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CONFIGURING AND PERFORMANCES OF REVERSIBLE DC-TRACTION SUBSTATIONS WITH COMPENSATION CAPABILITIES

BY

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Abstract. This paper is focused on the transforming the existing DC-traction substations with diode rectifiers into reversible substations with compensation capabilities. By adding a voltage source inverter-based active power filter between the DC-traction line and the AC-side, the required capabilities are ensured. Thus, in the traction regime of the DC-motors, the power quality is much improved by reducing the harmonic distortion factor of the current drawn from the power supply bellow the limit of 5 % provided by standards under almost unity power factor, whereas, in braking regime, an almost sinusoidal active current is injected into the power supply. The possibilities of coupling on both DC and AC sides are discussed, including design aspects of the coupling filters. Of the possible methods of control, the indirect control of the inverter AC-side current by means of supply current upstream the point of common coupling is the adopted solution. The good performance of the whole system is proven by simulation and experiment for the case of a DC-traction substation with 6-pulse diode rectifier.

Key words: DC-traction; active filtering; regeneration; indirect control, LCL filter.

1. Introduction

Most of the existing traction systems are equipped with DC-motors fed by the three-phase medium or high voltage power supply via traction

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substations (TSs) including traction transformers and uncontrolled rectifiers with six or twelve pulses. Thus, during the operation in traction regime of the motors, a non-sinusoidal current is drawn by the traction transformer from the power supply and there is an amount of absorbed reactive power. Moreover, when the operation in braking regime is required, only a small amount of the resulted electrical energy from the kinetic braking energy is reused by the auxiliary services. Of the remaining recovered energy, another part is used by nearby accelerating vehicles on the same line, if they exist, and the rest must be dissipated in braking resistors. Typically, in a metro network, the energy transfers between vehicles amount to 20,…,30% of the total consumption (Devaux, 2011).

In these conditions, two ways to increase the energy efficiency have been identified. The former is related to the operation in traction regime and consists of improving the power quality at the power supply side by active power filtering (Gunavardhini, 2016; Hosny, 2013). The active power filters (APFs) have proven their outstanding performance by reducing the harmonic distortion of the supply current, so that it falls within the current harmonic pollution norms, and ensuring the reactive power compensation. The results is an almost unity power factor at the power supply side. The latter is to recover the kinetic energy of the braking process as much as possible. The solutions implemented so far include storage in mobile or fixed equipment such as batteries or supercapacitors (Hayashiya, 2013; Suzuki, 2014) and the use of static converters to allow the recovered electrical energy to be transferred back into the power supply (Bae, 2005; Chuang, 2005; Cornic, 2010; de Jager, 2014; Ortega, 2011) and which, in most cases, require the replacement of the existing uncontrolled rectifier in the traction substation.

The system for active filtering and regeneration proposed and presented in this paper transforms an existing DC-traction substations in an active traction substation (ATS), based on a voltage source inverter (VSI) properly connected and controlled. It means that a reversible DC-traction substation with compensation capabilities is obtained. Concretely, sinusoidal currents under unity power factor conditions are drawn from the power supply in traction regime and injected into the power supply in braking regime.

The remaining of the paper is organized as follows. Section **2** introduces the structure of the system for active filtering and regeneration. Then, some design particularities are presented in Section **3**, followed by the substantiation of the control system in Section **4**. The performance assessment and validation are the subject of the Section **5**. The final section presents the main conclusions.

2. Setting-up the Structure of the Active DC-Traction Substations

In the foundation of the structure of the active traction substation (Fig. 1), it was assumed that the VSI-based active power filter is the basic structure.

In addition to the well-known function of harmonic filtering and reactive power compensation, it must also perform the function of sending to the AC power supply the active power recovered in the braking process of the train, in the form of a active sinusoidal current. It results that the system can operate in the following three regimes correlated with the operating modes of the traction substation:

1. Standby mode, when there is no train on the line powered by the traction substation or it is at rest.

2. Active filtering mode, when the traction substation provides to the DC-line the ative power required to drive the train in traction mode.

3. Regeneration mode, when the train is in braking mode and the traction rectifiers are blocked.

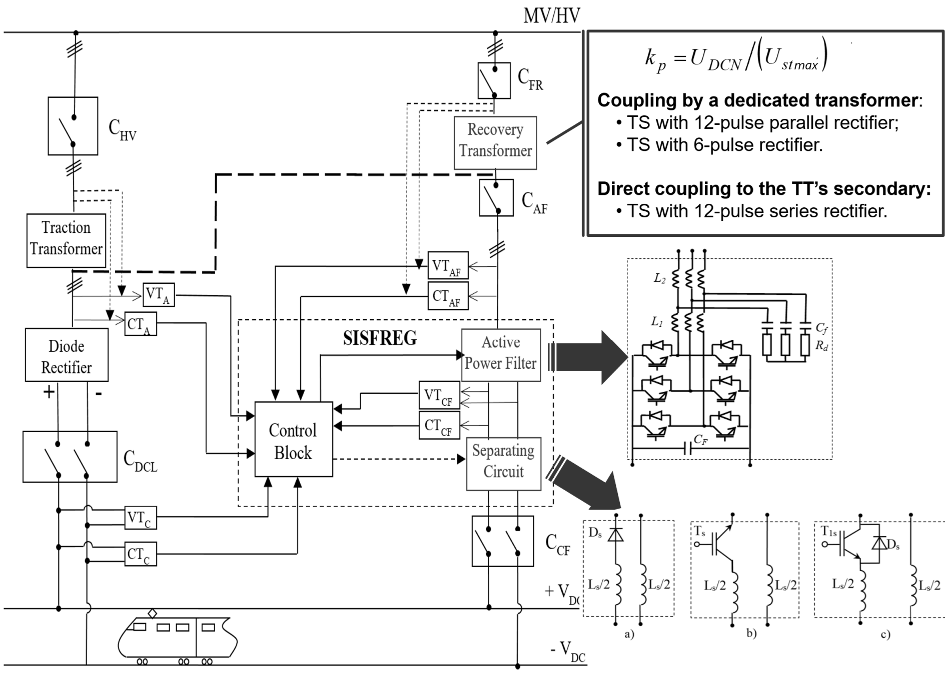


Fig. 1 – Block diagram of a reversible DC-traction substation with compensation capabilities.

Designed with IGBTs and connected properly, the active power filter has the intrinsic capability to provide an increased voltage of required value on the DC-side, which is required for the correct operation of the system in terms of the quality of the injected current.

The way of connection to the AC-side resulted from the analysis of the recovery and compensation capacity of the existing traction substations (Popescu, 2015). Thus, on the basis of an indicator k_p calculated as the ratio of the nominal DC-line voltage (U_{DCN}) and the magnitude of the AC-voltage in the secondary of the traction transformer (U_{stmax}),

$$k_p = U_{DCN} / U_{st\max} \,, \tag{1}$$

it has been proven that the needed over unity values are obtained only in the case of 12-pulse series rectifier. It means that the premise of obtaining a high quality AC-current through the connection in the TT's secondary is created only in the case of a substation provided with this type of rectifier. In the case of TSs provided with 6 or 12-pulse parallel rectifiers, adapting the voltage in the point of common coupling (PCC) to the nominal DC-line voltage is required. The use of a dedicated coupling transformer is the adopted solution in our approach.

Whatever the PCC and the AC-connection solution, by adding a passive filter of LCL type to the APF's AC-side, the influence of IGBTs' switching on the current injected in PCC is greatly reduced (Popescu, 2016b; Popescu, 2017).

As regards the connection of APF with the DC-line, the fulfillment of the requirements for the transition and operation in regeneration regime is ensured by a separation circuit, for which three structures with semiconductor power elements were grounded (Fig. 1). It is necessary to have an inductance as an energy buffer, which also ensures good dynamics of the current. Besides this, the simple addition of a separating diode (structure a)) ensures the natural disconnection of APF from the DC-line during the operation in traction regime, when the compensation function is performed (Popescu, 2016a). An IGBT can be also used to add some control capabilities (structures b) and c)).

In the foundation of the control structure, the indirect control of the current injected by APF, by means of the current upstream PCC regulation, has been adopted as a simple solution with good performance (Bitoleanu, 2016), (Bitoleanu, 2017; Popescu, 2015; Preda, 2015; Suru, 2015).

3. Design Particularities

To get the best performance of the system in both operating modes, some design criteria and particularities resulted from the conducted research.

The design features result from the high power of such a system, the need for operation in any operation mode and the required associated performance, respectively unity power factor and a harmonic distortion of the current upstream PCC below 5% in both active filtering and regeneration modes.

Fortunately, the current evolution of power electronics makes it available on the market IGBTs with voltage class over 2300 V and current over 1500 A.

Concerning the passive DC and AC connection circuits, important design features have resulted.

In the design of the DC-separating circuit, it was taken into account that it works in correlation with the compensation capacitor, but only during the regeneration mode, when the diode it contains is forward biased. Thus, conditions of achieving the objective of limiting the p.u. ripples of voltage and current on the DC-side (ε_u and ε_i) led to the proper design of the compensation capacitor and the separating inductance, respectively (Popescu & Bitoleanu, 2016a):

$$C_F \geq \frac{T_s P_{Nrec}}{\eta_r U_{CN}^2 \varepsilon_u}; \tag{2}$$

$$L_s \geq \frac{\eta_r T_s U_{CN}^2 \varepsilon_u}{4 P_{Nrec} \varepsilon_i}, \tag{3}$$

where: T_s is the period corresponding to the switching frequency, P_{Nrec} – the recovered rated power, η_r – the recovery electric efficiency, and U_{CN} – the rated DC-capacitor voltage.

The passive filter of LCL type with damping resistance on the AC-side of APF has peculiarities arising from the following functions it has to fulfill:

– ensuring the unaltered flow of all harmonics to be compensated by active filtering, which are contained in the prescribed compensating current;

– preventing the harmonics due to IGBTs switching from propagating into the power supply.

In our approach, the design of the coupling filter is based on the fact that APF behaves like a current source that provides a harmonic current to the passive broadband filter. Accordingly, information on the quality of the interface filter is provided by two transfer functions related to currents, i.e. input current – output current and input current - current through the capacitor C_f of the filter, respectively.

A first useful result in designing the LCL filter is that the amplification and the resonance frequency depend only on the pairs $R_d C_f$ and $L_2 C_f$ (Popescu & Bitoleanu, 2016b):

$$|G_1(j\omega)| = \left|\frac{I_2(s)}{I_1(s)}\right| = \sqrt{\frac{1+\left(R_d C_f\right)^2 \omega^2}{(1-L_2 C_f \omega^2)^2 + \left(R_d C_f\right)^2 \omega^2}}, \tag{4}$$

$$\omega_{res} = \frac{1}{R_d C_f}\sqrt{\sqrt{1+\frac{2\left(R_d C_f\right)^2}{L_2 C_f}} - 1}. \tag{5}$$

Highlighting a maximum loss on the damping resistance in relation to the damping resistance is another useful result in the design of the coupling filter, which has led to the definition of a performance indicator, with the meaning of an equivalent resistance – R_{ech} (Popescu & Bitoleanu, 2016b):

$$P_d / I_1^2 = 3R_d \frac{(\omega_{sw}^2 L_2 C_f)^2}{(1-\omega_{sw}^2 L_2 C_f)^2 + \omega_{sw}^2 R_d^2 C_f^2} = R_{ech}\,, \quad (6)$$

where: ω_{sw} is the switching angular frequency.

Another performance indicator, named magnitude performance indicator -*MPI* (Popescu & Bitoleanu, 2016b):

$$MPI = \sqrt{\sum_{k=1}^{N} \left(\left| G(j\omega_k) \right| / k \right)^2 \Big/ \sum_{k=1}^{N} \left(1/k^2 \right)}\,, \quad (7)$$

is used to evaluate the influence of imposing the attenuations A_N and A_{sw} on the magnitude of the harmonics to be compensated by active filtering.

To substantiate a design algorithm for the coupling filter, the conditions resulting from the functions it has to perform were taken into account (Popescu & Bitoleanu, 2016a, b), namely:

– the attenuation corresponding to the switching frequency must be above an imposed value A_{sw} ($A_{sw} < 0$):

$$20\lg\left| G_1(j\omega_{sw}) \right| = 10\lg \frac{1+\omega_{sw}^2 R_d^2 C_f^2}{(1-\omega_{sw}^2 L_2 C_f)^2 + \omega_{sw}^2 R_d^2 C_f^2} \le A_{sw}\,, \quad (8)$$

– the amplification corresponding to frequency f_N associated to the harmonic of the highest order (N) to be compensated must not exceed an imposed value A_N:

$$20\lg\left| G_1(j\omega_N) \right| = 10\lg \frac{1+\omega_N^2 R_d^2 C_f^2}{(1-\omega_N^2 L_2 C_f)^2 + \omega_N^2 R_d^2 C_f^2} \le A_N\,, \quad (9)$$

– the power losses on the damping resistance to be as low as possible and the value of *MPI* to be as close to 1.

The design algorithm in Fig. 2 illustrates the steps to get the filter parameters.

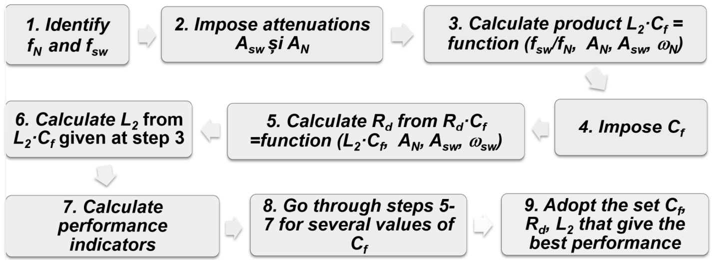


Fig. 2 – Flowchart of the design algorithm for the coupling passive filter.

4. Substantiation of the Control System

Arguments related to implementation and performance advantages, but also to the fact that the regenerative operation requires a supply current control loop, led to the conclusion that the most appropriate method of control is the indirect control, based on the output of the voltage control (Bitoleanu, 2016; Bitoleanu, 2017; Popescu, 2015; Suru, 2015). As shown in Fig. 3, a Proportional-Integrative (PI) voltage controller provides the magnitude of the reference active currents, while a block of synchronizing with the fundamental supply voltage provides the sine wave templates of these currents. Then, a hysteresis band current controller ensures the accurate tracking of the prescribed supply currents.

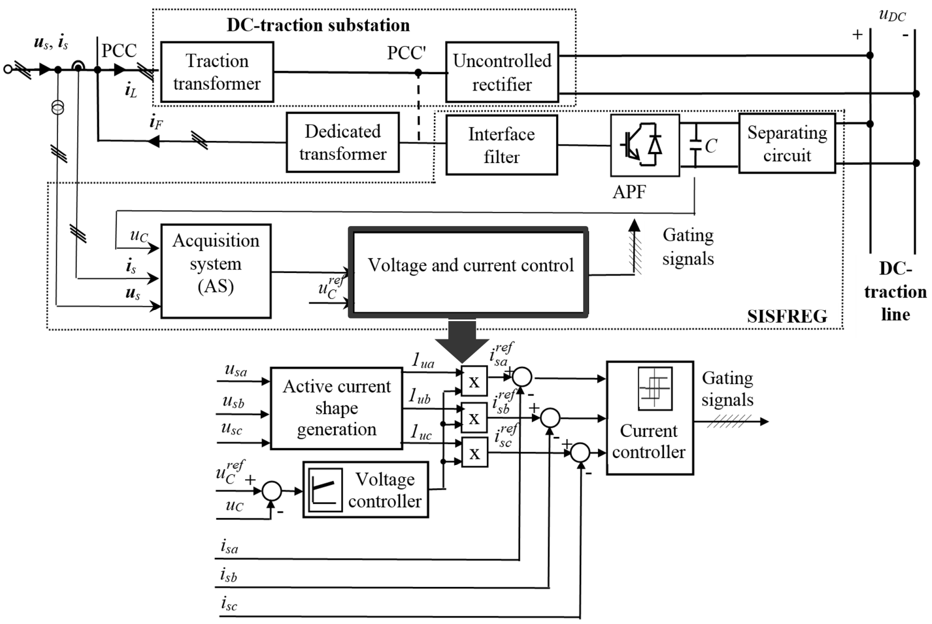


Fig. 3 – Structure of the indirect control system.

5. Performance Assessment and Validation

The performance of the conceived reversible traction substation, in terms of the harmonic distortion of the current upstream PCC and power factor at the supply side have been assessed in both simulation and experimental ways.

The results below correspond to the case of a reversible DC-traction substation with compensation capabilities, equipped with 6-pulse uncontrolled rectifier.

The main parameters of the system are summarized in Table 1.

Table 1

Main Parameters of the System

Parameters	Values
Rated apparent power	30 kVA
Rated supply voltage	380 V
Rated DC-line voltage	190 V
Compensation capacitance	2200 µF
Traction transformer (Y/y) parameters	380 V/150 V ; R_1=0.292 Ω; R_2=0.045 Ω; R_m=2.57 kΩ; $L_{σ1}$=1.5 mH ; $L_{σ2}$=0.23 mH; L_m=1.03 H
Recovery transformer (Y/d) parameters	380 V/130 V; R_1=0.966 Ω; R_2=0.337 Ω; R_m =566.83 Ω; $L_{σ1}$=3.1 mH; $L_{σ2}$=1.1 mH; L_m=4.682 H
LCL filter parameters	L_1=34 µH; C_f=10 µF; L_2=1.48 mH; R_d=27 Ω
DC-separating circuit inductance	4.9 µH
Current controller hysteresis band	0.75 A
Voltage controller parameters	K_p=3.53; T_i=1.8·10^{-3} s

A. Simulation results

Based on the conceived Matlab-Simulink of the whole system, the operation in traction regime, followed by the transition in braking regime (at t=0.6 s) and return to the traction regime (at t=0.8 s) have been simulated.

The time evolution of the voltage across the compensation capacitor together with the DC-line voltage (Fig. 4) illustrate the correct operation of the voltage control loop. The DC-capacitor voltage is kept to the prescribed value of 220 V, except during the unavoidable transient, and the DC-line voltage is limited during the braking regime.

As shown in Fig. 5, in traction regime, the currents absorbed by TT are distorted and their fundamentals lag the phase voltages, indicating a reactive power to be compensated. The harmonic spectrum (Fig. 6) illustrates the significant weight of harmonics of orders 5, 7, 11 and 13, leading to a total harmonic distortion factor (*THD*) of about 24%.

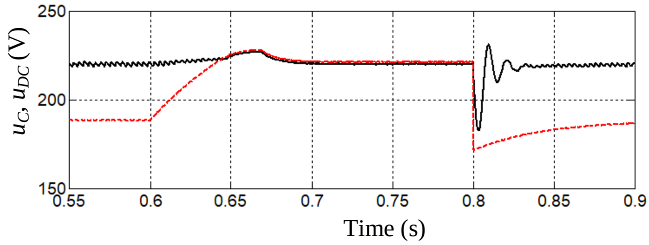


Fig. 4 – DC-capacitor voltage and DC-line voltage during successive operation in traction regime, braking regime, and return to the traction regime.

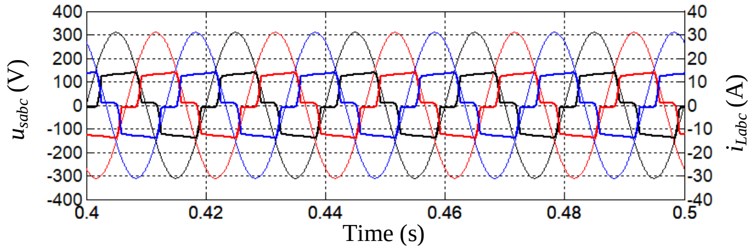


Fig. 5 – Supply phase voltages (u_{sa}, u_{sb}, u_{sc}) and currents in the primary of TT (i_{La}, i_{Lb}, i_{Lc}) in traction regime.

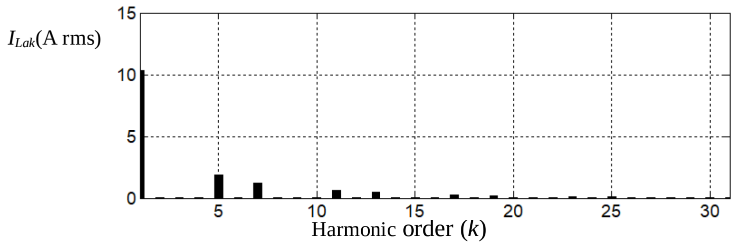


Fig. 6 – Harmonic spectrum of the current in the primary of TT in traction regime.

As a result of the proper currents injected by APF in order to compensate both harmonics and reactive power, the currents upstream PCC are in phase with the corresponding phase voltages and almost sinusoidal ($THD \approx \approx 2.4\%$) – Figs. 7 and 8.

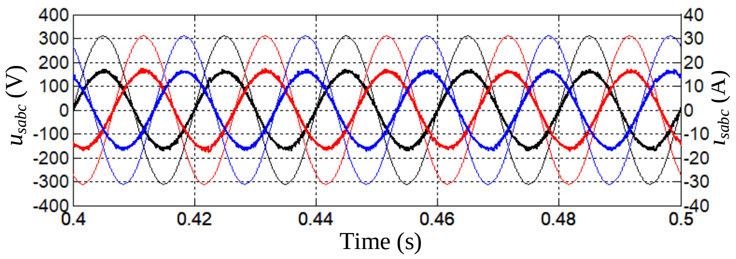


Fig. 7 – Supply phase voltages (u_{sa}, u_{sb}, u_{sc}) and currents upstream PCC (i_{sa}, i_{sb}, i_{sc}) in traction regime.

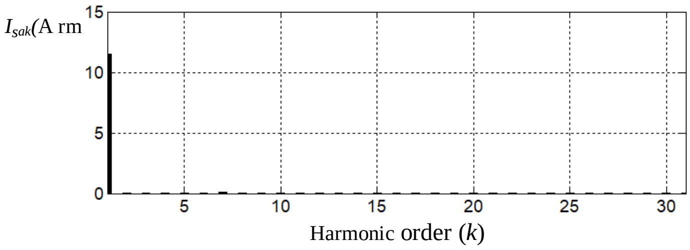


Fig. 8 – Harmonic spectrum of the current upstream PCC in traction regime.

As it can be seen in Figs. 9 and 10, during the braking regime of the traction motors, the supply currents upstream PCC are almost sinusoidal and in phase opposition with the corresponding voltages, meaning the operation in regeneration mode of the traction substation.

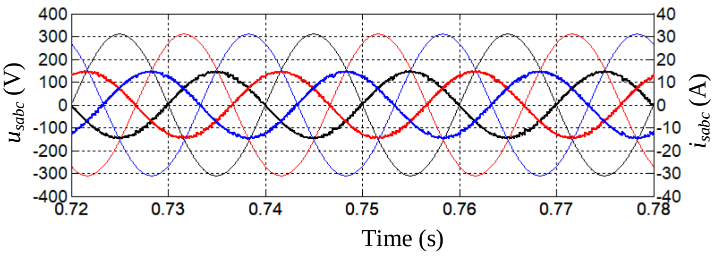


Fig. 9 – Supply phase voltages and currents upstream PCC in braking regime.

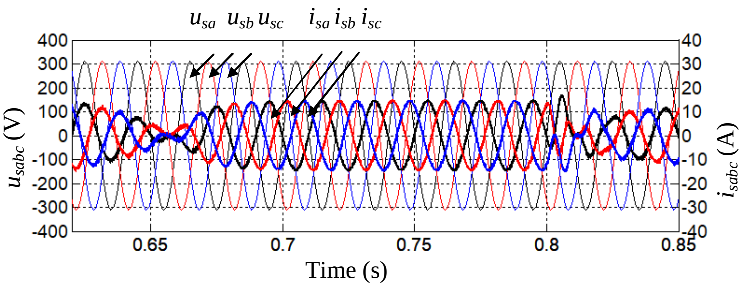


Fig. 10 – Supply phase voltages and currents upstream PCC during successive operation in traction regime, braking regime, and return to the traction regime.

B. Experimental results

A small scale laboratory setup has been conceived (Fig. 11) to verify the proper operation of the system. A synchronous machine was used as the equivalent of the vehicle. Its operation as a generator is equivalent to the traction regime, whereas the operation as a motor is equivalent to the braking regime. The real-time control has been implemented by using a dSPACE 1103 controller board working under the Matlab-Simulink environment.

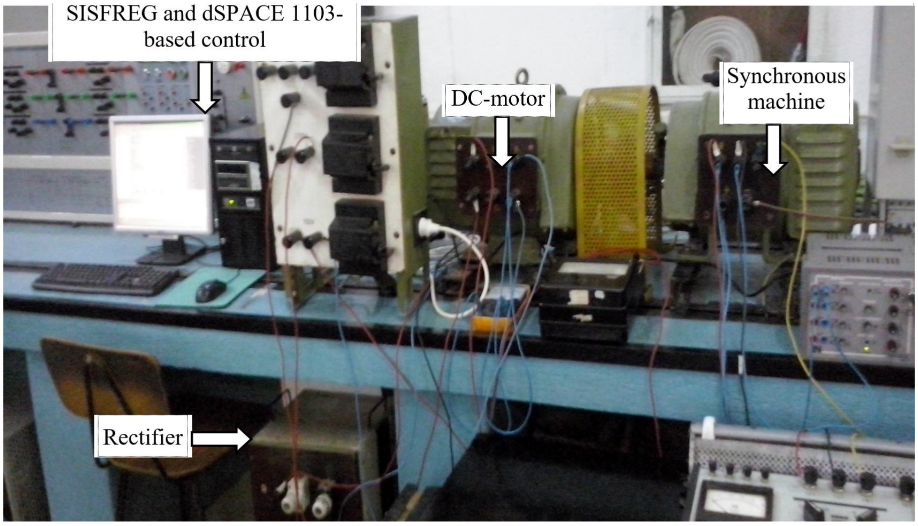
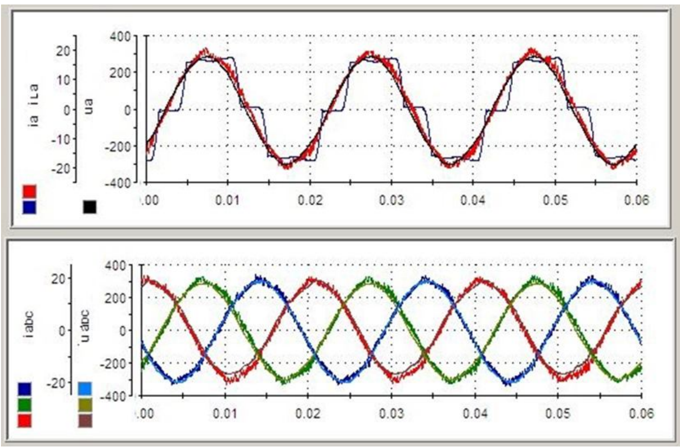


Fig. 11 – Picture of the laboratory setup.

The waveforms shown below (Figs. 12,…,14) are taken from the conceived Control Desk interface.



a

b

Fig. 12 – *a* – Currents in the TT's primary and upstream PCC; *b* – Supply voltages and current in active filtering mode.

As illustrated in Fig. 12, when active power is transmitted to the DC-motor through rectifier, the operation is in active filtering mode. The currents drawn from the power supply has the same phase as the voltages and a low harmonic distortion (*THD* ≈ 4.7%) due the IGBTs switching.

The DC-capacitor voltage accurately follows its set value, as depicted in Fig. 13.

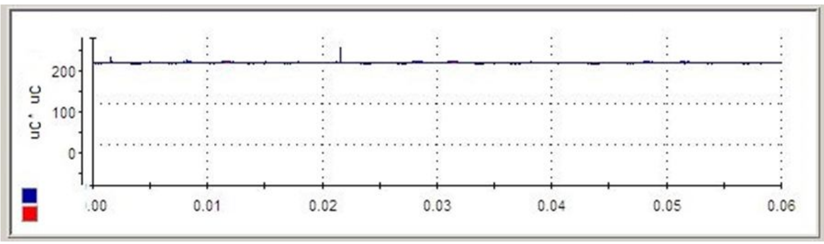


Fig. 13 – DC-capacitor voltage and its prescribed value in active filtering mode.

In regeneration-mode, the supply current lags the voltage by 180º (Fig. 14), illustrating the injection of an active power to the power supply. The degree of distortion of the current is similar to that obtained in active filtering mode (about 4.8 %).

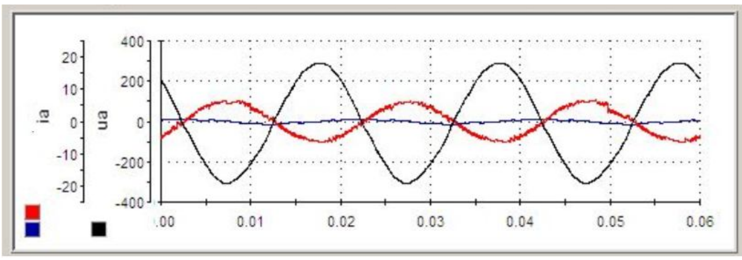


Fig. 14 –Supply phase voltage and active current injected in PCC in regeneration mode.

6. Conclusions

This paper proves that the DC-traction substations with uncontrolled rectifiers can be transformed into reversible substations with compensation capabilities by adding an APF properly connected and controlled in parallel with the traction rectifier.

Through the indirect control of the current provided by the active power filter, the measurement of load current is not required, the control implementation is simplified, the natural transition between the two modes of operation is ensured and good performance are obtained.

REFERENCES

Bae C.H., Han M.S., Kim Y.K., Choi C.Y., *Simulation Study of Regenerative Inverter for DC Traction Substation*, Proc. of ICEMS 2005, **2**, 1452-1456.

Bitoleanu A., Popescu M., Suru C.V., *Optimal Controllers Design in Indirect Current Control System of active DC-traction Substation*, Proc. of the Power Electron. and Motion Control (PEMC), Varna, Bulgaria, 904-909, 2016.

Bitoleanu A., Popescu M., Suru C.V., *Theoretical and Experimental Evaluation of the Indirect Current Control in Active Filtering and Regeneration Systems*, Proc. of 2017 Internat. Conf. on Optimization of Electrical & Electronic Equipment and Aegean Conf. on Electr. Machines and Power Electron., OPTIM-ACEMP 2017, Braşov, Romania, 759-764.

Chuang H.J., Chen C.S., Lin C.H., Chu S.H., *Optimization of Inverter Placement for Mass Rapid Transit Systems Using Genetic Algorithm*, IEE Proc.-Electr. Power Appl., **152**, 1, 1-6 (2005).

Cornic D., *Efficient Recovery of Braking Energy Through a Reversible DC Substation*, Proc. of Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS), Bologna, Italy, 1-9, 2010.

de Jager W.A.G., Huizer M., van der Pols E.K.H, *Implementation of an Active Regeneration Unit in A Traction Substation*, Proc. of the 16th European Conf. on Power Electron. and Appl., EPE'14-ECCE Europe, Lappeenranta, Finland, 1-9, 2014.

Devaux F.O., Tackoen X., *Overview of Braking Energy Recovery Technologies in the Public Transport Field*, Energy Recovery Working Paper, www.tickettokyoto.eu (2011).

Gunavardhini N., Chandrasekaran M., *Power Quality Conditioners for Railway Traction – a Review*, Automatika–Journal for Control, Measurement, Electronics, Computing and Communications, **57**, *1*, 150-162 (2016).

Hayashiya H., Kikuchi S., Matsuura K., Hino M., Tojo M., Kato T., Ando M., Oikawa T., Kamata M., Munakata H., *Possibility of Energy Saving by Introducing Energy Conversion and Energy Storage Technologies in Traction Power Supply System*, Proc. of the 15th European Conf. on Power Electron. and Appl., EPE 2013, Lille, France, 1-8.

Hosny W., Park H.-E., Song J.H., *Investigation of Shunt Active Power Filters in Railway Systems, Substation Installation*, Journal of Energy and Power Engineering, **10**, 1974-1979 (2013).

Ortega J.M., Ibaiondo H., Romo A., *Kinetic Energy Recovery on Railway Systems with Feedback to the Grid*, Proc. of the 9th World Congress on Railway Research, 2011.

Popescu M., Bitoleanu A., Dobriceanu M., *Investigations on the Coupling LCL Filter in Active Traction Substations*, Proc. of 2017 IEEE Int. Conf. OPTIM & ACEMP, 654–659.

Popescu M., Bitoleanu A., Preda A., *Design and Performances of the Separating Circuit in Regeneration and Filtering System for Active DC-traction Substations*, Proc. of the Internat. Symp. on Power Electron., Elect. Drives, Automation and Motion, SPEEDAM 2016, Capri, Italy, 1178-1183.

Popescu M., Bitoleanu A., Suru V., *Indirect Current Control in Active DC Railway Traction Substations*, Proc. of 2015 Internat. Aegean Conf. on Electr. Machines & Power Electron., 2015 Internat. Conf. on Optimization of Electr. & Electron. Equipment & 2015 Internat. Symp. on Advanced Electromechanical Motion Systems 2015, Side, Turkey, 192-197.

Popescu M., Bitoleanu A., Suru V., *On the Design of LCL Filter with Passive Damping in Three-Phase Shunt Active Power Filters*, Proc. of the Internat. Symp. on Power Electron., Elect. Drives, Automation and Motion, SPEEDAM 2016, Capri, Italy, 825-830.

Popescu M., Bitoleanu A., Suru V., Preda A., *System for Converting the DC Traction Substations into Active Substations*, Proc. of the 9th Internat. Symp. on Advanced Topics in Elect. Eng., ATEE 2015, Bucharest, Romania, 632-637.
Preda A., Popescu M., Linca M., *Conservative Power Theory (CPT) Method Applied in the Indirect Current Control for Active DC Traction Substations*, Athens: ATINER'S Conf. Paper Series, **TRA2015-1561**, 1-17 (2015).
Suru V., Popescu M., Deaconu I., *Study of Indirect Current Control Methods for Urban Traction Active DC Substations*, Annals of the University of Craiova, Electrical Engineering series, **39**, 157-163 (2015).
Suzuki T., Hayashiya H., Yamanoi T., Kawahara K., *Application Examples of Energy Saving Measures in Japanese DC Feeding System*, Proc. of the 2014 Internat. Power Electron. Conf., Hiroshima, Japan, 1062-1067.
* * * *IEEE Recommended Practice and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Std. 519-1992.

CONFIGURAREA ŞI PERFORMANȚELE SUBSTAȚIILOR REVERSIBILE DE TRACȚIUNE ÎN C.C. CU CAPABILITĂȚI DE COMPENSARE

(Rezumat)

Această lucrare se concentrează pe transformarea substațiilor de tracțiune în c.c. cu redresoare necomandate în substații reversibile, cu capabilități de compensare. Prin adăugarea unui filtru activ de putere cu structură de invertor sursă de tensiune între linia de tracțiune de c.c. şi partea de c.c.. capabilitățile necesare sunt asigurate. Astfel, în regimul de tracțiune al motoarelor de c.c., calitatea energiei electrice este mult îmbunătățită prin reducerea factorului de distorsiune armonică a curentului absorbit din rețea sub limita de 5% prevăzută de standarde, în condițiile unui factor de putere practic unitar, în timp ce, în regim de frână, un curent activ aproape sinusoidal este injectat în rețeaua de putere. Posibilitățile de cuplare atât pe partea de c.c., cât şi pe partea de c.a. sunt discutate, inclusiv aspecte de proiectare a filtrelor de cuplare. Dintre metodele posibile de control, controlul indirect al curentului de pe partea de c.a. a invertorului prin intermediul curentului la rețea înainte de punctul comun de conectare este soluția adoptată. Performanța bună a întregului sistem este dovedită prin simulare şi experiment pentru cazul unei substații de tracțiune în c.c. prevăzută cu redresor cu diode cu 6 pulsuri.