the improved p-q theory [15], [16], by using an expression proposed by authors and the fundamental component of the secondary voltages (Figure 6).

Thus, the active load current is calculated as:

$$\underline{i}_a = \frac{P_L}{U_{ph}^2}\underline{u}_1, \tag{6}$$

where P_L is load active power, U_{ph} is the rms value of voltages phasor modulus and $\underline{u}_1$ is the phasor of fundamental components of secondary voltages.

Also, in terms of the compensating capacitor voltage, the model is created to operate in open loop, i.e. the voltage control loop and the compensating capacitor are similar to an adequately connected DC source.

In order to calculate a lot of quantities used in determination the system performances, the model must contain different computation blocks for: the rms values of some AC currents and voltages (the rectifier input and the secondary winding output (before the connection of SISFREG)); the average DC current and voltage; the active powers at the rectifier input and at the secondary winding output (before the connection of SISFREG); the apparent powers at the rectifier input and at the secondary winding output (before the connection of SISFREG);

Figure 5. *The Simulink Model of the Vehicle-catenary Line Assembly*

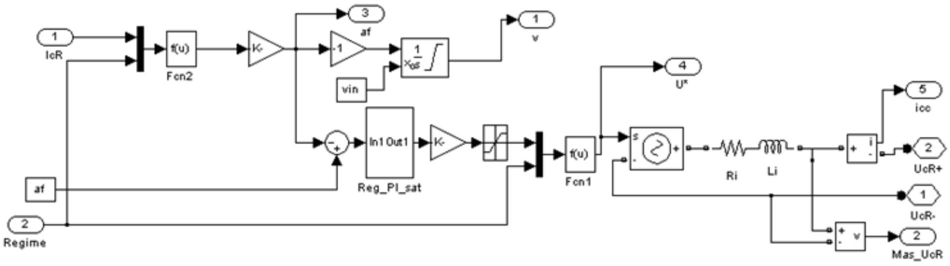
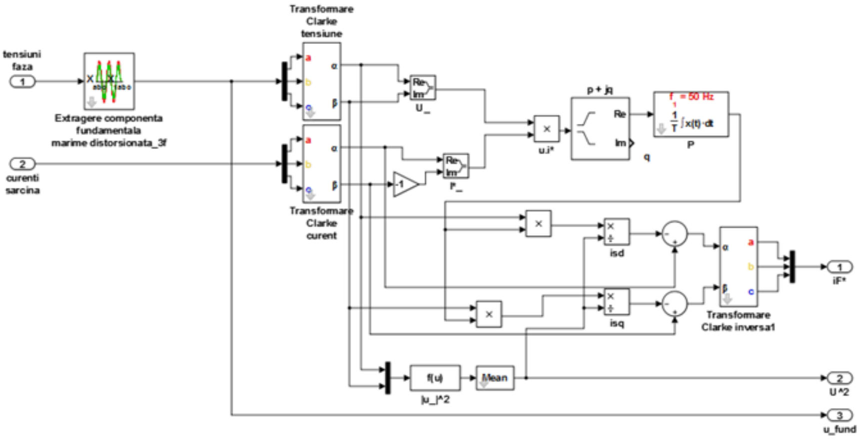


Figure 6. *The Simulink Model of the Active Current Computation by Improved p-q Theory*



the total harmonic distortion factor of the current at the rectifier input and at the secondary winding output (before the connection point of SISFREG); the filtering efficiency defined as a ratio between the total harmonic distortion factors, in the secondary winding, before (THD_L) and after filtering (THD_Y),

$$FE = \frac{THD_L}{THD_Y}; \qquad (7)$$

the total power factor at the secondary winding output (before the connection point of SISFREG), before and after compensation.

Performances in Regeneration Mode

To determine the performance during the regeneration mode, a braking deceleration of $2 \mathrm{ms}^{-2}$ was considered. Because there are two filtering and regeneration systems, one for each secondary, the reference current provides a recovery power of 1.2 MW, being half of the rated power. It was supposed that the filtering and regeneration system was connected to the Y secondary, and the line

DC voltage was limited to 1900 V. The obtained results are presented graphically (the phase current and voltage in the power grid – Figure 7, the voltages at the DC line and on the compensating capacitor - Figure 8 and the braking deceleration – Figure 9) and also numerically (Table 1).

It was supposed that, at t= 0.02 s, the deceleration of the train is prescribed (Figure 9). Due to the action of acceleration controller, the recovered current increases rapidly and the prescribed braking acceleration is obtained and maintained almost constant. In the grid, the steady state regime is obtained after 0.06 seconds and the recovered current is practically sinusoidal (Figure 7). Its total harmonic distortion factor is 1.6 %. The good dynamic performances are illustrated by the DC voltages evolution (Figure 8).

Figure 7. *The Voltage (in Black) and the Current (in Red) on the Grid Side during the Recovery Mode*

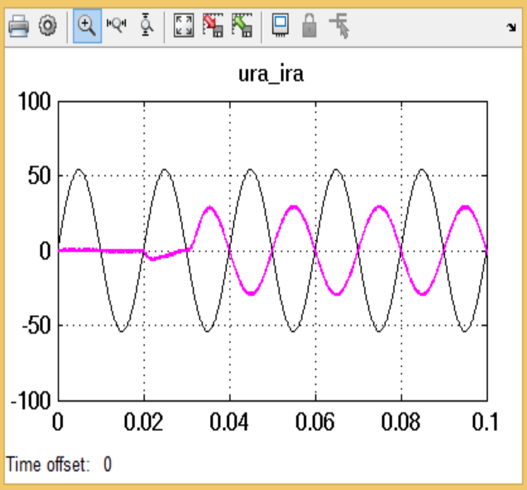


Figure 8. *The DC-line Voltage (in Black) and the Capacitor Voltage (in Red) during the Recovery Mode*

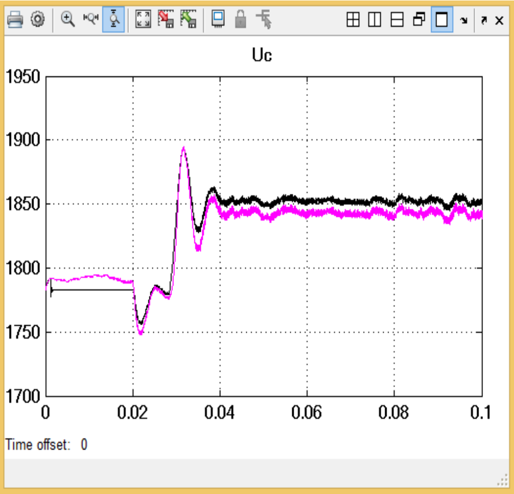
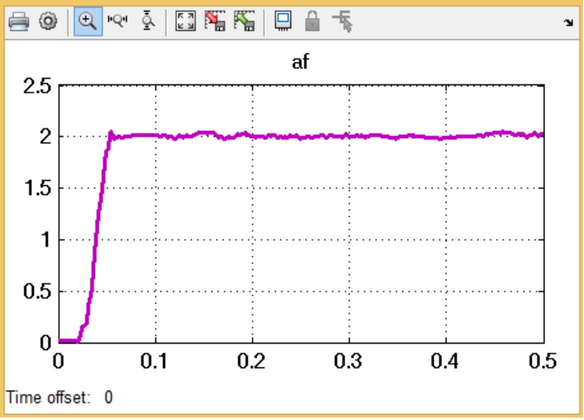


Figure 9. *The Braking Deceleration Evolution during the Recovery Mode*



Thus, the response time is only one period and the DC traction line voltage is kept below the maximum imposed value.

The energetic performances are very good (Table 1). It must be pointed out that both the network and the transformer secondary currents are almost sinusoidal, with a harmonic distortion factor below 1.6%.

Table 1. *The Main Energetic Performances of SISFREG in Regeneration Mode*

S_r[MVA]	P_r[MW]	η_y[%]	η_r[%]	THD_y[%]	THD_r[%]	I_{crec}[A]	P_{cc}[MW]	U_{cc}[V]
1.182	1.182	98.85	96.76	0.98	1.6	677	1.222	1883

Performances in Filtering Mode

In this operation mode, the series diode in the separating circuit is blocked being reverse biased (U_{cF}>U_c), so the separating circuit is idle. In the first stage, the two systems do not work simultaneously, that is one of them is uncontrolled.

The obtained results are presented graphically and also numerically (the performances are shown in Table 2). The quantities which emphasize the quantitative performances with respect to the filtering mode are:

- The total harmonic distortion factor of the current at the rectifier input (THDL) and at the secondary windings output (THDy and THDd) before the connection point of SISFREG;
- The filtering efficiency;
- The total power factor at the rectifier input (PFL) and at the secondary windings output (PFy and PFd) before the connection point of SISFREG.

Without filtering, the grid current has a distortion factor about 12% and its phase is delayed versus voltage (Figure 10). In the both cases, filtering in star or delta secondary, the performances are good and similar (Figure 11, Figure 12 and Table 2). Thus: the current distortion factors before PCC are less over 2%; the filtering efficiency is over 11 and the power factors increase by about 2 % after filtering.

Figure 10. *The Phase Voltage and the Current on the Grid in the Traction*

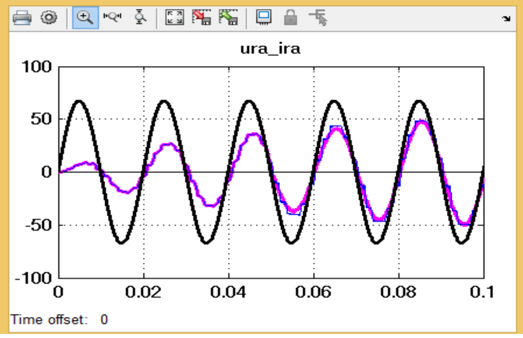


Figure 11. *The Voltage (in Black) and the Currents in the Star Secondary (in Blue – after PCC and in Red – before PCC)*

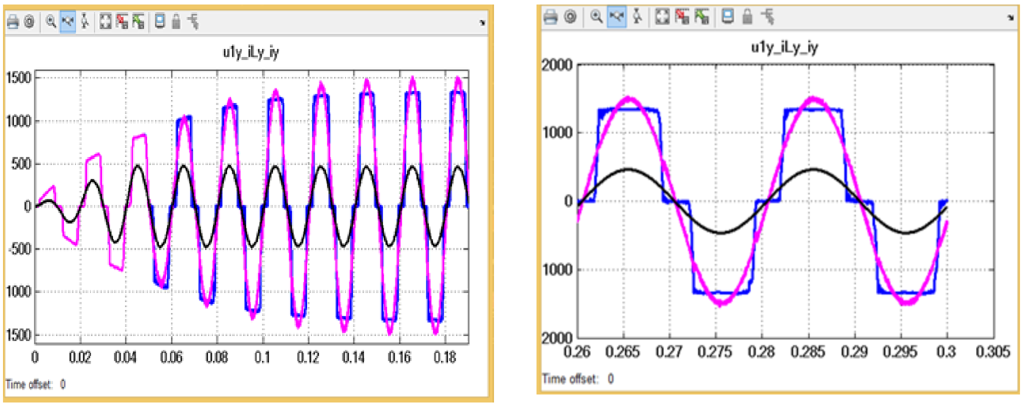
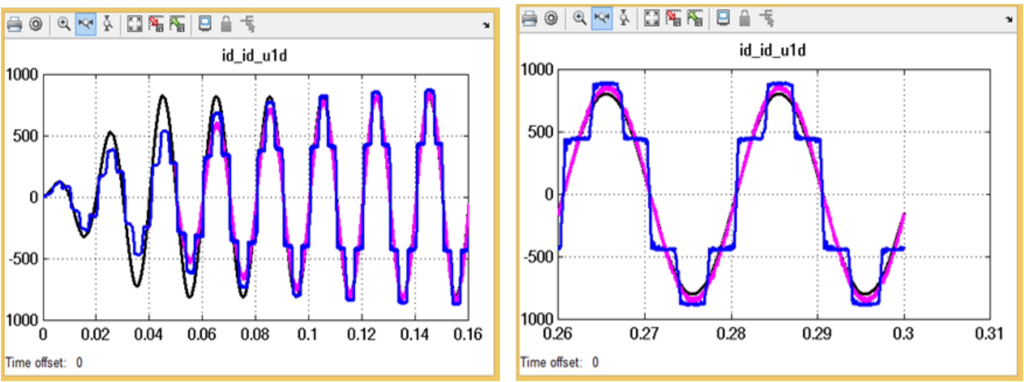


Table 2. *The Main Energetic Performances of SISFREG in Filtering Mode*

Winding	$P_{y/d}$[MW]	$S_{Ly/d}$[MVA]	$S_{y/d}$[MVA]	$THD_{y/d}$[%]	THD_L[%]	PF_y[%]	PF_L[%]	EF
y	1.037	1.213	1.186	2.15	25.17	87.5	85.5	11.69
d	1.023	1.194	1.166	2.3	26.3	87.77	86.67	11.43

Figure 12. *The Voltage (in Black) and the Currents in the Delta Secondary (in Blue – after PCC and in Red – before PCC)*



Conclusions

The Simulink results of the complete model, which took into account the specific features and the structure of a railway traction substation, but also the influence of the vehicle-traction line assembly, are in full compliance with the physical phenomenon and validate the correctness of the developed model. Analyzing the performances and the waveforms, the following conclusions are drawn:

1. The recovery capability of SISFREG by using the traction transformer is confirmed;

2. The generated current is practically sinusoidal and in phase opposition with the corresponding voltage;

3. The harmonic distortion is enclosed in the present standards (THDI is under 2% in regeneration mode and slightly over 2% in filtering mode);

4. The energetic performances in both regeneration and filtering modes are notable (the recovery efficiency over 96% and the filtering efficiency over 11);

5. If the both systems operate simultaneously, the inverter switching frequency (about 10 kHz) distorts the secondary winding voltages and this distortion is reflected in the primary winding.

The main contributions of the paper refer to:

- the idea to use a parallel active filtering system for energy breaking recovery;
- the structure of the separating circuit;
- the Simulink model of the vehicle-catenary line assembly in braking energy recovery mode, that includes a braking acceleration control loop having at its input the reference acceleration;
- the Simulink model of the entire filtering and regeneration system;
- the determination of the system performances;
- the demonstration that the proposed system is a viable technical solution for breaking energy recovery in the DC traction substations.

The future research will be orientated to the indirect control in filtering mode by using the grid current. This direction should be a solution for properly operation of the both systems.

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