Performance of an Active DC-Traction Substation with 12-Pulse Parallel Rectifier and Indirect Current Control

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Abstract **– The attention in this paper is directed to the transformation of an existing DC-traction substations equipped with 12-pulse parallel uncontrolled rectifier into an active substation. In this manner, the traction substation gains the capability of redirecting the braking energy to the power supply and the power quality indicators during the traction regime are greatly improved. The practical solution lies in adding a shunt active power filter, accompanied by appropriate circuits of connection on both the DC and AC sides, between the DC-traction line and the primary of the traction transformer via a dedicated recovery transformer. To control the current provided by the shunt active filter in both traction/active filtering and regeneration regimes, the indirect method of handling the supply current has been adopted. The reference supply current during the operation in traction regime is calculated based on instantaneous powers provided by the concepts of the instantaneous reactive power theory. Two compensation strategies have been implemented for this operation mode, i.e. the total compensation of the current harmonics and reactive power and the partial compensation (only the current harmonics). In regeneration mode, the traction rectifier is blocked and the reference supply current is given by the voltage controller. Based on the conceived Matlab/Simulink models of the whole system, the proper operation is confirmed and the good performance of the system during both traction/filtering and regeneration regimes is shown. Indeed, the total harmonic distortion of the supply current is always below the limits and recommendations of the power quality standards and the operation in regeneration mode is allowed.**

Keywords: *DC-traction, 12-pulse uncontrolled rectifier, braking energy recovery, active power filter, instantaneous reactive power theory, active substation.*

I. INTRODUCTION

Saving the traction energy in the urban and suburban DC-traction systems is a present concern of the specialists in the field of traction systems. Both the more efficient management of the energy consumption in the existing structures ([1], [2]) and the addition of specific devices to allow for reusing the kinetic energy during braking or to improve the power quality ([3]-[16]) have been considered in recent years.

Besides the modern solution of storage systems for the braking energy [3]-[5], the improvement of the traction substation structure in order to recycle the excessive regenerative braking energy by redirecting it back into the AC supply is a proposed solution [6], [7]. In [6], a specific converter, named HESOP, which was proposed by the French multinational company Alstom for a reversible substation, is presented. It consists of a controlled rectifier in antiparallel with an IGBT inverter. The Ingeber solution presented in [7] was proposed by the Ingeteam company and involves the addition of a boost DC-DC chopper in series with an inverter between the DC-line and the traction transformer.

The improvement of the power quality at the input of the DC-traction systems in traction regime is another actual concern. There are many contributions related to the harmonic cancelation, unbalance compensation and reactive power compensation in DC-traction systems by means of passive, active and hybrid filters [8]-[13].

The current advances in the field of power electronics and control techniques have allowed to conceive powerful static converters with specific control capabilities, so that both the braking energy recovery and the active power filtering to be carried out. Thus, the name “active substation” or “active regeneration unit” is associated with such a system [14]-[16].

This paper is aimed at analyzing the performance of an active DC-traction substation obtained by adding the regeneration and active filtering capabilities to an existing DC-traction substation with 12-pulse parallel diode rectifier, which is a common configuration existing DC railway traction systems [4], [15], [17], [18].

The rest of the paper is organized as follows. Section II introduces the configuration of the proposed active DC-traction substation, by emphasizing the structure and necessity of the components added in the power circuit, as well as the implementation of the adopted indirect current control. Section III presents the algorithm of reference current generation based on the application of the instantaneous reactive power concepts for the indirect control of the compensating current. In Section IV, the Matlab/Simulink model of the whole active DC-traction substation is presented. The next section presents the simulation results in both regeneration and active filtering regimes and illustrates the good performance of the proposed system. The main conclusions are outlined at the end of the paper.

II. STRUCTURE OF THE ACTIVE DC-TRACTION SUBSTATION

The block diagram in Fig.1 shows the addition of a parallel circuit to the existing traction substation in order to ensure the operation in regeneration and active filtering modes. As shown, a three-phase shunt active power filter

(SAPF) based on voltage source inverter (VSI) configuration is connected to the AC-power side by means of an interface passive filter and to DC-side by means of a separating circuit.

Starting from the fact that, in the case of the traction substation equipped with a 12-pulse parallel rectifier, the rated DC-voltage is below the magnitude of the line-to-line voltage in the traction transformer secondary [16], [19], the quality of the current injected by SAPF into the AC-line would not be acceptable if SAPF would be connected to traction transformer secondary [20]. Therefore, by using a dedicated recovery transformer, an appropriate AC voltage value is provided in its secondary and the point of common connection (PCC) to the power supply is placed in the traction transformer primary.

Getting a good dynamics of the current injected in PCC along with the switching harmonics cancellation are ensured by the adopted interface filter of second order [21], [22].

As regards the separating circuit on the DC-side, it is required so that the correct and natural transition from the traction/filtering regime to the regeneration regime and vice versa to be conducted [16], [23]. A power diode in series with an inductance has been adopted for this purpose (Fig. 2).

The control of the current i_F injected from the recovery transformer into PCC is performed indirectly, by means of the supply current i_s, that is the current drawn from the power line by the whole system.

As it can be seen in Fig. 1, there is a block for reference current calculation, whose inputs are the measured phase-voltages and the line currents in the traction transformer primary. The output quantity (i_s^{ref}) is the prescribed supply current during the active filtering regime. The instantaneous reactive power theory has been chosen as the mathematical foundation for the reference current calculation [24], [25]. It must be noted that, when the system operates in regeneration mode, the traction rectifier is blocked and $i_s^{ref} = 0$.

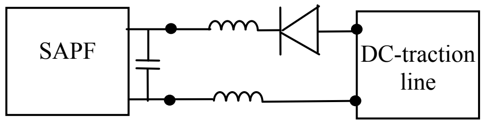

Fig. 2. Structure of the separating circuit.

The second component (i_{su}^{ref}) of the total prescribed supply current (i_{st}^{ref}) is provided by the voltage control block, based on a proportional-integral (PI) controller. During the operation in active filtering mode, it is the active current needed to cover the power losses and maintain the DC-capacitor voltage at its prescribed value. In regeneration mode, since the DC-capacitor voltages increases and the set capacitor voltage remains constant, the voltage control loop operates with negative error, the voltage controller is saturated, and i_{su}^{ref} is the reference regenerating current.

A hysteresis-band based controller receives the whole prescribed current together with the measured supply current and provides the IGBTs' gating signals by ensuring the accurate tracking of the set current.

III. Reference Current Generation

By adopting the concepts of the instantaneous reactive power theory [24] to calculate the reference current during the traction regime, either the total compensation of both current harmonic distortion and reactive power or only the partial compensation of harmonic distortion can be achieved [26], [27].

Thus, after expressing the so-called instantaneous active and reactive powers (p and q) and their DC and AC components (P, $p_{\sim}$, Q, $q_{\sim}$) in the primary of traction transformer before compensation, the decomposition of the distorted load current in accordance with both the adopted compensation strategy and method of current control allows making evident the reference current.

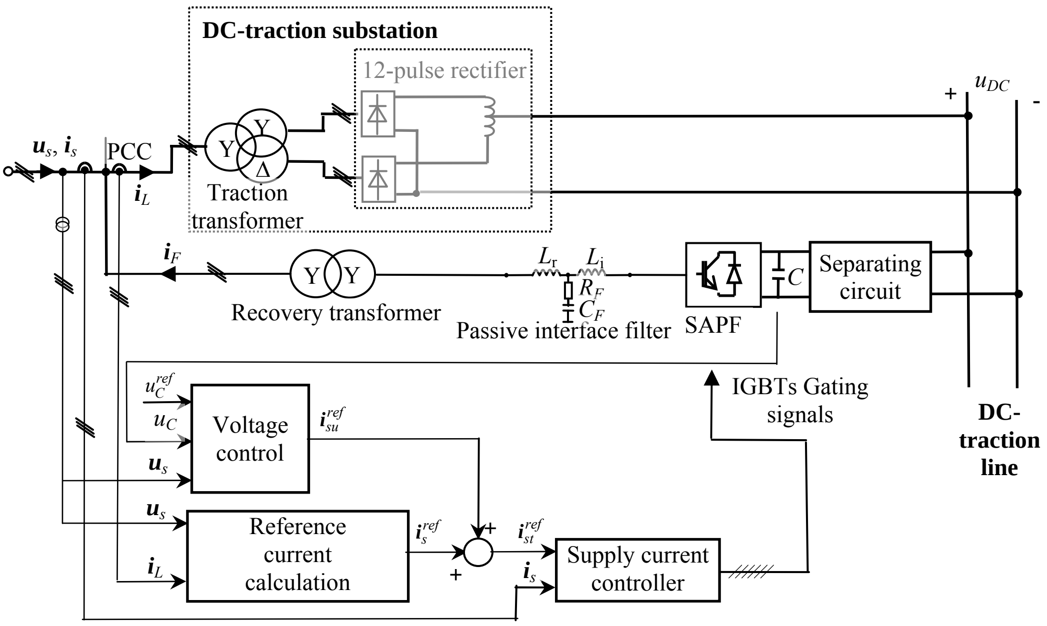

Fig. 1. Block diagram of the active DC-traction substation.

According to instantaneous reactive power theory, the components of instantaneous powers make use of the components of supply voltages ($u_{s\alpha}$, $u_{s\beta}$) and load currents ($i_{L\alpha}$, $i_{L\beta}$) vectors in the orthogonal stationary reference frame (α, β) [24].

They are obtained after the Clarke transformation from (a, b, c) coordinate frame, i.e.:

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & 1/\sqrt{3} & -1/\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}; \tag{1}$$

$$\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & 1/\sqrt{3} & -1/\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix}. \tag{2}$$

Thus, the instantaneous powers components can be expressed as:

$$p = \frac{3}{2}\left(u_{s\alpha} i_{L\alpha} + u_{s\beta} i_{L\beta}\right) = \frac{3}{2}\mathrm{Re}\left\{\underline{u}_s \cdot \underline{i}_L^*\right\}; \tag{3}$$

$$q = \frac{3}{2}\left(u_{s\beta} i_{L\alpha} - u_{s\alpha} i_{L\beta}\right) = \frac{3}{2}\mathrm{Im}\left\{\underline{u}_s \cdot \underline{i}_L^*\right\}; \tag{4}$$

$$P = \frac{1}{T}\int_{t-T}^{t} p(\tau) d\tau ; \tag{5}$$

$$Q = \frac{1}{T}\int_{t-T}^{t} q(\tau) d\tau ; \tag{6}$$

$$p_{\sim} = p - P ; \qquad q_{\sim} = q - Q . \tag{7}$$

In expressions (3) and (4), $\underline{i}_L^*$ is the conjugate of the load current vector,

$$\underline{i}_L^* = i_{L\alpha} - j \cdot i_{L\beta} . \tag{8}$$

In expressions (5) and (6), T is the observation period corresponding to the fundamental frequency.

Since the control of the supply current has been chosen as the control strategy, the above components of the powers are used to express the conjugate of the instantaneous apparent power vector ($\underline{s}^{ref*}$), which intervenes in the expression of the reference supply current [22],

$$\underline{i}_s^{ref} = \frac{2}{3} \cdot \frac{\underline{u}_s}{\left|\underline{u}_s\right|^2} \cdot \underline{s}^{ref*} , \tag{9}$$

where

$$\left|\underline{u}_s\right|^2 = u_{s\alpha}^2 + u_{s\beta}^2 , \tag{10}$$

and denotes the square of the supply voltage vector modulus.

In the case of total compensation strategy, the desired supply power after compensation is the active power P, which means that:

$$\underline{s}^{ref*} = P . \tag{11}$$

Consequently, expression (9) becomes:

$$\underline{i}_s^{ref} = \frac{2}{3} \cdot \frac{P}{\left|\underline{u}_s\right|^2} \cdot \underline{u}_s . \tag{12}$$

It must be noted that the factor $2P/(3\left|\underline{u}_s\right|^2)$ multiplying the supply voltages vector in (12) is constant and has the significance of an equivalent conductance only in the case of sinusoidal waveforms of the supply voltages. For the operation under nonsinusoidal voltage conditions, the following modified form of (12) can be used in order to express the reference current as the active component of the load current [22]:

$$\underline{i}_s^{ref} = \frac{2}{3} \cdot \frac{P}{\frac{1}{T}\int_{t-T}^{t} \left|\underline{u}_s\right|^2 d\tau} \cdot \underline{u}_s . \tag{13}$$

When the partial compensation is desired, only the current harmonics have to be cancelled and the reference instantaneous apparent power in (9) is:

$$\underline{s}^{ref} = P + jQ . \tag{14}$$

Thus, expression (9) becomes:

$$\underline{i}_s^{ref} = \frac{2}{3} \cdot \frac{\underline{u}_s}{\left|\underline{u}_s\right|^2} \cdot \left(P - jQ\right). \tag{15}$$

Based on the components $i_{s\alpha}^{ref}$ and $i_{s\beta}^{ref}$ of $\underline{i}_s^{ref}$, the phase components of the reference supply currents ($i_{sa}^{ref}, i_{sb}^{ref}, i_{sc}^{ref}$) are given after the reverse transformation from (α, β) reference frame to (a, b, c) reference frame, respectively:

$$\begin{bmatrix} i_{sa}^{ref} \\ i_{sb}^{ref} \\ i_{sc}^{ref} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{s\alpha}^{ref} \\ i_{s\beta}^{ref} \end{bmatrix}. \tag{16}$$

The block diagrams in Fig. 3 and Fig. 4 show the Matlab/Simulink implementation of the above algorithms for total compensation and partial compensation respectively.

Several blocks of type “Real-Imag to Complex” have been used to construct the vectors of the load currents, supply voltages and instantaneous apparent power. Besides, the blocks of type “Complex to Real-Imag” have been used to separate the real and imaginary parts of the instantaneous apparent power vector and of the calculated reference current.

Third-order Butterworth low pass filters with the passband edge frequency of 100π rad/s have been used to calculate the average values given in (5) and (6).

IV. Model of the Active DC-Traction Substation

The Matlab/Simulink model of the active DC-traction substation (Fig. 5) contains the models designed for each component shown in the general block diagram in Fig. 1.

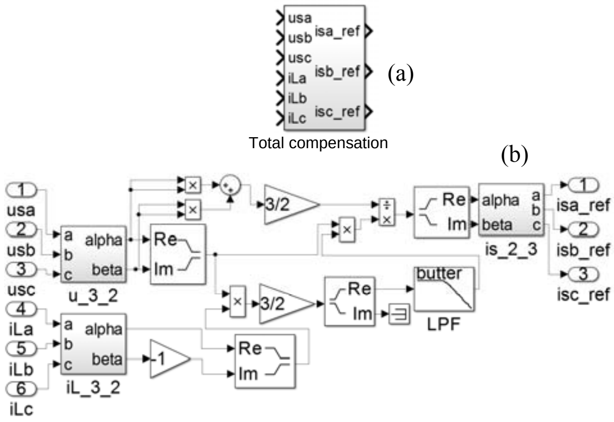

Fig. 3. Matlab/Simulink implementation of the reference current generation algorithm, for total compensation: (a) – mask block; (b) - structure.

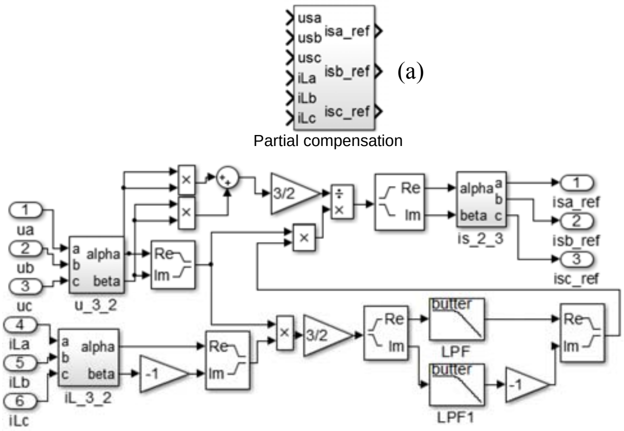

Fig. 4. Matlab/Simulink implementation of the reference current generation algorithm, for partial compensation: (a) – mask block; (b) - structure.

The block of 12-pulse parallel rectifier substation includes the models of the sinusoidal power supply (33 kV), the Y/y/d traction transformer (33 kV/ 1.2 kV/ 1.2 kV; 3.2 MVA), the two three-phase diode bridge rectifiers and the reverse magnetically coupled inductances for the parallel connection of the rectifiers.

The DC-traction line has been modeled taking into account that, in traction regime, it is an active load characterized by a back electromotive force corresponding to the operation speed, an equivalent resistance and an equivalent inductance.

During the regeneration, the maximal DC-line voltage is maintained and a constant acceleration is imposed, so that the DC-line current is constant.

The rated voltage of the DC traction line is 1500 V.

For the three-phase three wire system taken into account, the control algorithm described in Section I has been implemented in a specific block (“SAPF control”) based on only two line-to-line supply voltages and two load line currents.

The prescribed and measured values of the DC-capacitor voltage are also needed as inputs of the control block.

The secondary of the recovery transformer (Y/y; 2.2 MVA; 820 V/ 33 kV) is coupled to the traction transformer primary through a passive filter having L_r=0.2 mH; L_i=0.02 μH; R_F=1 mΩ; C_F=50nF.

In the coupling circuit on the DC-side, there is the compensation capacitor of 100 mF and the separating circuit including a diode in series with an inductance of 40 μH.

The parameters of the PI voltage controller are K_p=30.6 and T_i=3.94·10-4 s.

The hysteresis band imposed for the current controller is 0.5 A.

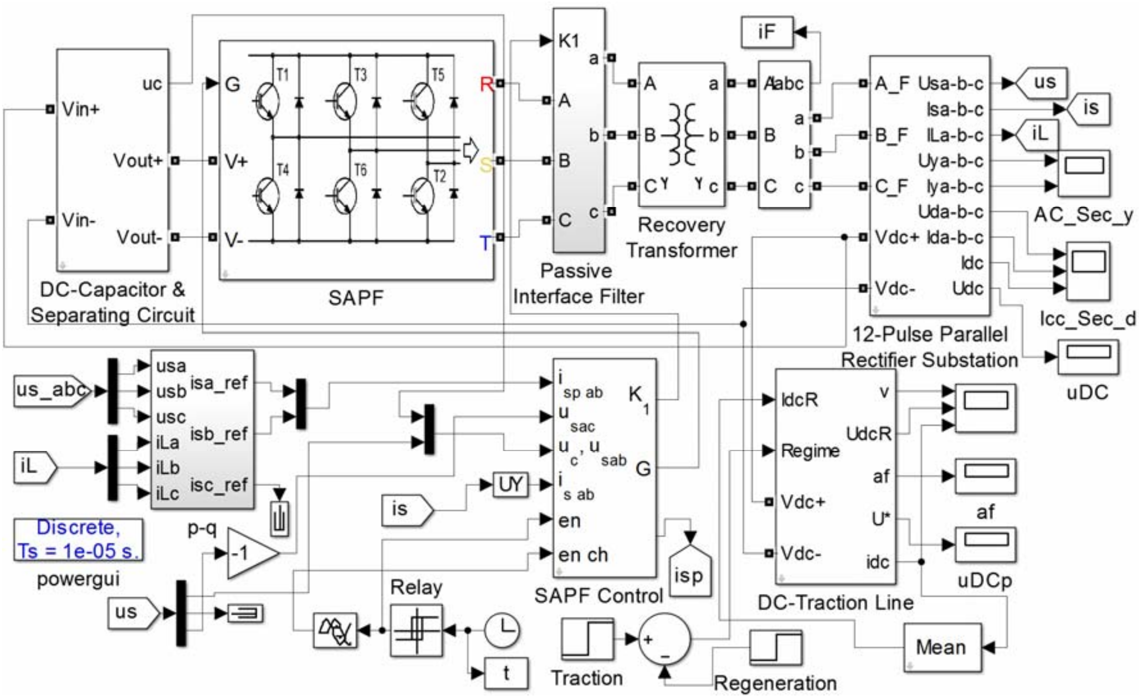

Fig. 5. Matlab/Simulink model of the active DC-traction substation with 12-pulse parallel uncontrolled rectifier.

V. Performance in Regenenation and Traction Regimes

The proper operation of the proposed system for compensation/regeneration has been verified by simulating the traction regime of the DC-traction substation which is accompanied by the active filtering of the harmonic currents and reactive power compensation, followed by the regime of braking energy regeneration. The assessment of the system performance in each regime has been performed too.

As shown in Fig. 6, when the system is put into operation, the natural charging of the DC-capacitor through the SAPF's diodes is followed by a ramp prescription to the set value of 1780 V. In less than 0.15 seconds, the prescribed voltage is reached, with a very low overshoot of about 0.62%. The traction rectifier provides the DC-line average voltage U_{DC}= 1500V.

The line currents in the primary of traction transformer are distorted (Fig. 7), having a distortion degree of about 12%, expressed by the value of the total harmonic distortion factor (THD_{iL}),

$$THD_{iL} = \sqrt{\left(\frac{I_L}{I_{L1}}\right)^2 - 1} \, . \qquad (17)$$

where I_L and I_{L1} are the global rms value and the fundamental rms value of the load current, respectively.

The waveforms of the line currents i_{La}, i_{Lb}, and i_{Lc}, associated with the phase voltages (Fig. 7) illustrate the existence of a reactive power, leading to a global power factor of 0.988.

In order to illustrate the capability of the control system to compensate both the harmonic distortion and reactive power, the active components of the load currents, which are sinusoidal currents in phase with the supply voltages, are provided by the block of reference current calculation. Thus, in the presence of SAPF, a proper current is injected on each phase in PCC, so that the supply current becomes almost sinusoidal (THD_{is} = 2.52%), with a remaining low distortion due to the IGBTs' switching, even in the case of well-designed interface filter (Fig. 8). As shown, the fundamental components of the compensated currents are in phase with the supply voltages (Fig. 9), leading to a global power factor of 0.999.

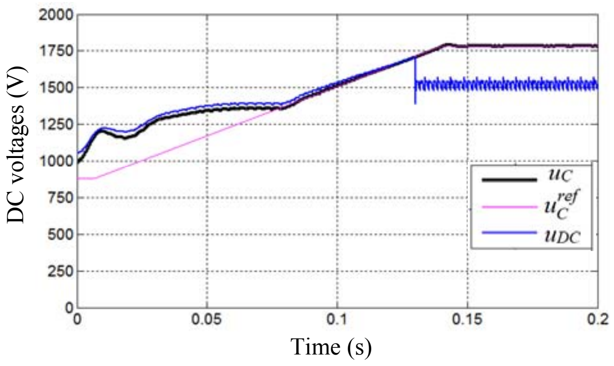

Fig. 6. DC-voltages during the startup process and traction/filtering regime.

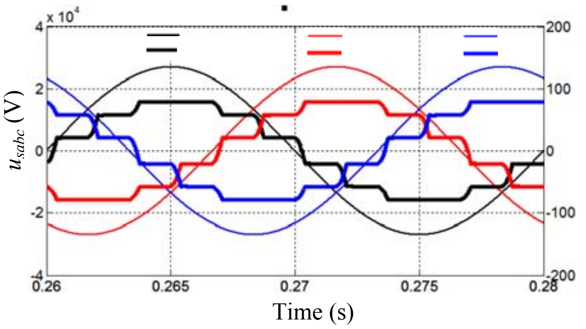

Fig. 7. Waveforms of voltages and currents in the primary of traction transformer during the traction/filtering regime.

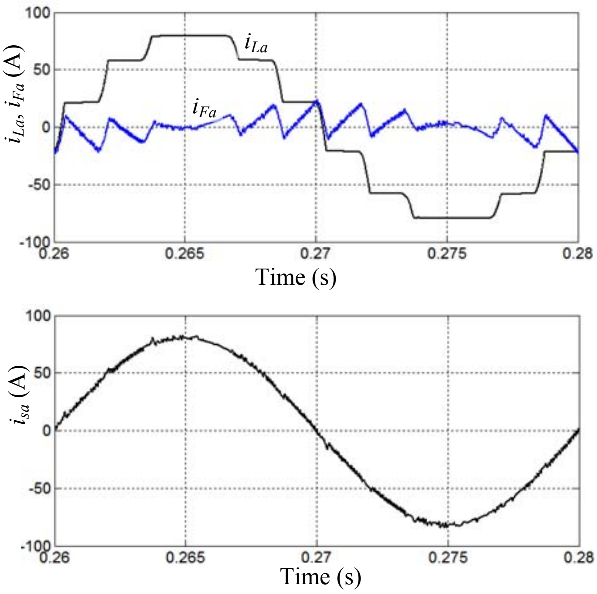

Fig. 8. Waveforms of currents in PCC on phase a, during the traction/filtering regime.

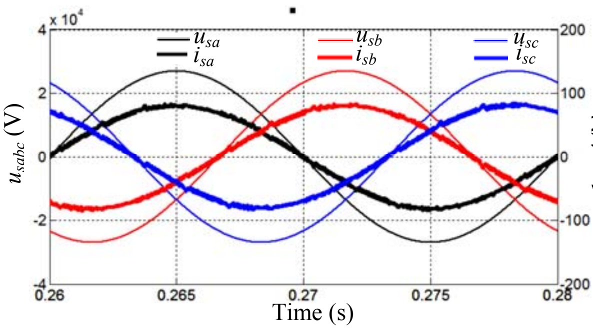

Fig. 9. Waveforms of voltages and supply currents during the traction/filtering regime.

At t=0.3 s, the traction motors pass to braking regime and, consequently, the necessity of transition in regeneration mode occurs. The DC-line voltage increases and, due to the proper operation of the control system, after reaching the maximum value of about 1845 V, it remains at the limited value of 1800 V during regeneration (Fig. 10). Compared to the prescribed value of 1780V, the voltage across the DC-capacitor voltage has an overshoot of 2.8%.

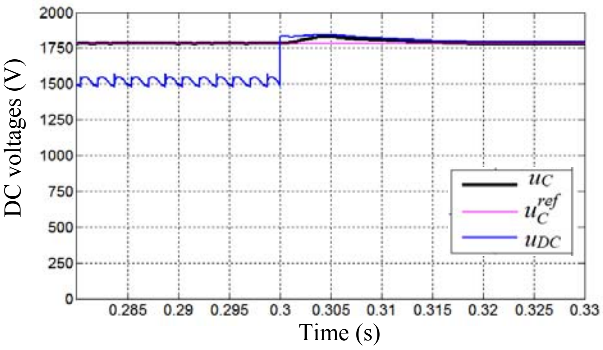

Fig. 10. DC-voltages when passing from the traction/filtering regime to the regeneration regime.

In less than 20 ms, the current in the primary of the traction transformer becomes zero (Fig. 11) and the current injected by SAPF becomes the regenerated current, which is almost sinusoidal (THD_{is} of about 2.5%) and in phase opposition with the corresponding phase voltage (Fig. 12).

During the operation in regeneration mode, a high value of the recovery efficiency, from the DC-line to the power supply (about 93%), is obtained.

At t = 0.5 s, when the traction motors passes again to traction regime, the DC-line voltage returns to the average value of 1500V after an overshoot of about 20% (Fig. 13). The DC-capacitor voltage has an oscillation of low amplitude and than it reaches again the set value of 1780 V.

SAPF starts operating in active filtering mode and, in less than one period of 20 ms, the suppy current passes from an active current injected in the power supply to an active curent drawn from the power supply (Fig. 14).

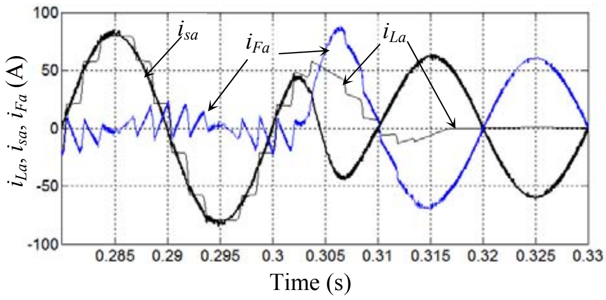

Fig. 11. Waveforms of currents in PCC on phase a, when passing from the traction/filtering regime to the regeneration regime.

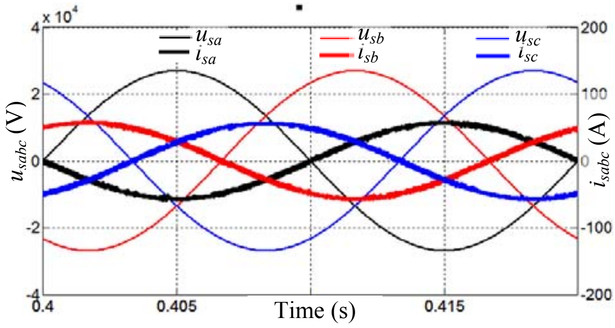

Fig. 12. Waveforms of voltages and supply currents during the regeneration regime.

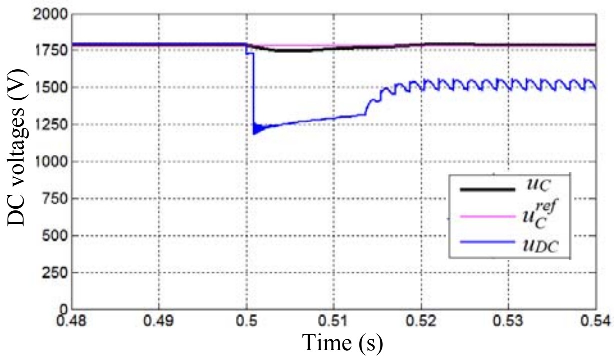

Fig. 13. DC-voltages when passing from the regeneration regime to the traction/filtering regime.

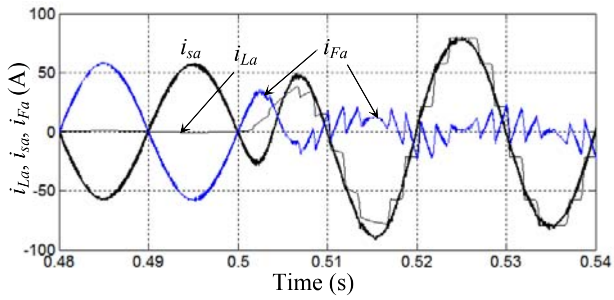

Fig. 14. Waveforms of currents in PCC on phase a, when passing from the regeneration regime to the traction/filtering regime.

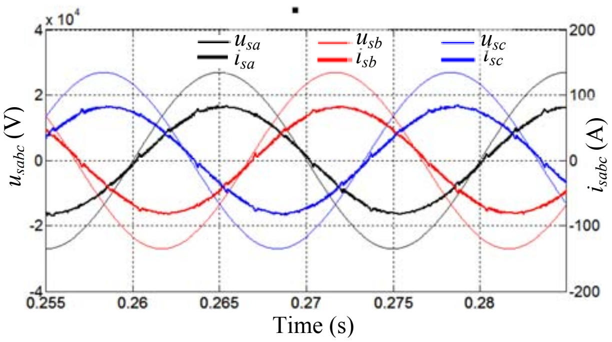

Fig. 15. Waveforms of voltages and supply currents during the traction/filtering regime when the partial compensation is imposed.

The second compensation strategy taken into consideration in simulation of the active filtering/traction regime is the partial compensation, even if the existing reactive power at the input of the uncontrolled rectifier is not significant. This time, the reference supply current is calculated in accordance with (15) and the structure of the associated block is shown in Fig. 4. As shown in Fig. 15, the fundamental components of the compensated supply currents lag behind the supply voltages, leading to a global factor of 0.996, compared to the values of 0.988 without compensation and 0.999 in the case of total compensation.

VI. CONCLUSIONS

The analysis performed in this paper shows that an existing DC-traction substation with 12-pulse parallel diode rectifier can be converted into an active substation being able to ensure the recovery of the braking energy and to absorb an almost sinusoidal current from the power supply during the traction regime.

For this purpose, a parallel system containing a SAPF based on VSI configuration, together with the needed components for connection and a specific control strategy, is proposed to be added.

In substantiating the indirect control of the current injected by SAPF into the power line by means of the supply current, a DC-voltage loop is proposed to feed the inner current loop. The calculation of the reference supply current to be tracked during the traction regime of the substation makes use of the instantaneous reactive power theory. In regeneration mode, the reference current is provided by the DC-voltage controller.

The proper operation of the whole active DC-traction substation has been clearly confirmed by Matlab/Simulink extensive simulations. It is proven that the proposed system is able to pass without problems from one regime to another. Moreover, the control system ensures almost sinusoidal supply currents (*THD* of about 2.5%) in the both operation regimes.

It is shown that two compensation goals for the operation in traction/active filtering mode, i.e. total and partial compensation, can be implemented with good results by the adopted method of reference current generation.

As further research, the implementation of the control algorithm on an experimental platform based on dSPACE control board is intended to be made.

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