Athens Institute for Education and Research
ATINER

ATINER's Conference Paper Series
TRA2015-1552

Synchronous Reference Frame Method Applied in the Indirect Current Control for Active DC Traction Substation

Mihaela Popescu
Professor
University of Craiova
Romania

Alexandra Preda
Assistant
University of Craiova
Romania

Vlad Suru
Lecturer
University of Craiova
Romania

An Introduction to ATINER's Conference Paper Series

ATINER started to publish this conference papers series in 2012. It includes only the papers submitted for publication after they were presented at one of the conferences organized by our Institute every year. This paper has been peer reviewed by at least two academic members of ATINER.

Dr. Gregory T. Papanikos
President
Athens Institute for Education and Research

This paper should be cited as follows:

Popescu, M., Preda, A. and Suru, V. (2015). **"Synchronous Reference Frame Method Applied in the Indirect Current Control for Active DC Traction Substation",** Athens: ATINER'S Conference Paper Series, No: **TRA2015-1552.**

Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
Tel: + 30 210 3634210 Fax: + 30 210 3634209 Email: info@atiner.gr URL: www.atiner.gr
URL Conference Papers Series: www.atiner.gr/papers.htm

ISSN: 2241-2891
09/08/2015

Synchronous Reference Frame Method Applied in the Indirect Current Control for Active DC Traction Substation

Mihaela Popescu
Professor
University of Craiova
Romania

Alexandra Preda
Assistant
University of Craiova
Romania

Vlad Suru
Lecturer
University of Craiova
Romania

Abstract

This paper is focused on the increasing the energy efficiency of a DC-traction substation with 12-pulse parallel diode rectifier, by transforming it into an active substation, being able to ensure both power quality improvement and braking energy recovery. A system for active filtering and regeneration, named SISFREG, is proposed to be connected between the catenary-line and the primary of the traction transformer, via a dedicated transformer. The main component of SISFREG is a shunt active power filter based on voltage source inverter structure, whose control guarantees the keeping of the prescribed voltage on the DC-side and the proper current at the inverter output by the indirect control of the supply current. The Synchronous Reference Frame method is used to generate the sinusoidal reference supply current in phase with the fundamental of the supply voltage, so that the total compensation strategy is implemented. Based on the Matlab/Simulink model of the whole system, the proper operation is confirmed and the good performance of the system during both filtering and regeneration modes is proven.

Keywords: DC traction, energy recovery, active filtering, indirect current control, synchronous reference frame.

Acknowledgments: 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).

Introduction

A current concern of the specialists in the field of DC-traction systems is finding performant solutions for increasing the energy efficiency.

One of the research directions is directed towards improving the power quality at the input of the traction transformer during the operating in traction regime through passive and active compensators [1]-[3].

On the other hand, based on the capability of DC-traction motors to operate in regeneration regime, the reuse of the normally wasted braking energy is another preoccupation. In addition to the braking energy storage in on-board or mobile batteries or supercapacitors, the solution of equipping the existent substations with bidirectional static converters became attractive with new technological achievements in the field of power semiconductor devices and their control. For instance, an outcome of RailEnergy cooperative research program was the HESOP energy recovery system, which is a fully integrated reversible DC substation for a 750 Vdc application containing a thyristor rectifier bridge associated with an IGBT converter [4]. By Sitras Thyristor Controlled Inverter (TCI) to be connected in parallel with the traction uncontrolled rectifier, the global powerhouse Siemens provides another solution to acquire the capability to return the braking energy to the system [5]. In the Ingeber solution adopted by the company Ingeteam Traction, a series connection between a boost DC-DC converter and an inverter is coupled in the existing traction transformer secondary [6].

In a so-called “active substation”, new functions such as harmonic filtering, reactive power compensation and voltage regulation may be carried out in addition to the recovery of braking energy [7].

In order to perform the active filtering function, the control of the instantaneous active and reactive powers is usually adopted [8]-[10]. In [11], the generation of the reference current is based on the selective harmonic extraction method applied to the load current, by using three synchronously rotating reference frames.

The active DC traction substation, which is the subject of this paper, is obtained starting from a common traction substation with 12-pulse parallel uncontrolled rectifier by adding a shunt active power filter (SAPF) based on structure of voltage source inverter (VSI) between the DC-line and power supply via a dedicated transformer. At the DC and AC sides of SAPF, passive circuits for separation and coupling are provided.

The paper is organized as follows. *Structure of the System for Regeneration and Active Filtering* Section presents the structure of whole DC traction system allowing the operation in filtering and regeneration modes. *Reference Current Calculation through the Synchronous Reference Frame Method* Section describes the indirect current control implementation through the method of synchronous reference frame. Then, after introducing the Simulink model of the system, the next section presents the model-based performance in both filtering and regeneration regimes. The paper ends with the main conclusions.

Structure of the System for Regeneration and Active Filtering

Based on the common configuration of a DC-traction substation with 12-pulse parallel diode rectifier, a system allowing the braking energy recovery and active filtering function, named SISFREG, is proposed to be added, as shown in Figure 1.

The main component is the VSI-based SAPF, whose coupling to the DC-traction line must be made through a separating circuit acting as an energy buffer and ensuring the decoupling during the operating in filtering mode. A series connection of a diode and inductance is the adopted structure of the separating circuit.

On the AC side of SAPF, a passive coupling filter of second order (LLC) handles the current dynamics and prevents the high order switching harmonics from propagating into the power supply [12].

Taking into account that the rated DC voltage provided by the 12-pulse parallel diode rectifier is below the magnitude of the line-to-line voltage in the transformer secondary [13], [14], the direct connection to the secondary of the existing traction transformer is not a viable solution. Indeed, the quality of the current injected into the AC-line depends on the difference between the DC-side voltage and the magnitude of the supply voltage [15]. Thus, a dedicated transformer is the adopted solution of coupling to the power supply (Figure 1).

As regards the control strategy, the indirect control of the current at the SAPF output through the regulation of the supply current is taken into consideration.

The prescribed supply current ($\boldsymbol{i}_s^{ref}$) is generated as an active current based on the sensed supply voltage and load current ($\boldsymbol{i}_L$), which is the current in the traction transformer primary. By using the Synchronous Reference Frame (SRF) method to calculate $\boldsymbol{i}_s^{ref}$, sinusoidal waveform of the supply currents are prescribed, so that the perfect harmonic cancelation (PHC) strategy is implemented.

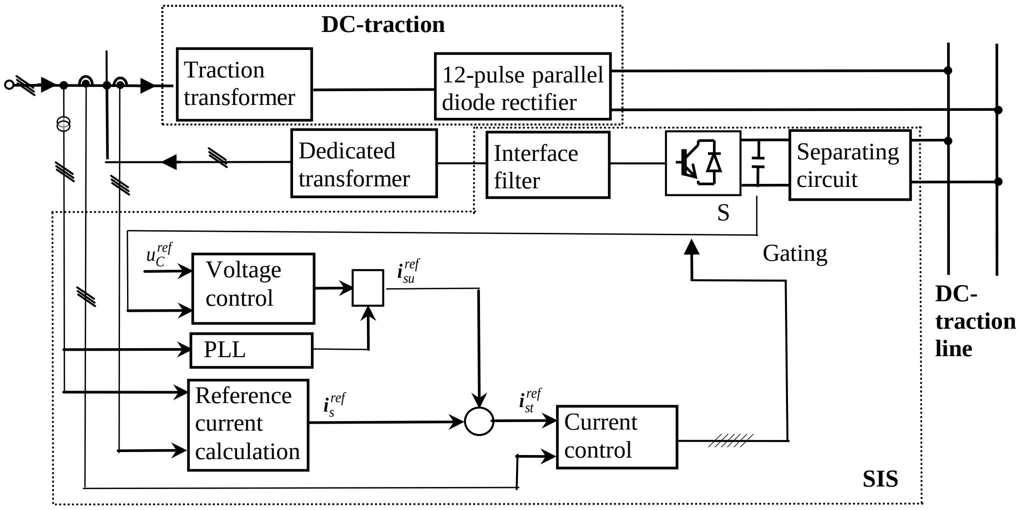
As it is shown in Fig. 1, an additional component of the prescribed current ($\boldsymbol{i}_{su}^{ref}$) is needed to cover the power losses and keep the set value of the voltage on the DC capacitor. The magnitude of this active current is given by the voltage controller of proportional-integral (PI) type and its sinusoidal shape is provided by means of a phase-locked loop (PLL) circuit [16].

Thus, the total reference current to be accurately tracked by the actual supply current is:

$$\boldsymbol{i}_{st}^{ref} = \boldsymbol{i}_s^{ref} + \boldsymbol{i}_{su}^{ref} \, . \qquad (1)$$

A simple hysteresis-band controller allowing a quick current controllability has been chosen for this purpose.

Figure 1. *Block Diagram of the Proposed Active DC Traction Substation*
been chosen for this purpose.



Reference Current Calculation through the Synchronous Reference Frame Method

The flexibility of the synchronous reference frame (SRF) theory in separating the harmonic components of a distorted signal made this method to be widely used in the control of SAPF [17]-[20]. The principle is based on the fact that the harmonics frequency changes in a rotating reference frame, so that the fundamental and harmonic components can be isolated with low and high pass filters.

The transformation of the load current from the phase coordinate system (a, b, c) to the rotating orthogonal reference frame (d, q) having the d-axis aligned with the voltage space phasor is performed in two stages.

First, the Clarke transform modifies the three-phase system to the stationary two-phase orthogonal frame (α, β),

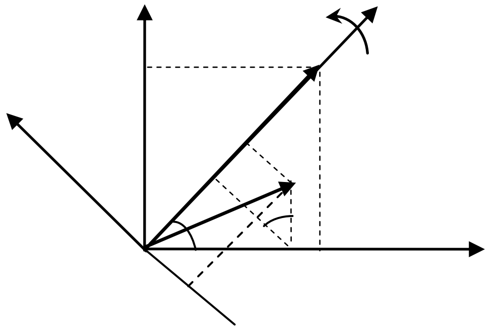
$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & 1/\sqrt{3} & -1/\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}. \qquad (2)$$

Then, the forward Park transformation allows passing the current components from the stationary (α, β) frame to the synchronous (d, q) frame,

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix}, \qquad (3)$$

where θ is the position angle of the rotating axis d (the voltage phasor angle) (Figure 2).

Figure 2. *Voltage and Current Phasors in the Stationary (α, β) Frame and the Synchronous (d, q) Frame*



Based on Figure 2, the trigonometric functions in (3) can be expressed as

$$\sin(\theta) = u_{s\beta} / |\underline{u}_s|, \quad \cos(\theta) = u_{s\alpha} / |\underline{u}_s|, \tag{4}$$

where:

$$\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & 1/\sqrt{3} & -1/\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix}, \tag{5}$$

$$|\underline{u}_s| = \sqrt{u_{s\alpha}^2 + u_{s\beta}^2} . \tag{6}$$

In this manner, a synchronization circuit with the supply voltage is not needed [18], [20].

In SRF, the DC component of i_{Ld}, which is I_{Ld} and can be obtained through a low pass filter, is associated to the active component of fundamental load current.

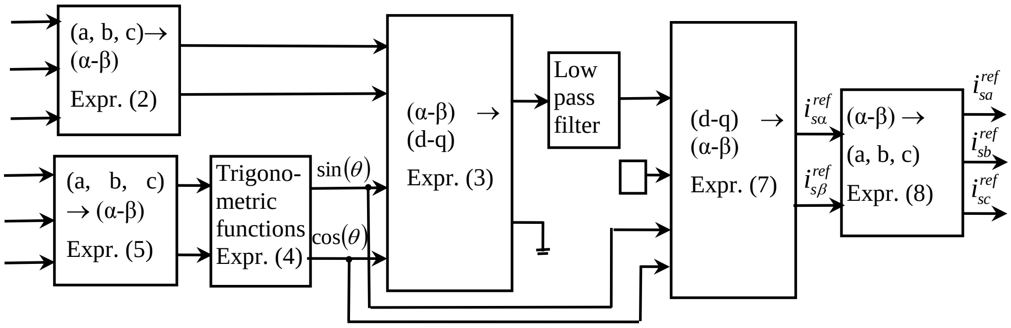
In order to compensate the reactive power, the d-q components of the reference supply current (i_{sd}^{ref} , i_{sq}^{ref}) are imposed to be I_{Ld} and zero. Their passing from SRF to (a, b, c) frame is achieved by successive reverse Park and Clarke transforms, as follows:

$$\begin{bmatrix} i_{s\alpha}^{ref} \\ i_{s\beta}^{ref} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_{Ld} \\ 0 \end{bmatrix} \cdot . \tag{7}$$

$$\begin{bmatrix} i_{sa}^{ref} \\ i_{sb}^{ref} \\ i_{sc}^{ref} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{s\alpha}^{ref} \\ i_{s\beta}^{ref} \end{bmatrix} . \tag{8}$$

The above algorithm is schematized in Figure 3.

Figure 3. *Block Diagram of the Reference Current Calculation*



Simulink Model

A specific Matlab/Simulink model of the whole active DC-traction substation has been created in order to verify the correctness of the proposed solution and to assess its performance during the filtering and regeneration regimes (Figure 4).

As shown, in the model of 12-pulse parallel rectifier DC-traction (Figure 5), the Y/y/d traction transformer of rated power of 3.2 MVA provides 1.2 kV in each secondary to supply the two uncontrolled bridge rectifiers. Two reverse magnetically coupled inductances are used for the parallel connection of the rectifiers.

The DC traction line was modeled taking into account that, in traction regime, it is an active load with 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.

A recovery transformer of connection Y/y, 2.2 MVA and 820 V/ 33 kV is used.

On the DC-side, the compensating capacitor of 100 mF is coupled with the DC-line by means of the separating circuit consisting of a diode and an inductance of 40 μH.

Figure 4. *Simulink Model of the Active DC Traction Substation*

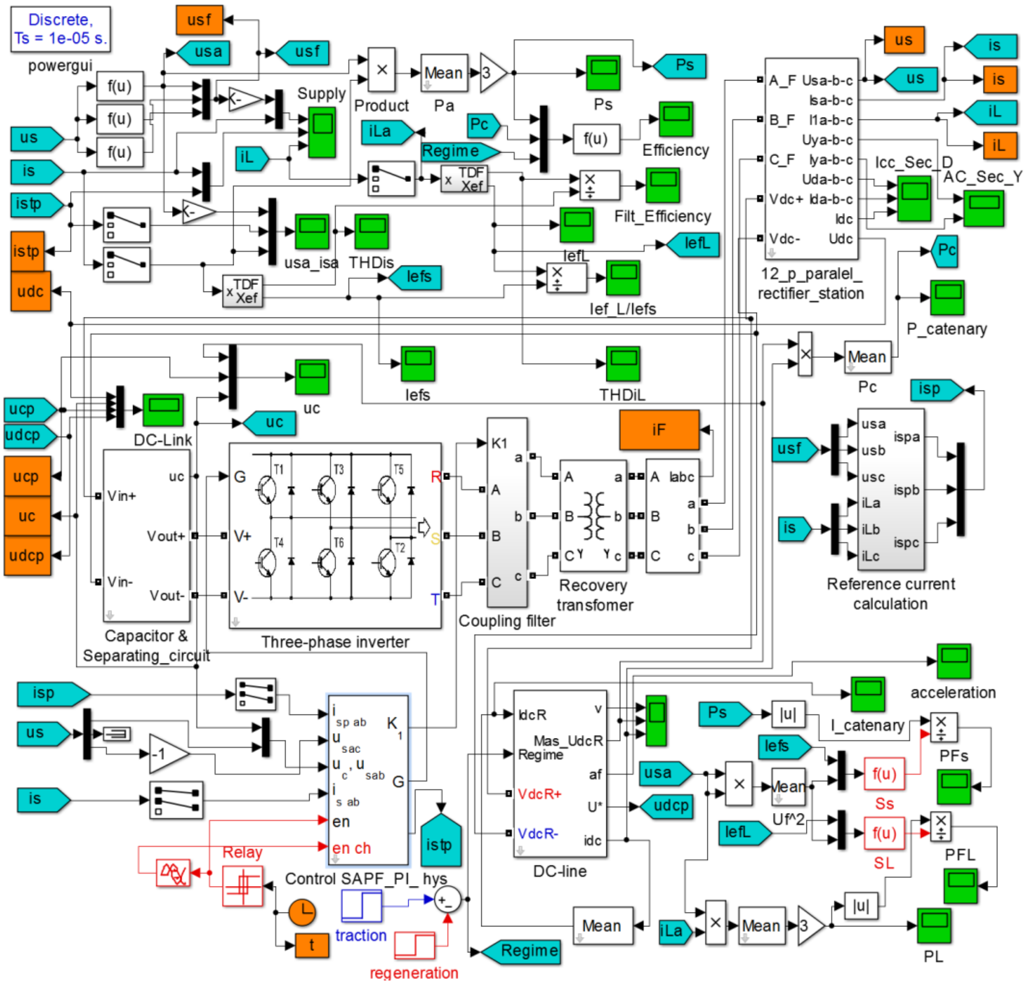
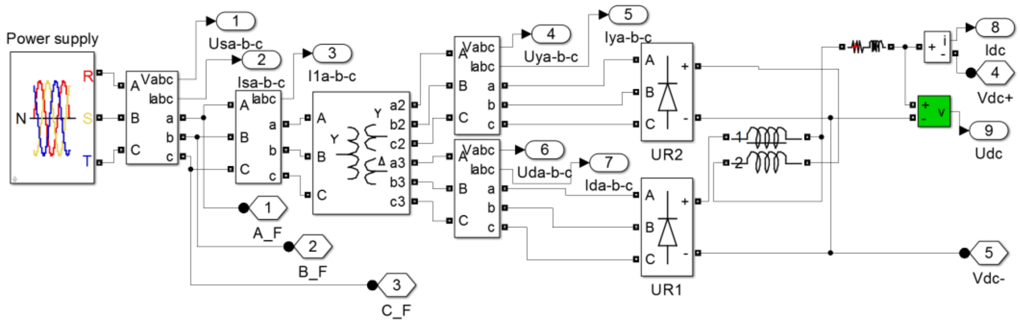


Figure 5. *Simulink Model of the DC Traction Substation with 12-Pulse Parallel Rectifier*



The control block of the three-phase three-wire system receives two of the generated reference currents, actual supply currents, line-to-line voltages in the transformer primary, together with the DC-capacitor voltage.

The parameters of the PI voltage controller are $K_p=30.60$ and $T_i=3.947 \cdot 10^{-4}$ s. The hysteresis band imposed for the current controller is 0.5 A.

The initial charging of the compensating capacitor through a limiting resistor and contactor K_1 is taken into consideration. After the generation of the total reference currents, including the components needed to keep the DC-voltage at the prescribed value, the three-phase hysteresis band controller gives the gating signals for IGBTs.

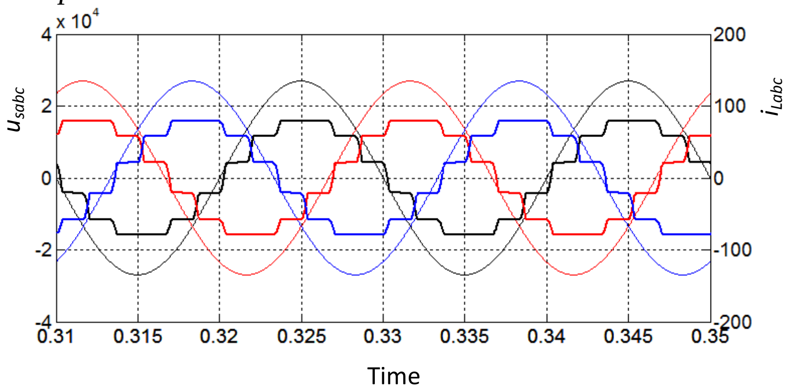
Different blocks are added in the Simulink model to assess the performance of the system for filtering and regeneration.

Simulation Results

The operation of the proposed active traction substation has been simulated for both filtering and regeneration regimes.

First, till t=0.5 s, the system is in traction mode and a distorted current of *THD*=12% is drawn in the traction transformer primary (Figure 6). The global power factor (*PF*) is of about 0.988.

Figure 6. *Phase Voltages and Currents in the Traction Transformer Primary without Compensation*



During this regime, SISFREG operates as an active power filter (Figure 7), by compensating the current harmonics and the reactive power, so that the supply current becomes almost sinusoidal (*THD*≈2.8%) and in phase with the voltage (*PF*≈0.999). The rms supply current has a small increase, from 57.65 A to 57.75 A in order to cover the power losses and keep the DC capacitor voltage at the prescribed value of 1782 V.

From t=0.5 s to t=0.8 s, the operation in regeneration mode is required, the traction rectifier being blocked. During this regime, a constant acceleration of 2 m/s^2 is imposed, leading to a constant DC current (about 2000 A). The AC current injected to the power supply has a low *THD* (about 2.7%). As shown in Figure 8, the supply current is 180 degree out of phase with the AC voltage. The recovery efficiency, from the catenary line to the AC-line is of about 0.95.

Figure 7. *Phase Voltage and Current in the Traction Transformer Primary Before and After Compensation*

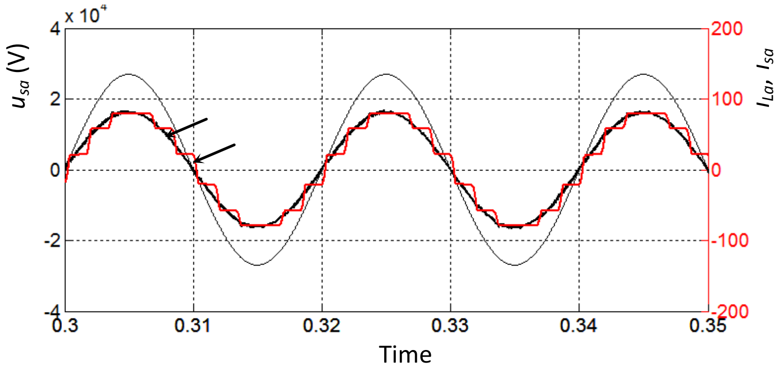
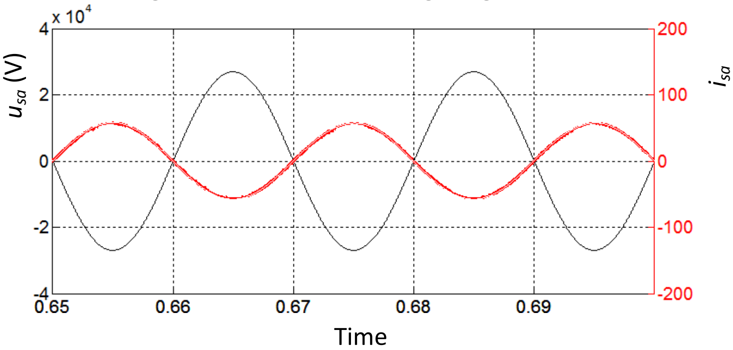


Figure 8. *Phase Voltage and Current during Regeneration*



At *t*=0.8 s, no regeneration current is needed and the SISFREG passes again in filtering mode.

The waveform in Figure 9 shows the evolution of the voltages on the DC-side during the whole simulation period. First, the DC-capacitor is charging naturally through the APF's diodes. Then, through a ramp prescription, the set value of 1782 V is reached with a very low overshoot of about 0.5%. Withal, the average catenary-line voltage has the rated value of 1500 V.

In regeneration mode, the catenary-line voltage increases and exceeds for a short time the prescribed value of 1800 V by about 2.5%. The DC-capacitor remains at its prescribed value which is below catenary-line voltage. During the system transition to the filtering regime, the catenary-line voltage reaches the average value of 1500 V with an overshoot of about 18%.

Is it can be seen in Figure 10, when the system passes from an operating mode to the other, a half-period of 10 ms is sufficient to change the sense of power flow.

The correctness of the system operation is highlighted also by the waveforms of traction transformer and recovery transformer currents in the point of common coupling (Figure 11).

It can be seen that the recovery transformer injects either the compensating current or the regenerated current, whereas the traction transformer current exists only during the traction regime.

Figure 9. *Waveforms of the Prescribed (in Magenta) and Actual (in Black) Voltage across the DC-Capacitor Voltage and the DC-Line Voltage (in Blue)*

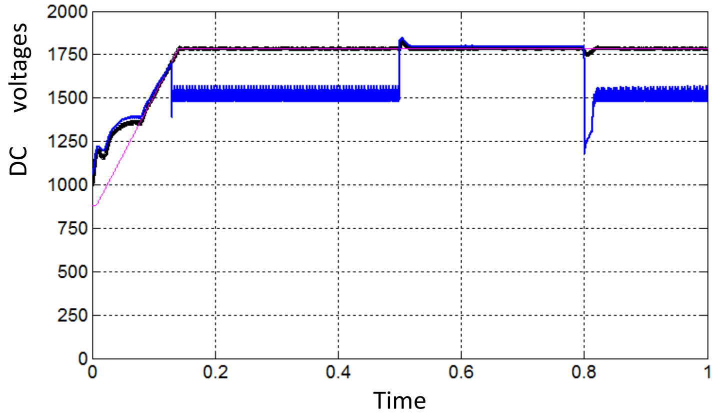


Figure 10. *Phase Voltage and Supply Current when the System Passes from the Filtering to Regeneration Regime (a) and Vice Versa (b)*

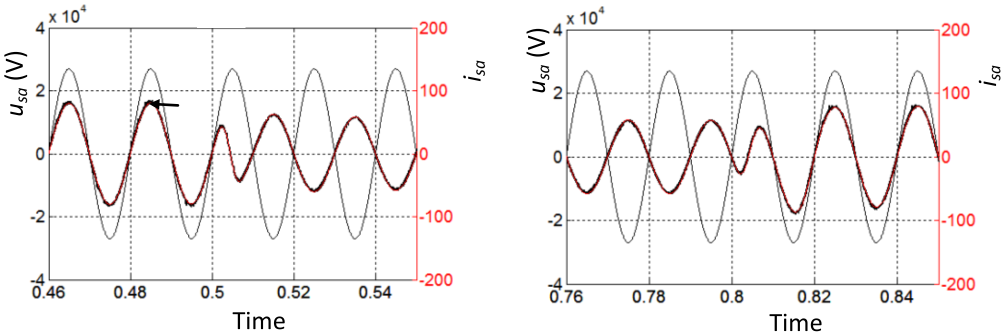
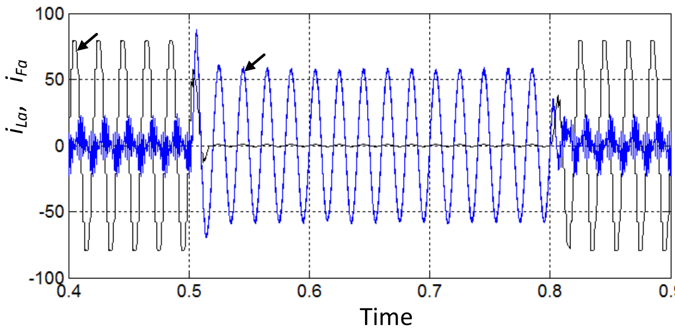


Figure 11. *Current in the Primary of Traction Transformer (in Black) and Current in the Secondary of Recovery Transformer (in Blue)*



Conclusions

In the proposed structure of the system for converting a DC-traction substation with 12-pulse parallel diode rectifier into an active substation, besides the SAPF, a dedicated transformer on the AC-side and a separating circuit on the DC-side are needed.

In the adopted implementation, the indirect current control involves the generation of the prescribed supply current based on the sensed voltages and currents in the traction transformer primary by using the SRF method. The control scheme, with a PI controller to keep the set DC-side voltage and a hysteresis controller to track the set supply currents, allows obtaining nearly sinusoidal supply currents and unity power factor in both filtering and regeneration regimes.

Further research is intended to develop and implement the control algorithm on an experimental platform based on dSPACE control board.

References

[1] Lao, K. W., Dai, N., Liu, W. G., and Wong, M. C. 2013. Hybrid power quality compensator with minimum dc operation voltage design for high-speed traction power systems. *IEEE Trans. Power Electron.* 28, 4 (April 2013), 2024-2036.

[2] Bahrani, B. and Rufer, A. 2013. Optimization-based voltage support in traction networks using active line-side converters. *IEEE Trans. Power Electron.* 28, 2 (Feb. 2013), 673–685.

[3] Shishime, K. 2012. Practical applications of the railway static power conditioner (RPC) for conventional railways. *MEIDEN Review*. 3, 156, 38-41.

[4] Cornic D. 2010. Efficient recovery of braking energy through a reversible dc substation. In *Proceedings of the Electrical Systems for Aircraft, Railway and Ship Propulsion* (Bologna, Italy, Oct. 19-21, 2010). ESARS '2010.

[5] Siemens. 2010. Sitras TCI–Thyristor controlled inverter for DC traction power supply. *Siemens AG 2010*, https://w3.usa.siemens.com/mobility/us/Documents/en/rail-solutions/railway-electrification/dc-traction-power-supply/sitras-tci-en.pdf

[6] Ortega, J. M., Ibaiondo, H. and Romo, A. 2011. Kinetic energy recovery on railway systems with feedback to the grid. In *Proceedings of the 9th World Congress on Railway Research* (Lille, France, May 22-26, 2011).WCRR '2011.

[7] Warin, Y., Lanselle, R., and Thiounn M. 2011. Active substation. In *Proceedings of the 9th World Congress on Railway Research* (Lille, France, May 22-26, 2011). WCRR '2011.

[8] Bueno, A., Aller, J. M., Restrepo, J., and Habetler, T. 2010. Harmonic and balance compensation using instantaneous active and reactive power control on electric railway systems. In *Proc. Appl. Power Electron. Conf. Expo*. (Palm Springs, CA, Feb. 21-25, 2010), 1139 -1144. APEC '2010

[9] Ramos, G., Cantor, E., Rios, M. A., and Roa, L. F. 2011. Instantaneous p-q theory for harmonic compensation with active power filter in dc traction systems. In *Proceedings of International Conference on Power Engineering, Energy and Electrical Drives* (Malaga, Spain, May 11-13, 2011). POWERENG '2011.

[10] Bitoleanu, A. and Popescu, M. 2011. How can the IRP p-q theory be applied for active filtering under nonsinusoidal voltage operation? *Przegląd Elektrotechniczny*, 87, 1, 67-71.

[11] Terciyanli, A., Acik, A., Cetin, A., Ermis, M., Cadirci, I., Ermis, C., Demirci, T., and Bilgin, H.F. 2012. Power quality solutions for light rail public transportation

systems fed by medium-voltage underground cables. *IEEE Trans. Ind. Appl.*, 48, 3 (May/June 2012), 1017-1029.

[12] Bitoleanu, A., Popescu, M., Marin, D., and Dobriceanu, M. 2010. LCL interface filter design for shunt active power filters. *Advances in Electrical and Computer Engineering*, 10, 3 (Aug. 2010), 55-60.

[13] Bitoleanu, A., Mihai, D., Popescu, M., and Constantinescu, C. 2000. *Convertoare statice si structuri de comanda performante*. Sitech, Craiova, 2000.

[14] Popescu, M., Bitoleanu, A., Suru, V., and Preda, A. 2015. System for converting the dc traction substations into active substations. In *Proc. International Symposium on Advanced Topics in Electrical Engineering* (Bucharest, Romania, May 7-9, 2015). ATEE '2015.

[15]Bitoleanu, A. and Popescu, M. 2010. *Filtre active de putere*. Universitaria Craiova, 2010.

[16] Popescu, M., Bitoleanu, A., and Suru, V. 2013. A DSP-based implementation of the p-q theory in active power filtering under nonideal voltage conditions. *IEEE Transactions on Industrial Informatics*, 9, 2 (May 2013), 880-889.

[17] Bhattacharya, S. and Divan D. 1995. Synchronous frame based controller implementation for a hybrid series active filter system. *In Proc. 30th Industry Applications Society Annual Meeting* (Orlando, FL, Oct. 8-12, 1995), 2531-2540. IAS '95.

[18] Soares, V., Verdelho, P., and Marques, G. D. 2000. An instantaneous active and reactive current component method for active filters. *IEEE Trans. Power Electron.*, 15, 4 (Jul. 2000), 660-669.

[19] Bhattacharjee, K. 2013. Design and simulation of synchronous reference frame based shunt active power filter using SIMULINK. In *Proc. Conference on Challenges in Research & Technology in the Coming Decades* (Ujire, India, Sept. 27-28, 2013). CRT '2013.

[20]Popescu, M., Dobriceanu, M., Linca, M., and Oprea, G. 2014. Orthogonal reference frame based methods in three-wire active power line conditioners: Practical evaluation under unbalanced load and nonideal voltage conditions. In *Proc. International Conference on Optimization of Electrical and Electronic Equipment* (Brasov, Romania, May 22-24, 2014), OPTIM '2014.