On the Implementation of FBD-Theory Concepts in the Control of Active DC-Traction Substations

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

Abstract - **This paper is focused on the transformation of a classical DC-traction substation with twelve-pulse uncontrolled rectifier into an active traction substation by adding a dedicated system for active filtering and regeneration called SISFREG. The connection of SISFREG to the AC-side is performed in the primary of the traction transformer via a passive coupling filter and a recovery transformer, whereas an active separating circuit ensures the connection to the DC-traction line. The new functions added to the DC-traction substation lead to the increasing the energy efficiency of the whole system in both traction and braking regimes of the vehicles' traction motors. The control of the current provided by the shunt active filter, which is the main component of SISFREG, is achieved in indirect mode, by means of the current upstream the point of common coupling. In the generation of the set current, the concepts of the Fryze-Buchholz-Depenbrock theory are implemented. Thus, an active current is always imposed at the power supply side and the current control loop guarantees almost sinusoidal current and global unity power factor. A complex Simulink model of the whole system, including facilities for energetic analysis, has been developed and the simulation results show good performances in both steady-state and dynamic regimes.**

Keywords: *FBD theory, energy efficiency, DC traction, active substation, braking energy recovery, active filtering.*

I. Introduction

In the classical DC-traction substations, the existence of the uncontrolled rectifiers to feed the DC-traction line has the effect of current harmonic pollution in the AC power supply and low power factor. Besides the problems in the power quality area, there is a huge waste of energy because of the non-receptivity of the traction power systems for the regenerative energy during the braking regime of the traction motors.

In order to increase the energy efficiency in the DC-traction substations, several solutions are reported in the literature, involving the use of specific static converters, such as static VAR compensators and active power filters [1]-[12].

The flexible and performant shunt active power filter (SAPF) is the most common solution to improve the power quality in traction regime [3]-[6]. As the control algorithm is a key factor, different approaches were formulated, most of them based on synchronously rotating reference frame [3], direct power control [4], or the so-called p-q theory of the powers [5].

On the other hand, in order to send the energy resulted during the braking regime into the power supply, the bidirectional power flow between the DC and AC networks must be ensured. To transform the existing DC-traction substations into reversible substations, controlled converters should be used instead of diode rectifiers [7], [8].

Additional capabilities can be obtained for the DC-traction substation by connecting a regeneration system to the already existing traction transformer, in parallel with the diode rectifier. In [9], a voltage source inverter is coupled in the traction transformer secondary and, on the DC-side, a boost chopper is inserted.

In this paper, the attention is directed to the control system of an active DC-traction substation with 12-pulse diode rectifier which is obtained by adding a SAPF, together with proper connecting circuits, between the catenary line and AC-line [10]-[12]. Both the improvement of the power quality and the reuse of the kinetic braking energy are allowed.

The remaining paper is organized as follows. Section II describes the structure of the system, including the control part. The next section introduces the Fryze-Buchholz-Depenbrock (FBD) theory as a tool for current decomposition and its application in the generation of the reference current. In Section IV, the conceived Simulink model of the whole active DC-traction substation is presented. The performances of the system for active filtering and regeneration in terms of power quality aspects and energy efficiency are then illustrated. The main conclusions and further research are emphasized at the end of the paper.

II. Configuration of the Active DC-Traction Substation

As shown in the left side of Fig. 1, the existing DC-traction substation consists of the traction transformer (TT) with wye and delta connections in the two secondary windings and a 12-pulse diode rectifier.

The system for active filtering and regeneration named SISFREG is conceived around a SAPF to allow the regeneration of the braking energy and to lead to an almost unity power factor during traction regime [10]-[12]. It is connected in parallel with the existing traction substation and coupled to the AC power supply by means of a recovery transformer.

It must be mentioned that, by connecting the SAPF directly in the secondary of the traction transformer, the magnitude of the voltage in the point of common coupling (PCC) would be too high compared to the voltage on the DC-side. A correct correlation between the two voltages is required in order to avoid an injected current of poor quality [13].

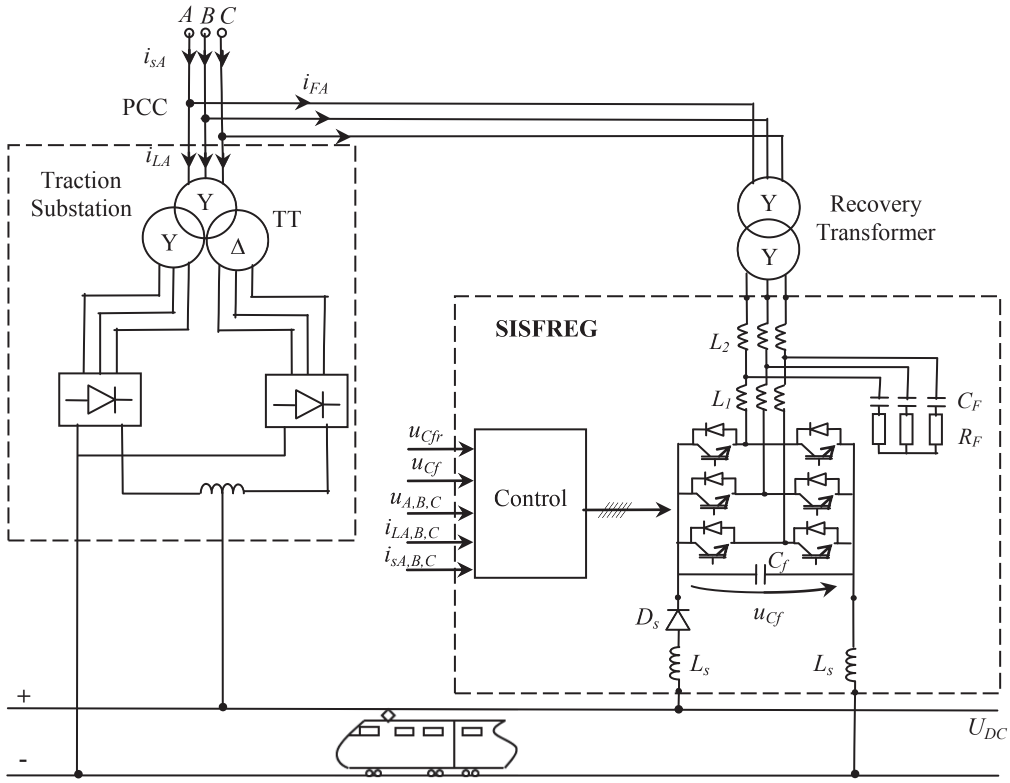

Fig. 1. Structure of the active DC-traction substation with twelve-pulse uncontrolled rectifier.

Indeed, the magnitude of the AC voltage in the traction transformer secondary ($\sqrt{2}U_s$) can be expressed as a function of the no-load average voltage at the output of the 12-pulse rectifier (U_{DC0}) as follows [14]:

$$\sqrt{2}U_s = \frac{\pi}{3} \cdot U_{DC0} \approx 1.05 \cdot U_{DC0} . \quad (1)$$

On the other hand, taking into account a voltage drop in the rectifier's output circuit of about 5 %, the no-load average voltage can be expressed by highlighting the rated DC voltage (U_{DCN}) as follows:

$$U_{DC0} \approx 1.05 U_{DCN} . \quad (2)$$

Consequently,

$$\sqrt{2}U_s \approx 1.1 \cdot U_{DCN} , \quad (3)$$

revealing the need of either decrease the voltage in PCC or increase the voltage on the DC-side.

By adopting an interface filter of third order (LCL type) provided with damping resistance, the behavior of the system against the high order switching harmonics is improved [15], [16].

As shown in Fig. 1, a separating circuit consisting of diode D_s and inductances L_s ensures the connection to the DC-traction line. In this manner, the natural transition between the active filtering and regeneration regimes is guaranteed and a correct dynamics of the current is ensured [12].

In the control part, the measured quantities are: the voltage across the compensation capacitor of SAPF (u_{Cf}), the voltages in PCC ($u_{A,B,C}$), the supply currents upstream PCC ($i_{sA,B,C}$) and the currents in the traction transformer primary ($i_{LA,B,C}$).

As illustrated in the principle control scheme of Fig. 2, the control of the current injected into PCC by SAPF via the recovery transformer is performed in indirect mode, by means of the current upstream PCC. Thus, the measuring of the SAPF's currents is not required.

First, the prescribed voltage on the DC-side must be ensured by an active component of the current provided at the output of voltage controller (i_{sru}) [17]. The measured voltages in PCC are needed too, to generate the shape of these currents.

On the other hand, to improve the waveform of the current drawn from the power supply in traction regime and compensate the reactive power, the associated component of the reference current (i_{src}) is generated according the the FBD-theory concepts. Detailed information are given in Fig. 3 and next section.

It must be noticed that, during the operation in regeneration mode, the traction rectifier is blocked due to the increased voltage on the DC-side and, consequently, only reference current i_{sru} exists.

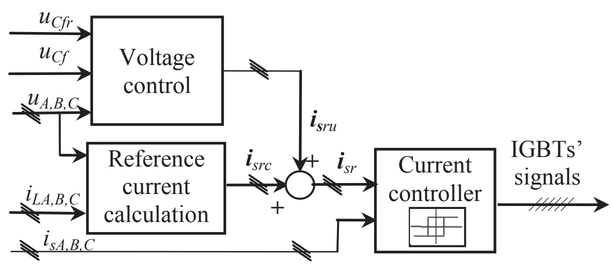

Fig. 2. Simplified structure of the control block.

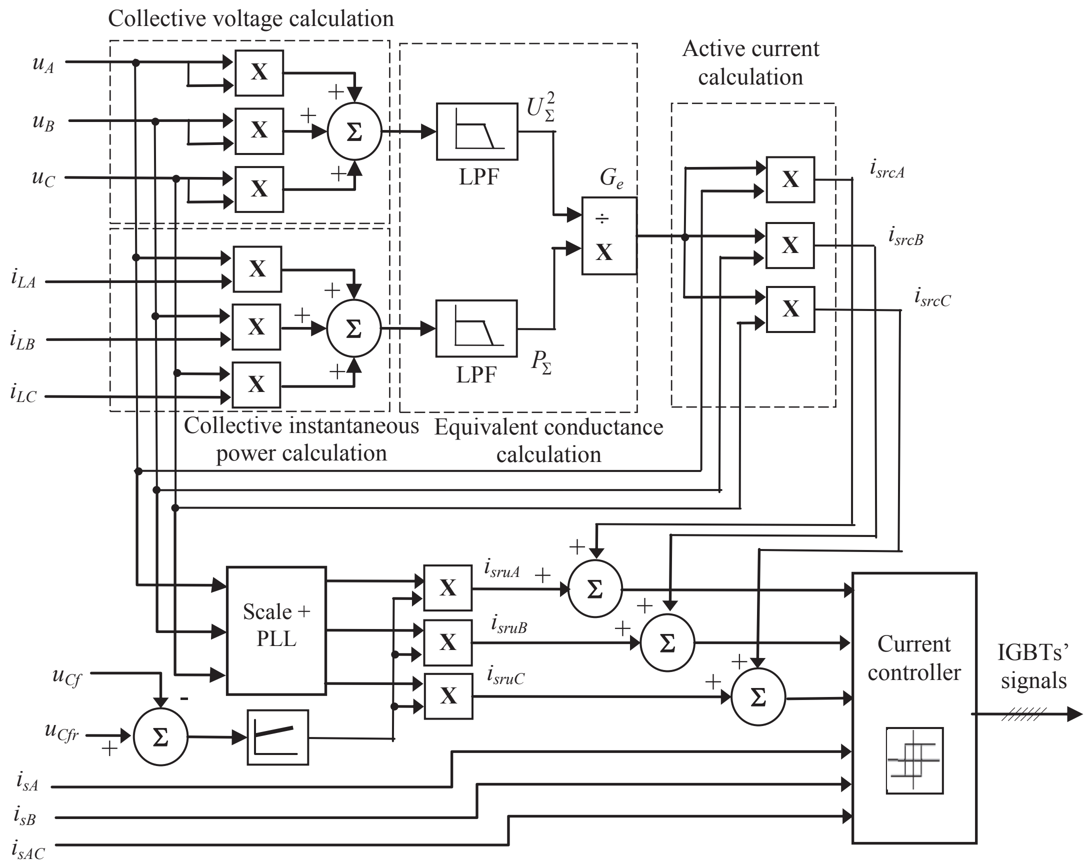

Fig. 3. Detailed structure of the control block based on FBD-theory concepts.

III. FRYZE-BUCHHOLZ-DEPENBROCK THEORY - A TOOL FOR CURRENT DECOMPOSITION

The mathematical foundation of the so-called Fryze-Buchholz-Depenbrock theory attracted the researchers' attention in the field of the shunt active power filters control. Concretely, the algorithm of the compensating current generation includes the current components defined in the FBD theory [2], [18]-[22].

The FBD time-domain theory was originally proposed in 1931 by S. Fryze for single-phase circuits, and then successively enhanced by F. Buchholz (in 1993) and M. Depenbrock (in 1993) [19], [23].

In accordance with FBD theory, the active components of the currents in the traction transformer primary are calculated as follows:

$$i_{LaA} = G_e \cdot u_A\,;\quad i_{LaB} = G_e \cdot u_B\,;\quad i_{LaC} = G_e \cdot u_C\,, \tag{4}$$

where G_e is the equivalent conductance,

$$G_e = \frac{P_\Sigma}{U_\Sigma^2}\,. \tag{5}$$

The quantities used in expression (5) denote:

- the square of the collective rms voltage in the three-phase system,

$$U_\Sigma^2 = \frac{1}{T}\int_{t-T}^{t} u_\Sigma^2 \cdot dt\,, \tag{6}$$

where the collective instantaneous voltage (u_Σ) is:

$$u_\Sigma = \sqrt{u_A^2 + u_B^2 + u_C^2}\,; \tag{7}$$

- the collective active power (P_Σ),

$$P_\Sigma = \frac{1}{T}\int_{t-T}^{t} p_\Sigma \cdot dt\,, \tag{8}$$

where the collective instantaneous power (p_Σ) is:

$$p_\Sigma = u_A i_{LA} + u_B i_{LB} + u_C i_{LC}\,. \tag{9}$$

As shown in Fig. 3, U_Σ^2 and P_Σ can be calculated by means of low pass filters (LPFs) as the DC components of the associated instantaneous quantities.

The remaining components of the currents in the primary of the traction transformer are non-active components, i.e.:

$$i_{Lnk} = i_{Lk} - i_{Lak}\,;\quad k = A, B, C. \tag{10}$$

From the compensation point of view, the active components given in (4) are the reference currents and the non-active components given in (10) are related to the compensating currents, that is:

$$i_{srcA} = i_{LaA}\,;\quad i_{srcB} = i_{LaB}\,;\quad i_{srcC} = i_{LaC}\,; \tag{11}$$

$$i_{FrA} = -i_{LnA}\,;\quad i_{FrB} = -i_{LnB}\,;\quad i_{FrC} = -i_{LnC}\,. \tag{12}$$

IV. SIMULINK MODEL OF THE ACTIVE DC-TRACTION SUBSTATION

The entire active DC-traction substation has been modeled under the Matlab-Simulink environment (Fig. 4). The active currents calculation is implemented in the block “FBD”, whereas “Control block” includes the voltage and current control loops and provides the gating signals for the the inverter’s IGBTs.

The model of the existing traction substation with 12-pulse parallel rectifier DC-traction contains a Y/y/d traction transformer of rated power of 3.2 MVA and 1.2 kV in each secondary and the two uncontrolled bridge rectifiers connected by reverse magnetically coupled inductances. The rated voltage of the DC traction line is 1500 V.

The Y/y recovery transformer has the rated power of 2.2 MVA and the rated voltages of 820 V/ 33 kV.

Both the compensation capacitor of 100 mF and the separating circuit (L_s = 40 µH) are included in the block “DC-link”.

As regards the DC-traction line, during the traction regime,it behaves as an active load with a back electromotive force corresponding to the operation speed, an equivalent resistance and an equivalent inductance. In regeneration mode, the maximal DC-line voltage is maintained and a constant acceleration is imposed, so that the DC-line current is constant.

The LCL interface filter with damping resistance is characterized by L_1=21.5 µH; L_2=0.21 mH; C_F=29 µF; R_F=4.3 Ω.

In the voltage control loop, the proportional constant and integrative time constant of the PI controller are: K_p=14.07; T_i=7.89·10^{-4} s. A hysteresis band (0.5 A) current controller regulates the current upstream PCC.

V. PERFORMANCE OF THE ACTIVE DC-TRACTION SUBSTATION

The developed model for the DC-traction substation (Fig. 4) has been used to verify the proper operation of the whole system through simulation. Moreover, the performance of SISFREG has been assessed in both operation regimes of the system.

As shown in Fig. 5, the operation in traction regime of the traction substation occurs till t=0.4 s. During the first time interval (about 0.14 seconds), the DC-capacitor is charging and reaches the set value of 1783V (i.e. about 10 % higher than U_{DC0}), which is maintained during the whole operation period. At t=0.4 s, the transition to the regeneration regime is correlated with the increase of the DC-line voltage. A constant acceleration is imposed, so that the DC-line current is constant and the maximal DC-line voltage is handled (maximal 1800 V). The overshoot of DC-line is below 3%. It can be seen that, when the system passes again into the filtering regime (t=0.55 s), the overshoot is higher (below 20%). Fig. 6 shows the nonsinusoidal currents drawn by the traction transformer from the power supply during the traction regime.

The associated harmonic distortion factor factor (*THD*) is of about 11.91%. This value is determined mainly by the presence of harmonics up to order 37 (Fig. 7). There is a small amount of reactive power, so that the global power factor is of about 0.988.

The collective active power and equivalent conductance calculated in accordance with the FBD theory (Fig. 8) lead to the active and non-active components of the current illustrated in Figs. 9 and 10.

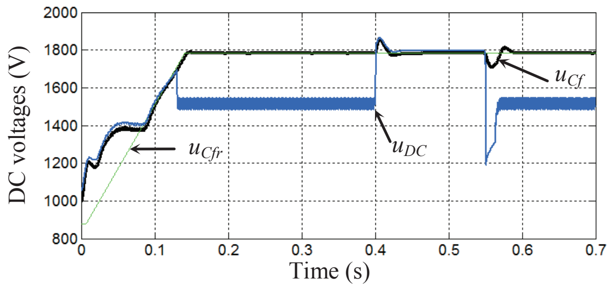

Fig. 5. The DC-line voltage (in blue) along with the compensation capacitor voltage (in black) and its set value (in green).

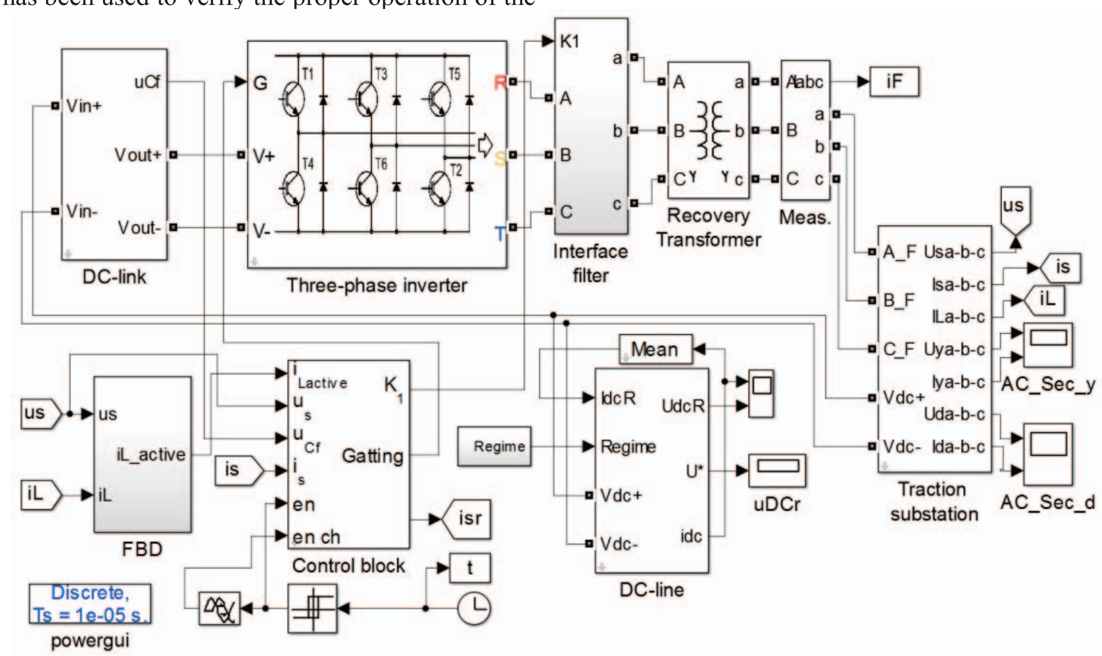

Fig. 4. The Simulink model of the active DC-traction substation with twelve-pulse uncontrolled rectifier..

As expected, the active components of the current in the traction transformer primary are sinusoidal (Fig. 9).

The distorted non-active components of the three currents (Fig. 10) will be the currents needed to be injected in PCC in order to compensate the harmonic distortion and reactive power.

As it can be seen in Figs. 5 and 11, the voltage control circuit succeeds in keeping this prescribed voltage across the compensation capacitor, which is imposed to be by 10 % higher than U_{DC0}.

When looking at the currents upstream PCC in traction regime (Fig. 12), their waveforms are almost sinusoidal (THD = 2.62 %) and the harmonic content hardly can be seen (Fig. 13), which confirms the operation of SISTREG in active filtering mode. The active filtering efficiency, in terms of ratio of THD values before and after compensation, is of about 4.5.

Moreover, by compensating the reactive power in addition to the current harmonics, the power factor becomes very close to unity (PF = 0.999).

The waveforms of the three currents in phase A of PCC (Fig. 14) confirm once again the proper operation of the active DC-traction substation during the traction regime.

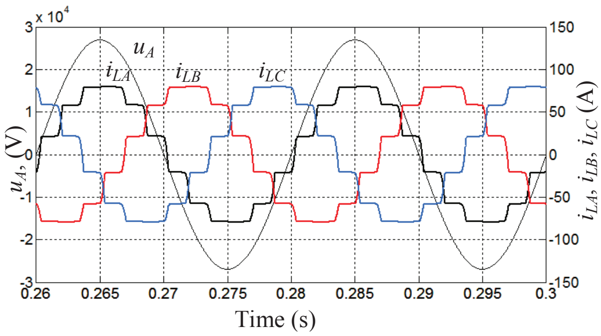

Fig. 6. Currents and voltage on phase A in the TT's primary.

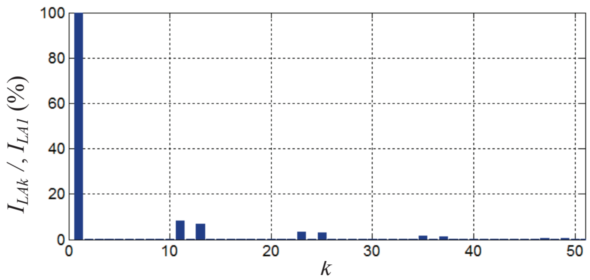

Fig. 7. Harmonic spectrum (p.u.) of the current in the TT's primary.

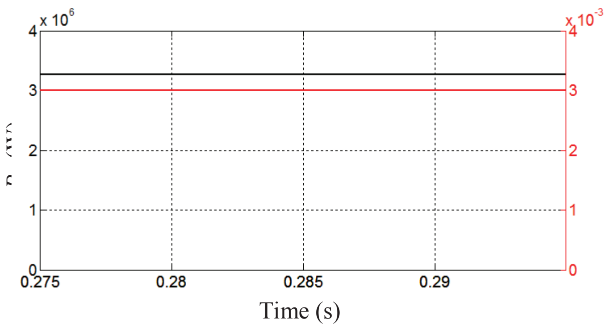

Fig. 8. Collective active power and equivalent conductance.

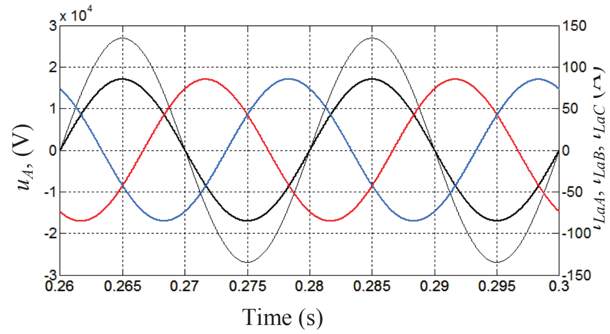

Fig. 9. Active components of the currents and voltage on phase A in the TT's primary.

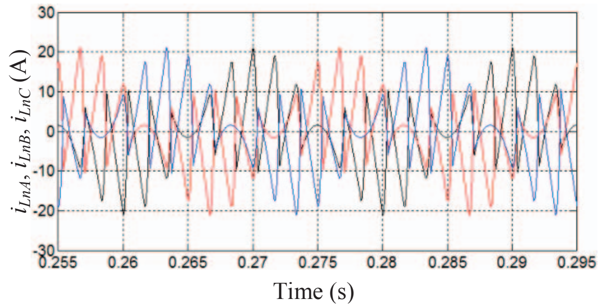

Fig. 10. Non-active components of the currents in the TT's primary.

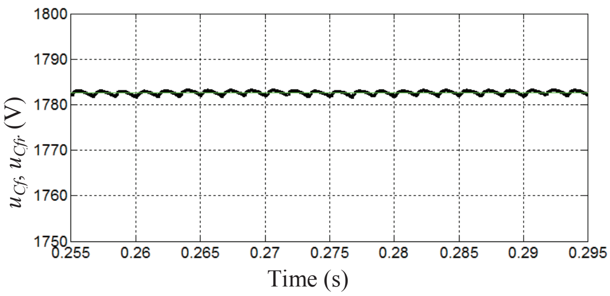

Fig. 11. Voltage across the compensation capacitor and its set value.

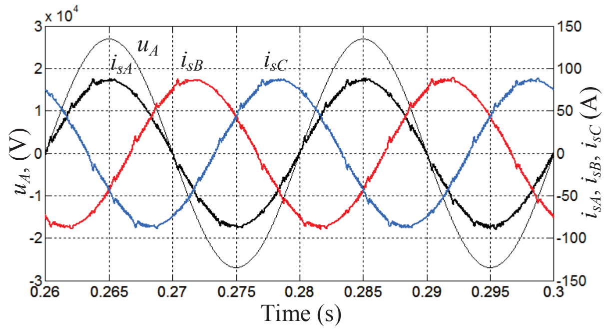

Fig. 12. Currents and voltage on phase A upstream PCC during the operation in traction regime.

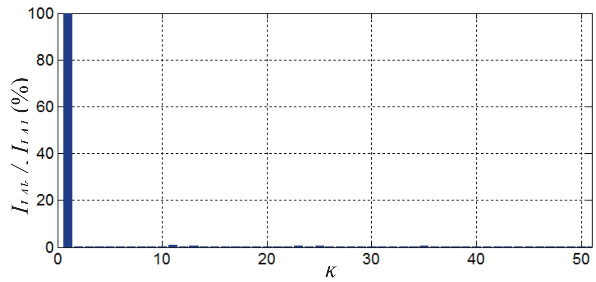

Fig. 13. Harmonic spectrum (p.u.) of the current upstream PCC during the operation in traction regime.

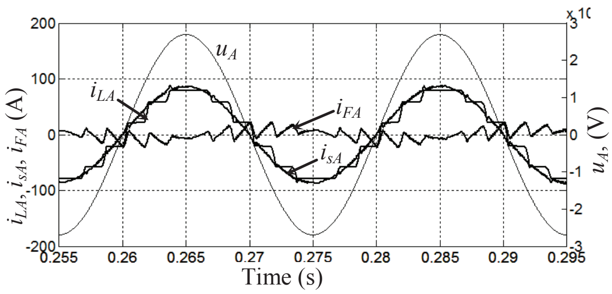

Fig. 14. Currents in phase A of PCC and phase voltage during the operation in traction regime.

When the transition to the braking regime occurs (t = 0.4 s), due to the DC-line voltage increasing (Fig. 5), the separating diode D_s is forward biased and the traction rectifier is blocked. SISFREG operates in regeneration mode.

The waveform of the current in the traction transformer primary when the system operates in successive regimes of traction and regeneration illustrates the blockage of the traction rectifier in traction regime (Fig. 15).

In order to track the reference current whose components are shown in Fig. 16, SISFREG injects a proper current in PCC (Fig. 17). Fig. 16 illustrates that, during the active filtering regime of SISFREG, the component i_{sru} of the prescribed active, which comes from the output of the voltage control block and corresponds to the power losses covering, represents about 5.7 % of the prescribed active component i_{src} provided by the FBD-based reference current calculation block.

As shown in Fig. 18 and Fig. 19, the resulted supply current upstream PCC is almost sinusoidal in both steady-state regimes and it has the same phase as the supply voltage.

As it is clear from Fig. 18, during the regeneration mode, there is a phase-opposition between the currents upstream PCC and the associated voltages.

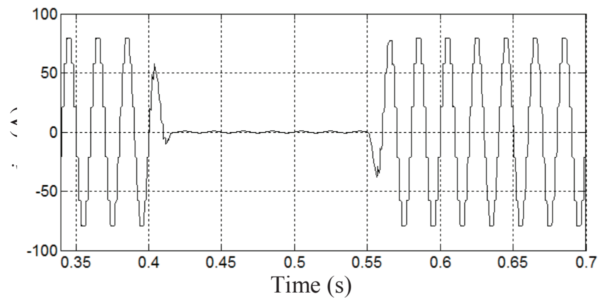

Fig. 15. Current on phase A in the primary of traction transformer when the system operates in successive regimes of traction and regeneration.

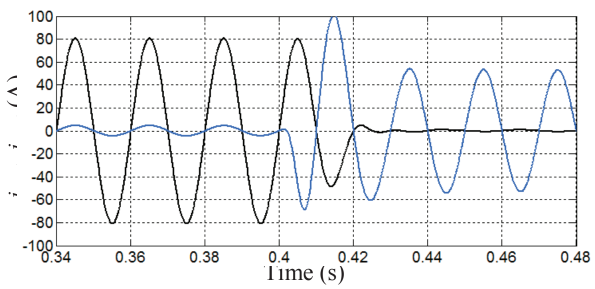

Fig. 16. The two components of the reference current on phase A during two successive regimes: i_{srcA} (in black); i_{sruA} (in blue).

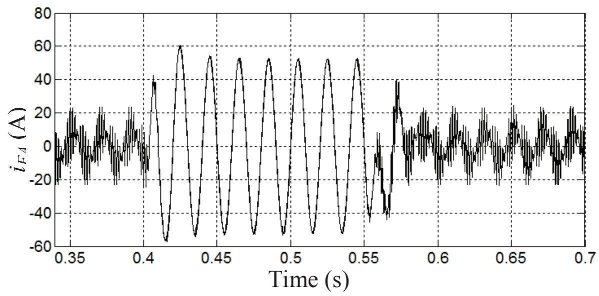

Fig. 17. Current on phase A injected by SISFREG in PCC when the system operates in successive regimes of traction and regeneration.

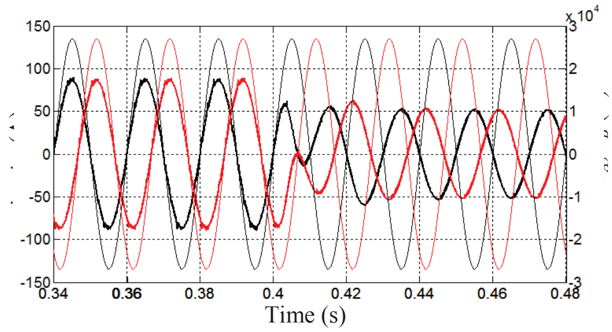

Fig. 18. Currents (thick line) and phase voltages (thin line) on phases A (in black) and B (in red) upstream PCC during two successive traction and regeneration regimes.

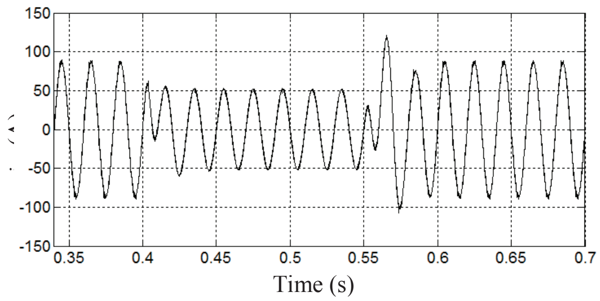

Fig. 19. Current on phase A upstream PCC when the system operates in successive regimes of traction and regeneration.

The active power at the power supply side shown in Fig. 20 highlights the injection of a significant amount of active power during the regenerative braking regime of the traction motors.

Figs. 5, 15, 17 and 19 illustrate a more lasting dynamic regime when SISFREG passes from regeneration mode to active filtering mode, compared to the reverse transition.

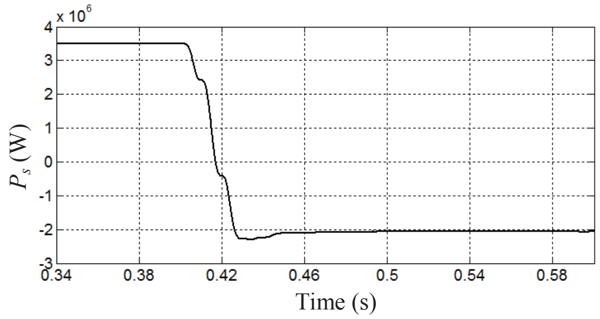

Fig. 20. Active power at the power supply side during the traction and regeneration regimes.

VI. Conclusions

The model-based analysis performed in this paper shows that the current decomposition provided by the Fryze-Buchholz-Depenbrock theory can be successfully used in the control of an active DC-traction substation with 12-pulse uncontrolled rectifier, when the indirect control of the current is adopted.

The complete Matlab-Simulink model of the system has been developed and the simulation conducted for the operation in successive regimes of traction and regenerative braking accompanied by power quality analysis show the proper behavior and good energetic performances.

Specifically, there is an almost sinusoidal current at the power supply side, whose harmonic distortion factor is below 3 % in both operation regimes and almost unity power factor is achieved. Thus, the supply current is within the limits stipulated in the IEEE-519 recommendations [24].

Moreover, the natural transition between the two operation regimes is ensured.

In the further research, the proposed control algorithm will be implemented on a dSPACE control board working under Matlab/Simulink environment, within an experimental setup of small scale.

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).

Received on July 26, 2016
Editorial Approval on November 15, 2016

References

[1] T. Rekha, A. Bisharathu Beevi, “Power quality control in DC traction systems using static var compensator and harmonic filter,” *International Journal of Engineering Research & Technology*, vol. 3, issue 10, pp. 733-740, Oct. 2014.

[2] Z. Sun, X. Jiang, D. Zhu, and G. Zhang, “A novel active power quality compensator topology for electrified railway,” *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 1036–1042, Jul. 2004.

[3] 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*, issue 10, pp. 1974-1979, Oct. 2013.

[4] A. Bueno, J.M. Aller, J. Restrepo, and T. Habetler, “Harmonic and balance compensation using instantaneous active and reactive power control on electric railway systems,” *Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition*, 2010, pp. 1139 – 1144.

[5] 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,” *International Conference on Power Engineering, Energy and Electrical Drives* (POWERENG), 11-13 May 2011, pp. 1-5.

[6] A.M. Rezkalla, “Active filters application for metro a.c substations,” *23 rd International Conference on Electricity Distribution,* Lyon, 15-18 June 2015

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

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

[9] 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.

[10] Mihaela Popescu, A. Bitoleanu, V. Suru, and A. Preda, “System for converting the dc traction substations into active substations,” in *Proc. 9th International Symposium on Advanced Topics in Electrical Engineering* (ATEE 2015), May 2015, pp. 632-637.

[11] Mihaela Popescu, A. Bitoleanu, and V. Suru, “Indirect current control in active DC railway traction substations,” in *Proc. ACEMP-OPTIM-ELECTROMOTION Joint Conference*, Sept. 2015, pp. 192-197.

[12] Mihaela 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. SPEEDAM* 2016, Capri, Italy, June 2016, pp. 1180-1185.

[13] A. Bitoleanu, Mihaela Popescu, *Filtre active de putere*, Universitaria Craiova, 2010.

[14] A. Bitoleanu, S. Ivanov, Mihaela Popescu, *Convertoare statice*. INFOMED Craiova, 1997.

[15] Mihaela Popescu, A. Bitoleanu, and V. Suru, “On the design of LCL filter with passive damping in three-phase shunt active power filters,” in *Proc. SPEEDAM* 2016, Capri, Italy, June 2016, pp. 826-831.

[16] Mihaela Popescu, A. Bitoleanu, 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* (PEMC) 2016, Varna, Bulgaria, Sept. 25-30, 2016, pp. 868-873.

[17] Mihaela Popescu, A. Preda, and V. Suru, “Synchronous Reference Frame Method Applied in the Indirect Current Control for Active DC Traction Substation,” *Athens: ATINER'S Conference Paper Series*, No: TRA2015-1552, pp. 1-14, Aug. 2015.

[18] V. Staudt, “Dynamic parallel compensation of active non-linear loads using the FBD-method,” in *Proc. 7th International conference on harmonics and quality of power* (ICHQP VII), Las Vegas, USA, 1996, pp. 21-26.

[19] M. Depenbrock and V. Staudt, “The FBD-method as tool for compensating total nonactive currents,” in *Proc. 8th IEEE ICHQP’98 Conf.*, Athens, Greece, 1998, pp. 320–324.

[20] J. Kang, J. Y. Zheng and W. Zeng, “Application of FBD-method to real time current detection in three-phase four-wire system,” *Electric Power Automation Equipment*, vol. 26, no. 8, 2006.

[21] Z. Y. Guo, Y. Q. Zhou and L. M. Guo, “Current detection for four-phase transmission system based on FBD Method”, in *Proc. of the Chinese Society for Electrical Engineering*, 2007.

[22] A. Bitoleanu and Mihaela Popescu, “Shunt active power filter: Overview on the reference current methods calculation and their implementation,” *4th International Symposium on Electrical and Electronics Engineering* (ISEEE 2013), Galati, Romania, 2013, pp.1-12.

[23] M. Depenbrock, “The FBD-method, a generally applicable tool for analyzing power relations,” *IEEE Trans. Power Syst*., vol. 8, pp. 381–387, May 1993.

[24] IEEE recommended practice and requirements for harmonic control in electrical power systems, *IEEE Std. 519-1992.*