DC-Traction Substation with Improved Power Quality and Regeneration Capability

Mihaela Popescu, Alexandru Bitoleanu, Constantin Vlad Suru, and Mircea Dobriceanu
University of Craiova, Faculty of Electrical Engineering, Craiova, Romania
mpopescu@em.ucv.ro, alex.bitoleanu@em.ucv.ro, vsuru@em.ucv.ro, mdobriceanu@em.ucv.ro

Abstract – **In the DC-traction substations, the diode rectifiers are commonly used to provide the needed DC-voltage for vehicles. Unfortunately, they attract important issues of power quality, of which the most significant is the injection of harmonic currents into the AC power supply. Withal, the feedback of the recovered braking energy into the power supply is not possible. This paper is focused on the transforming a DC-traction substation with six-pulse uncontrolled rectifier into an active substation, leading to substantially improved power quality and energy efficiency. These effects are obtained through an IGBT-based voltage source inverter with a proper control, connected between the DC-traction line and the power supply via a dedicated transformer and specific interfacing circuits. The indirect current control is based on the concepts of the p-q theory of the powers and intermediate use of the synchronous reference frame, so that perfect harmonic cancellation is imposed even under distorted supply voltages. The conceived Matlab-Simulink model of the system for active filtering and regeneration is presented and the simulation results illustrate very good performance in both operating regimes of the system. Experiments on a 30 kVA reduced-scale laboratory setup controlled and monitored by a dSPACE 1103 based platform verify the feasibility and effectiveness of the proposed scheme. Both the harmonic distortion of the current upstream the point of common coupling and the power factor are significantly improved.**

Cuvinte cheie: *calitatea energiei electrice, distorsiune armonică, filtru activ de putere, regenerare, substaţie de tracţiune în c.c., teoria p-q.*

Keywords: *power quality, harmonic distortion, active power filter, regeneration, DC-traction substation, p-q theory.*

I. INTRODUCTION

The widespread of the DC traction systems in the urban and suburban areas in the last decades was accompanied by the power quality issues generated by the existence of the uncontrolled traction rectifiers. Indeed, the usual six-pulse or twelve-pulse series/parallel diode rectifiers of the traction substations lead to distorted currents drawn from the power supply, with a distortion degree over the limit recommended by the specific standards, such as IEEE-519-1992 [1]. Thus, reducing the harmonic distortion, as well as increasing the power factor and the global energy efficiency of the system are actual concerns [2]–[3].

The simple and quite cheap solution of connecting tuned passive filters in the traction substations is still taken into consideration to mitigate specific harmonics of great weight or a bandwidth of severe harmonics of the load current [4]–[6]. However, due to their constant parameters and possible occurrence of resonance problems, they are not efficient solutions for dynamic nonlinear loads.

For high power twelve-pulse rectifier loads, the idea of connecting a dominant harmonic active filter based on square-wave inverters switching at 5th and 7th harmonic frequencies coupled in series with 11th and 13th passive filters was proposed in [7] as a cost-effective harmonic filtering solution. In [8], the harmonic isolation of high-power rectifier loads at the critical frequencies is achieved by a hybrid solution of a small rating selective active power filter with reduced switching frequency which is connected in series with a low-cost power factor correction capacitor. Good synchronization is obtained through current controllers based on infinite-impulse response second-order digital resonant filters.

The current developments in the field of power electronics allowed for focused attention on implementing the high performance solution of active power filtering in the traction substations, so that various compensation objectives can be achieved [2], [9]–[13].

Besides the specialists' concern to improve the power in traction regime, the increase of the energy efficiency during the braking regime is a topical objective. Normally, in the DC-traction systems, the regenerated braking energy is used only when other trains are powered simultaneously and in the same electrical section, so that less than 20% of this energy is reused [14]–[15]. Through reversible substations, including inverters to enable a bidirectional power flow, the expected recovery percentage may be up to 25% (annual recovery over 11 % of the substation consumption for the particular case of Metro Bilbao) [16]. Thyristor-based inverters for DC reversible traction system was achieved for the power-supply system of Kobe Metro in Japan even in the 1980s [17]. By the Siemens' Sitras® TCI solution consisting of a thyristor controlled inverter for DC traction power supply, the DC substations equipped with uncontrolled rectifiers can acquire the capability to return the surplus energy to the power system [18]. In the HESOP energy recovery system implemented by Alstom, a thyristor rectifier bridge replaces the standard diode rectifier to increase the regeneration domain range and an antiparallel IGBT inverter ensures the harmonic compensation, the power factor improvement and the power load management [19].

The static converter in the structure cast in one piece and called "Active Substation with direct return" supplies the catenary, ensures the return of the not used braking energy to the power supply and adds new functions such as the harmonic compensation and voltage regulation [20].

In this paper, an active DC traction substation is obtained by connecting a voltage source inverter (VSI), acting as an shunt active power filter (SAPF), between the DC-traction line and power supply, in antiparallel with the existing traction substation with six-pulse diode rectifier. The paper is organized as follows. Section II introduces the structure of the active DC-traction substation. Then, the indirect control of the current injected by VSI in the point of common coupling (PCC) by means of the supply current regulation is presented in section III. After describing the Simulink model of the whole system in section IV, the next section presents the performance of the system in traction and regeneration regimes. Both simulation and experimental results on a small-scale setup are presented. Some concluding remarks are given at the end of the paper.

II. SYSTEM CONFIGURATION

The schematic power structure in Fig. 1 illustrates the existing DC-traction group consisting of the traction transformer and the six-pulse diode-bridge rectifier, as is the case of Bucharest metro traction substations.

The IGBT-based VSI is the main component of the system for active filtering and regeneration. Its proper operation, in terms of quality of the current injected in PCC and the resulted waveform and phase of the supply current upstream PCC irrespective the operation regime, requires the use of specific circuits of connection on both DC and AC sides [21].

Besides the common capacitor of high capacitance on the DC-side, the separation between the catenary line and SAPF in traction regime is achieved by introducing a proper designed inductance in series with a diode [22].

On the other hand, the connection on the AC-side is achieved by a passive filter of type LCL provided with damping resistance to reject the IGBTs' high order switching harmonics [23]. A dedicated coupling transformer is the adopted solution to ensures the proper correlation between the DC-capacitor voltage and the SAPF's AC voltage [21].

As regards the control of the currents injected into PCC by SAPF (i_{FA}, i_{FB}, i_{FC}), it can be achieved in direct mode needing their measurement, or in indirect mode by means of the measurement and control of the currents drawn from the AC power supply (i_A, i_B, i_C) which are actually the currents of interest [24]–[27].

In the case of the direct current control, a non-sinusoidal reference current must be generated and tracked, leading to potentially worsened harmonic distortion of the supply current. On the other hand, in the case of indirect current control, sinusoidal reference source currents and their actual currents counterparts are involved in the IGBTs' gating signals generation, leading to better attenuation of the harmonic distortion of the controlled current.

In this paper, the indirect current control has been taken into consideration, and the required input quantities of the control block are: the supply currents and voltages (i_A, i_B, i_C, u_A, u_B, u_C), the currents in the traction transformer primary (i_{LA}, i_{LB}, i_{LC}), and the voltage across the DC-capacitor (u_{Cd}). Obviously, the prescribed capacitor voltage (U_{Cdp}) must be provided (Fig. 1).

III. INDIRECT CURRENT CONTROL

In order to prescribe sinusoidal supply currents in phase with the corresponding supply voltages, the fundamentals of the so-called p-q theory of the powers [28] have been applied. To impose the perfect current harmonic cancellation even under nonsinusoidal voltage conditions, the fundamental components of the supply voltages have been calculated (Fig. 2) and used in the control scheme, by working in the rotating Synchronous Reference Frame (SRF) d-q, with d-axis aligned with the voltage vector [12].

Thus, the voltage components in SRF (u_d, u_q) are given by the forward Park transformation as follows [12], [29]:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} \dfrac{u_\alpha}{\sqrt{u_\alpha^2 + u_\beta^2}} & \dfrac{u_\beta}{\sqrt{u_\alpha^2 + u_\beta^2}} \\ -\dfrac{u_\beta}{\sqrt{u_\alpha^2 + u_\beta^2}} & \dfrac{u_\alpha}{\sqrt{u_\alpha^2 + u_\beta^2}} \end{bmatrix} \cdot \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}, \tag{1}$$

where u_α and u_β are the voltage components in the stationary coordinate system (α, β) specific of the p-q theory.

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & 1/\sqrt{3} & -1/\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix}. \tag{2}$$

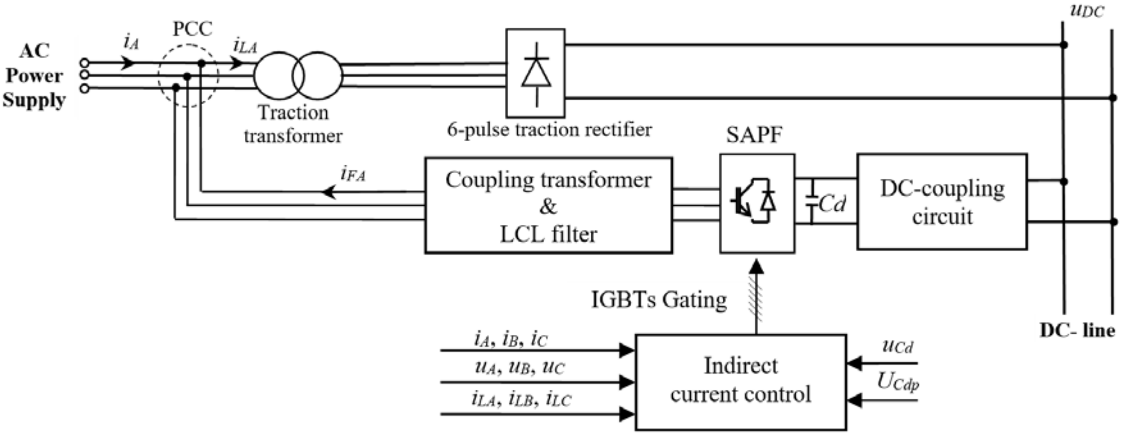


Fig. 1. Schematic diagram of the DC-traction substation with active filtering and regeneration capabilities.

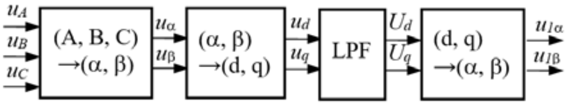


Fig. 2. Block diagram for the generation of the fundamental components of the voltage phasor in the stationary reference frame.

After separating the DC components (U_d, U_q) through low pass filters (LPFs), the following reverse Park transformation provides the pair ($u_{1\alpha}$, $u_{1\beta}$), meaning the voltage fundamental components (Fig 2).

$$\begin{bmatrix} u_{1\alpha} \\ u_{1\beta} \end{bmatrix} = \begin{bmatrix} \dfrac{u_\alpha}{\sqrt{u_\alpha^2 + u_\beta^2}} & -\dfrac{u_\beta}{\sqrt{u_\alpha^2 + u_\beta^2}} \\ \dfrac{u_\beta}{\sqrt{u_\alpha^2 + u_\beta^2}} & \dfrac{u_\alpha}{\sqrt{u_\alpha^2 + u_\beta^2}} \end{bmatrix} \cdot \begin{bmatrix} U_d \\ U_q \end{bmatrix}. \tag{3}$$

The components $i_{L\alpha}$ and $i_{L\beta}$ of the current in the traction transformer primary are provided by Clarke's transformation from (A, B, C) frame to (α, β) frame, as in the case of voltage.

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & 1/\sqrt{3} & -1/\sqrt{3} \end{bmatrix} \cdot \begin{bmatrix} i_{LA} \\ i_{LB} \\ i_{LC} \end{bmatrix}. \tag{4}$$

In accordance with the p-q theory principle of the harmonic and reactive power compensation [12], the prescribed supply current is expressed as:

$$\underline{i}_{pc} = i_{pc\alpha} + j \cdot i_{pc\beta} = \frac{2P}{3\sqrt{u_{1\alpha}^2 + u_{1\beta}^2}} \cdot \left(u_{1\alpha} + j u_{1\beta}\right). \tag{5}$$

The active power (P) intervening in (5) is the mean value of the instantaneous "active" power (p) over the previous period T, i.e.:

$$P(t) = \frac{1}{T} \int_{t-T}^{t} p(\tau) d\tau \, ; \tag{6}$$

$$p = \frac{3}{2} \cdot \left(u_{1\alpha} i_{L\alpha} + u_{1\beta} i_{L\beta}\right). \tag{7}$$

The global block diagram of the reference current generation to achieve the goal of perfect harmonic cancellation is shown in Fig. 3. It includes the block for generation the voltage fundamental components described in Fig. 2.

As illustrated in Fig. 3, a low pass filter is used to calculate the active power as the DC component of p. It can be easily implemented by a Butterworth filter of third order.

The prescribed supply currents (i_{pcA}, i_{pcB}, i_{pcC}) are the outputs of a block that changes the frame (α, β) to the phase coordinate frame (A, B, C), as follows:

$$\begin{bmatrix} i_{pcA} \\ i_{pcB} \\ i_{pcC} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{pc\alpha} \\ i_{pc\beta} \end{bmatrix}. \tag{8}$$

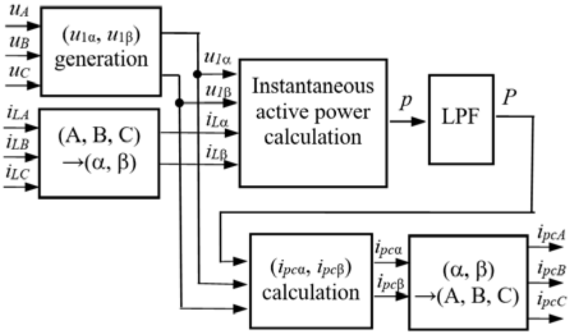


Fig. 3. Block diagram of the reference current generation to achieve the goal of perfect harmonic cancellation.

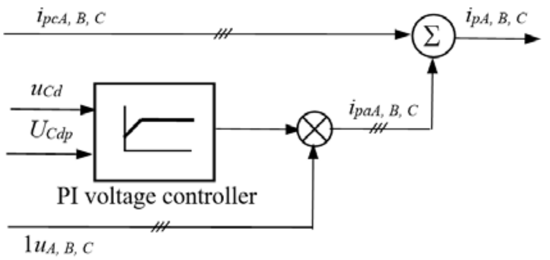


Fig. 4. Block diagram showing the components of the total prescribed current.

For the control system to be able to ensure accurate tracking of the prescribed current, the voltage across the DC-capacitor must be kept constant. This requirement is ensured by the voltage control loop, providing the magnitude of the additional active currents (i_{paA}, i_{paB}, i_{paC}) to be prescribed on each phase, through which the all power losses are covered (Fig. 4).

The templates of unity magnitude ($1u_A$, $1u_B$, $1u_C$) of these active currents are generated by a voltage synchronization circuit of PLL type [30].

Finally, the total prescribed supply currents are:

$$i_{pk} = i_{pck} + i_{pak} \, , \qquad k = A, B, C \, . \tag{9}$$

They are provided to a hysteresis band current controller, along with the measured supply currents, to force the latter to be sinusoidal and having the same zero crossing points as the supply voltages.

It must be noticed that, during the system operation in regeneration mode, the traction rectifier is blocked due the increased DC-voltage, the currents in the traction transformer are practically absent, so that only the active components i_{paA}, i_{paB} and i_{paC} are to be tracked by the AC supply currents. The PI voltage controller operates with negative error and gives a negative output corresponding to the magnitude of the regenerated current.

IV. MODELING THE SYSTEM FOR ACTIVE FILTERING AND REGENERATION

The whole active DC-traction substation with six-pulse diode rectifier and indirect control of the current based on the p-q theory of the powers has been modeled in the Matlab-Simulink environment (Fig. 5).

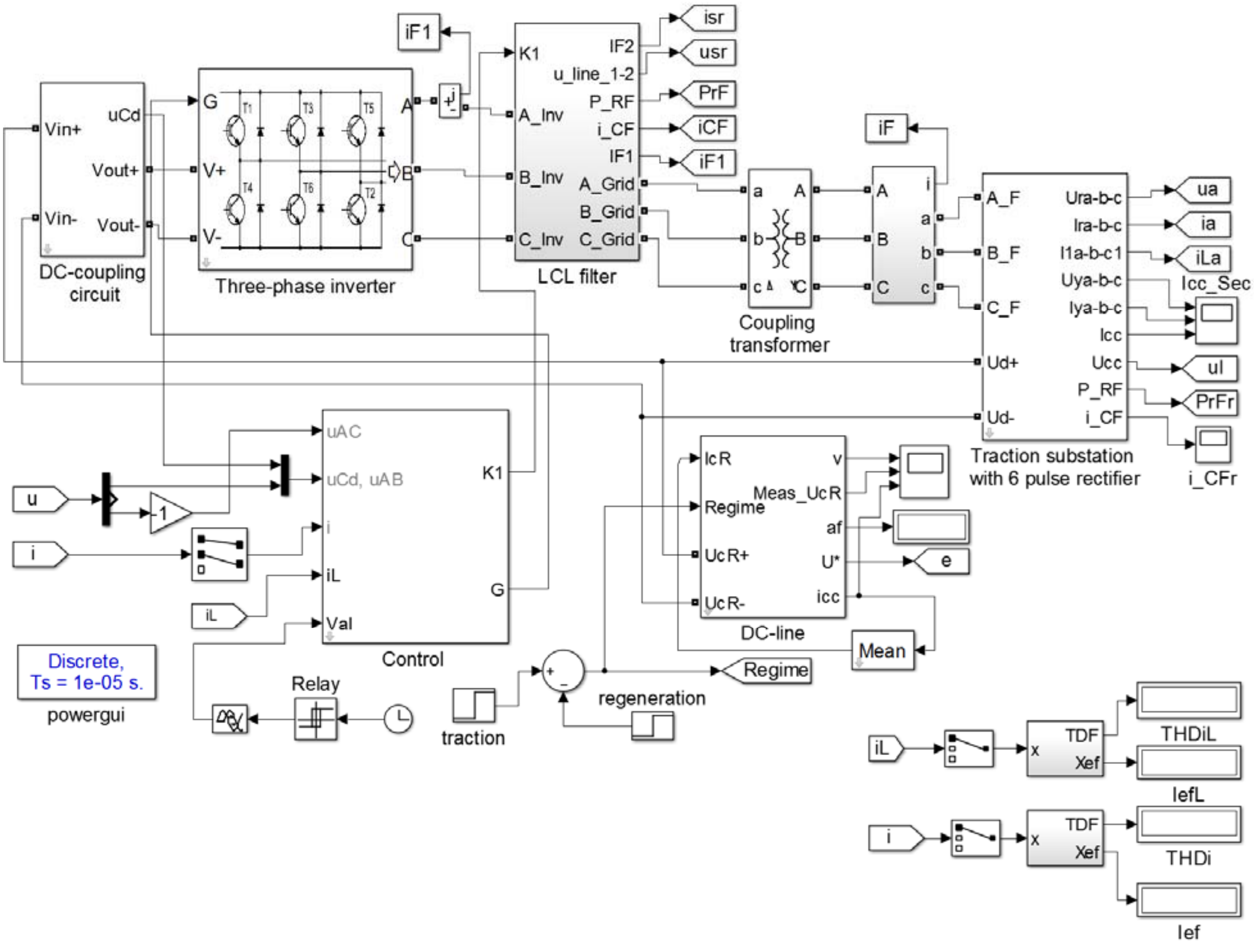


Fig. 5. Simulink model of the system.

To allow a subsequent experimental validation, the simulation parameters in the power structure correspond to a small scale setup of 30 kVA rated power and 380 V rated voltage. The voltage in the secondary of the YY traction transformer is 150 V [27].

In traction regime, the DC-line is modeled as an active load (equivalent resistance, equivalent inductance and back electromotive force associated to the operation speed). In regeneration regime, the DC-line current is constant, as constant acceleration is imposed and the maximal DC-line voltage is limited.

The coupling transformer is of connection Yd, 380 V/130 V and the parameters of the coupling LCL filter are: the supply-side inductance - 1.71 mH; the inverter-side inductance - 34 μH; the filtering capacitor - 5 μF; the damping resistance - 41 Ω.

The capacitance of the inverter's DC-capacitor is of 2200 μF and the prescribed value of the voltage across it is 220 V.

A small inductance of 4.9 μH is connected in series with the separating diode in the DC-coupling circuit.

V. PERFORMANCE OF THE SYSTEM IN ACTIVE FILTERING AND REGENERATION REGIMES

The performance of the system in active filtering and regeneration modes, in terms of total harmonic distortion factor (*THD*) of the AC supply current and power factor has been assessed first by simulation and then validated in experimental way.

A. Simulation Results

The proper behavior of the whole system during the traction regime of the DC-traction substation is illustrated though the waveform of the phase currents correlated to those of the voltages on the AC-side (Fig. 6 and Fig. 7). As shown in Fig. 6, distorted currents (*THD* ≈ 24 %) are drawn in the traction transformer primary from the power supply, and the fundamentals of the currents and voltages have not the same phase (*PF* ≈ 0.94).

The effect of the correct generated currents injected into PCC is reflected in almost sinusoidal supply currents in phase with the corresponding voltages (*THD* ≈ 3.6 %; *PF* ≈ 1), as it can be seen in Fig. 7.

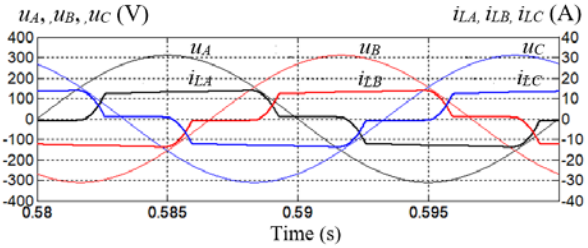


Fig. 6. Phase voltages and currents in the primary of the traction transformer during the traction regime.

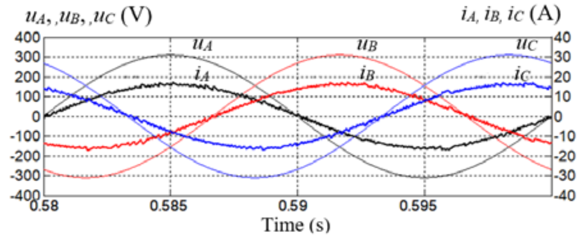


Fig. 7. Phase voltages and currents drawn from the AC power supply during the traction regime.

Thus, the operation in traction regime of the traction substation is accompanied by the active filtering mode of VSI and improved power quality is ensured.

During the braking regime of the traction motors, almost sinusoidal currents ($THD \approx 2.8$ %) are injected into the power supply through PCC (Fig. 8), whereas the traction rectifier's diodes are reverse biased. The phase opposition of phase currents and voltages is illustrated too. Thus, the braking regime is accompanied by the regeneration mode of VSI.

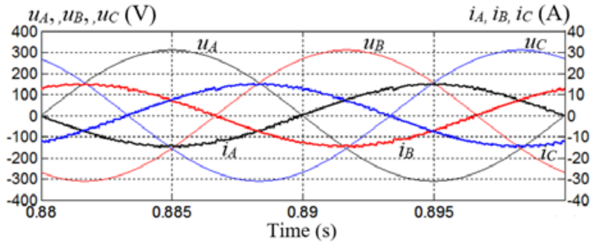


Fig. 8. Phase voltages and currents drawn from the power supply during the regeneration regime.

B. *Experimental Results*

Experimental tests have been conducted on a laboratory test bench of small scale (30 kVA). It contains a six-diode bridge rectifier supplied to the grid by an transformer and an antiparallel IBGT-based VSI connected to the power supply through an LCL filter with damping resistance and a coupling transformer.

All the parameters are the same as those used in simulation. A DC motor supplied by the rectifier is the equivalent of the DC-traction motor and a synchronous machine (SM) connected to the AC power supply is the equivalent of the vehicle. When SM acts as generator, the operation of the system is equivalent to the traction regime, whereas when SM acts as motor, the operation of the system is in regeneration regime.

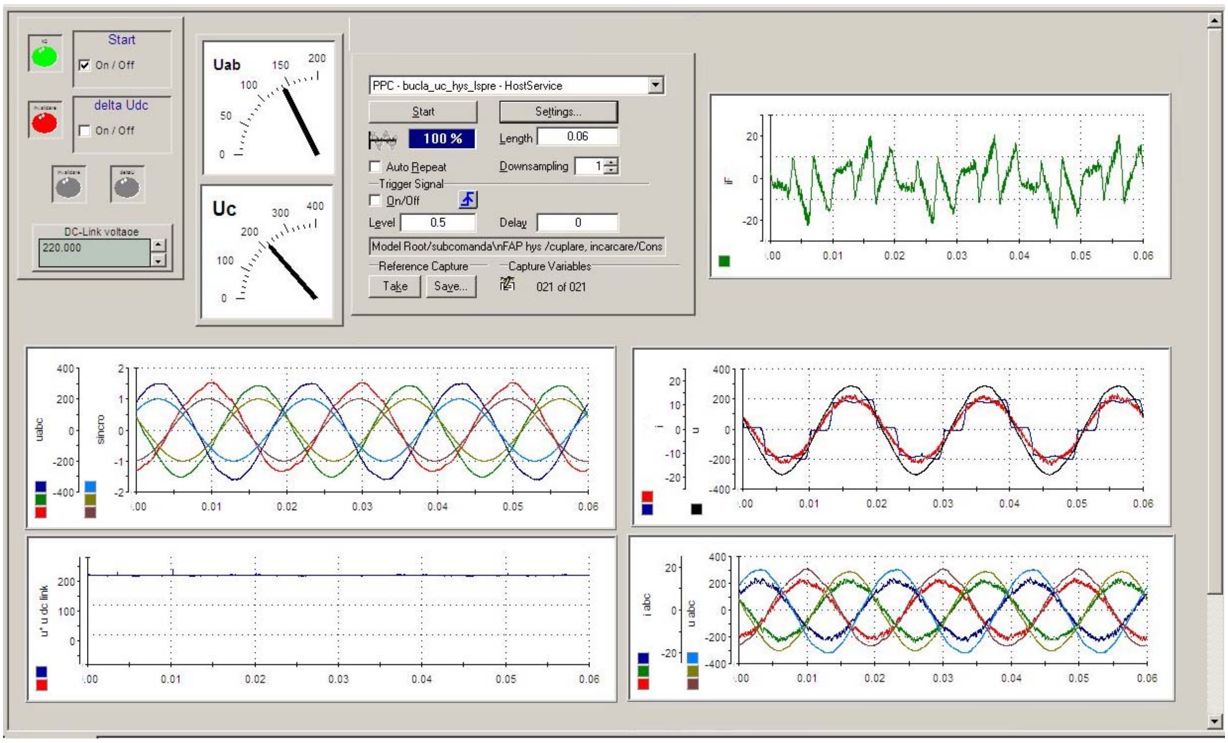
A dSPACE 1103 PPC controller board working under Matlab-Simulink environment has been used for the real-time control of the system. The adopted sampling time is 20 μs.

A specific Control Desk interface has been conceived to facilitate the user intervention and to show the acquired quantities of interest and their time-evolution.

The waveforms included in the Control Desk interfaces shown in Fig. 9 and Fig. 10 correspond to the active filtering regime of VSI and to the regeneration regime, respectively.

Through the acquired DC-capacitor voltage shown in the bottom left corner of the Control Desk panels, the proper operation of the voltage control loop is highlighted. Indeed, the DC-capacitor voltage is accurately kept to the prescribed value of 220 V.

As shown in the top left, under conditions of a non-ideal system of supply voltages, sinusoidal templates of unity magnitude are generated for the proper control.


Start ☑ On / Off

delta Udc ☐ On / Off

DC-Link voltage 220.000

PPC - bucla_uc_hys_Ispre - HostService

100 %

Length 0.06

☐ Auto Repeat

Downsampling 1

Trigger Signal ☐ On/Off

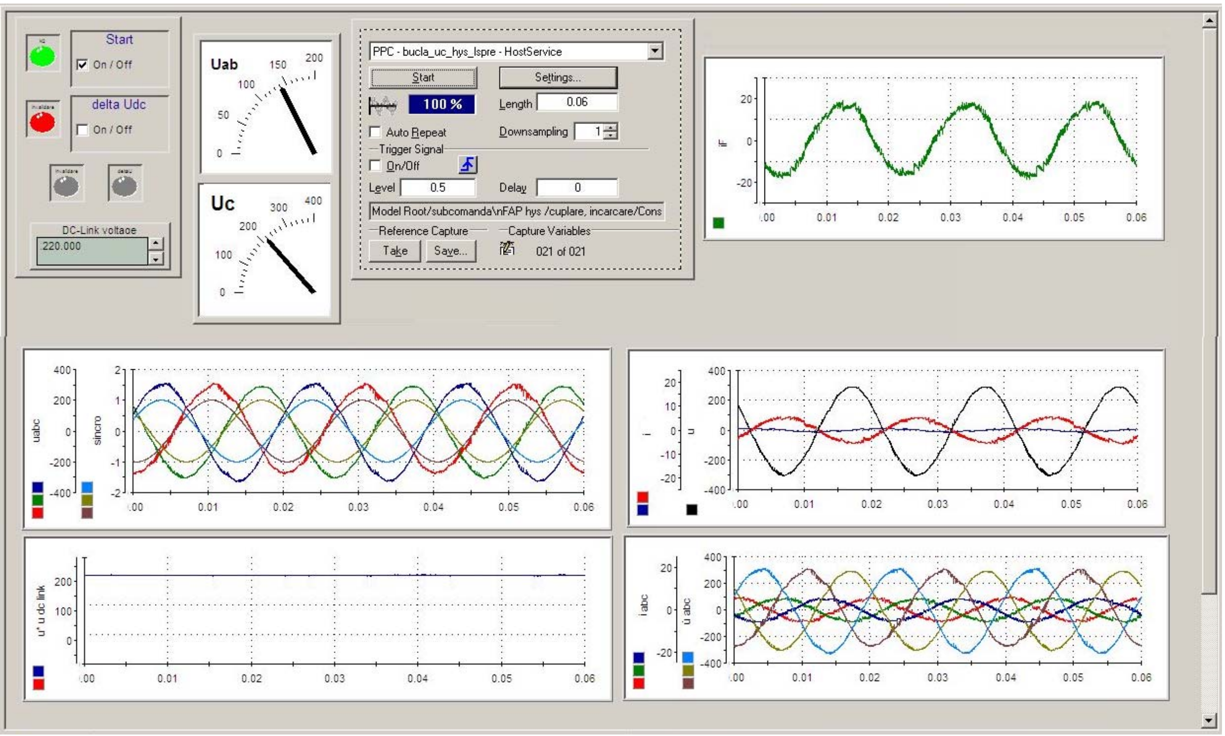
Level 0.5

Delay 0

Model Root/subcomanda\nFAP hys /cuplare, incarcare/Cons

Capture Variables 021 of 021

Fig. 9. Acquired quantities in the Control Desk interface during the traction regime.



☑ On / Off

☐ On / Off

DC-Link voltage: 220.000

PPC - bucla_uc_hys_lspre - HostService

100 %

Length: 0.06

☐ Auto Repeat

Downsampling: 1

☐ On/Off

Level: 0.5

Delay: 0

Model Root/subcomanda\nFAP hys /cuplare, incarcare/Cons

021 of 021

Fig. 10. Acquired quantities in the Control Desk interface during the regeneration regime.

The current injected in PCC (shown in the top right side) leads to a supply current almost sinusoidal, compared to the current downstream of PCC, and in phase (Fig. 9) / phase opposition (Fig. 10) with the voltage (shown in the middle right side).

The three phase systems of voltages and currents upstream of PCC (shown in the bottom right side) confirms the good power quality performance (*THD* ≈ 4.9 %, *PF* ≈ 1 in the equivalent traction regime and *THD* ≈ 3.5 %, *PF* ≈ 1 in regeneration regime).

VI. CONCLUSION

The results presented in this paper based on simulation under Matlab-Simulink and experimental validation under nonideal laboratory conditions illustrate the real possibility to turn a DC-traction substation with diode rectifier into an active one. For the indirect control of the current injected by the antiparallel voltage source inverter, the proposed p-q theory based strategy is a proper method, leading to good performance in both active filtering and regeneration modes of the system. The harmonic distortion of the supply current upstream the PCC is much diminished and the global power factor is very close to 1.

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).

Contribution of authors:

First author – 50%

First coauthor – 20%

Second coauthor – 20%

Third coauthor – 10%

Received on July 17,2017

Editorial Approval on November 15, 2017

REFERENCES

[1] *IEEE Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Std. 519–1992.

[2] N. Gunavardhini and M. Chandrasekaran, “Power quality conditioners for railway traction - A review,” *Automatika*, vol. 57, no. 1, pp. 150–162, 2016.

[3] S. H. Hosseini, F. Shahnia, M. Sarhangzadeh, and E. Babaei, “Power quality improvement of DC electrified railway distribution systems using hybrid filters”, in *Proc. Electrical Machines and Systems*, vol. 2, no. 2, pp. 1273–1277, Oct. 2005.

[4] A. Kusko and S. M. Peeran, “Tuned filters for traction rectifier sets,” *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 6, pp. 1571–1579, Nov. 1985.

[5] Y. Djeghader, L. Zellouma, H. Labar, R. Toufouti, and Z. Chelli “Study and filtering of harmonics in a DC electrified railway system,” in *Proc. 7th Int. Conf. on Modelling, Identification and Control*, Dec. 2015.

[6] Y Djeghader, L Zellouma, Z Chelli, “Filtering of harmonics in DC traction substation,” *Journal of Electrical Engineering*, vol. 17, no. 2, pp. 29–35, 2017.

[7] P. T. Cheng, S. Bhattachaarya, and D. M. Divan, “Application of dominant harmonic active filter system with 12 pulse nonlinear loads,” *IEEE Trans. Power Delivery*, vol. 14, pp. 642–647, Apr. 1999.

[8] D. Basic, V. S. Ramsden, and P. K. Muttik, “Harmonic filtering of high-power 12-pulse rectifier loads with a selective hybrid filter system,” *IEEE Trans. Ind. Electron.*, vol. 48, no. 6, pp. 1118–1127, Dec. 2001.

[9] G. Ramos, E. Cantor, M.A. Rios, and L.F. Roa, “Instantaneous p-q theory for harmonic compensation with active power filter in DC traction systems,” in *Proc. Internat. Conference on Power Engineering, Energy and Electrical Drives*, pp. 1-5, May 2011.

[10] W. Hosny, H.-E. Park, and J.-H. Song, “Investigation of shunt active power filters in railway systems, substation installation,” *Journal of Energy and Power Engineering*, pp. 1974–1979, Oct. 2013.

[11] A. M. Rezkalla, “Active filters application for metro a.c substations,” in *Proc. 23rd International Conference on Electricity Distribution*, June 2015.

[12] M. Popescu and A. Bitoleanu, “Simulink library for reference current generation in active DC traction substations.” *International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, vol. 9, no. 8, pp. 578–585, 2015.

[13] M. Popescu, A. Bitoleanu, and A. Preda, “Improvement of Power Quality and Energy Efficiency in Bucharest Metro Traction Substations,” in *Proc. 2016 IEEE Int. Power Electron. and Motion Control Conf. and Expo*., pp. 898–903, Sept. 2016.

[14] A. Adinolfi, R. Lamedica, C. Modesto, A. Prudenzi, and S. Vimercati, “Experimental assessment of energy saving due to trains regenerative braking in an electrified subway line,” *IEEE Trans. on Power Delivery*, vol. 13, no. 4, pp. 1536–1542, 1998.

[15] S. S. Fazel, S. Firouzian, and B. K. Shandiz, “Energy-efficient emplacement of reversible DC traction power substations in urban rail transport through regenerative energy recovery,” *International Journal of Railway Research*, vol. 1, no. 2, pp. 11–22, 2014.

[16] J.M. Ortega, H. Ibaiondo, and A. Romo, “Kinetic energy recovery on railway systems with feedback to the grid,” in *Proc. 9th World Congress on Railway Research*, May 22–26, 2011.

[17] T. Suzuki, “DC power supply system with inverting substations for traction systems using regenerative brakes,” *IEE Proceedings B Electric Power Application*, vol. 129, no. 1, pp. 18–26, Jan. 1982.

[18] SIEMENS, Sitras TCI, “Thyristor controlled inverter for DC Traction power supply,” *Siemens AG 2010*.

[19] D. Cornic, “Efficient recovery of braking energy through a reversible dc substation,” in *Proc. Electrical Systems for Aircraft, Railway and Ship Propulsion*, pp.1–9, Oct. 2010.

[20] Y. Warin, R. Lanselle, and M. Thiounn, “Active substation,” in *Proc. 9th World Congress on Railway Research*, Lille, France, May 2011.

[21] M. Popescu, A. Bitoleanu, V. Suru, and A. Preda, “System for converting the DC traction substations into active substations,” in *Proc. Int. Symposium on Advanced Topics in Electrical Engineering*, pp. 632–637, May 2015.

[22] M. Popescu, A. Bitoleanu, and A. Preda, “Design and performances of the separating circuit in regeneration and filtering system for active DC-traction substations,” in *Proc. Int. SPEEDAM 2016*, pp. 1178–1183, June 2016.

[23] M. Popescu, A. Bitoleanu, and A. Preda, “A new design method of an LCL filter in active DC-traction substations,” in *Proc. 17th Int. Conf. on Power Electronics and Motion Control*, pp. 868–873, Sept. 2016.

[24] A. Sakthivel, P. Vijayakumar, and A. Senthilkumar, “Performance assessment of direct and indirect current control strategies for shunt active power filter,” *ARPN Journal of Engineering and Applied Sciences*, vol. 10, no. 9, pp. 4243-4250, May 2015.

[25] A. Bitoleanu, M. Popescu, and C.V. Suru, “Theoretical and experimental evaluation of the indirect current control in active filtering and regeneration systems,” in *Proc. 2017 Int. Conf. OPTIM and ACEMP*, pp. 759–764, May 2017.

[26] Y. Hoon, M. A. M. Radzi, M. K. Hassan, and N. F. Mailah. “A self-tuning filter-based adaptive linear neuron approach for operation of three-level inverter-based shunt active power filters under non-ideal source voltage conditions,” *Energies*, vol. 10, 758, May 2017.

[27] M. Popescu, A. Bitoleanu, V. Suru, and M. Dobriceanu, “Increasing power quality in a 6-pulse DC-traction substation,” in *Proc. 11th International Conference on Electromechanical and Power Systems*, pp. 518–523, Oct. 2017.

[28] H. Akagi, Y. Kanazawa, and A. Nabae, “Instantaneous reactive power compensators comprising switching devices without energy storage components,” *IEEE Trans. Ind. Appl*., no. 3, pp. 625–630, 1984.

[29] V. Soares, P. Verdelho, and G. D. Marques, “An instantaneous active and reactive current component method for active filters,” *IEEE Trans. Power Electron*., vol. 15, no. 4, pp. 660-669, 2000.

[30] M. Popescu, M. Dobriceanu, M. Linca, and G. Oprea, “Orthogonal reference frame based methods in three-wire active power line conditioners: Practical evaluation under unbalanced load and non-ideal voltage conditions,” in *Proc. OPTIM 2014*, pp. 532–539, May 2014.