On Braking Efficiency of Urban Electric Transportation Systems Based on Power Electronics

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Abstract**—The paper deals with specific matters related to the electric braking processes in urban transportation systems that use power electronics (choppers). One presents theoretic aspects concerning the braking processes at urban electric traction d.c. motors, including the cases when power electronics are used. Problems related to the designing stage and to the optimum solution determination are addressed. The advantages of using a mixed electric braking system that use both resistive and respectively regenerative braking are emphasized. The designed and realized equipment are tested on stand. In the end one presents the efficiency of the adopted solution as revealed by tests on a tram. Aspects concerning both the resistive and respectively regenerative brakings are presented.**

Keywords-component: braking processes; d.c. motors; choppers; urban transportation systems

I. INTRODUCTION

The use of power electronics in modern driving systems used in urban transportation systems results in many benefits concerning the improvement of both urban transportation safeness and respectively driving equipment reliability [1].

The transportation companies focus their efforts toward the increase of passengers comfort and transport activity efficiency improvement [9], [10]. To meet the urban transportation requirements in a short time, some efforts were done in order to develop the tram transportation systems. They have in view the European and global trends: significant energy savings, reducing of maintaining and exploiting costs, reducing of costs per passenger/kilometer and an increase in passengers comfort, increase of vehicle commercial speed, improvement of transportation services etc. [3], [5].

Therefore a solution was adopted for the modernization of existing tram vehicles through major changes in the power circuit. Initially designed for a direct voltage of 600 V d.c., they are endowed with two serial d.c. motors with series excitations of 300 V d.c. Because each traction motor would have to operate to a voltage greater than the rated voltage, the solution (for a low energy efficiency) was to introduce a series resistance in the rotor circuit. Moreover, the accelerator would suffer some modifications and, in long run, some trams would be out of order due to the technical problems appearing especially in the electric driving system. Considering the high energy consumption, the solution with resistance in the rotor circuit was often abandoned. This thing is reflected in the low operating time of the whole electric driving system.

A reliable technical alternative is to supply the systems through variable d.c. regulators with IGBT components. These changes focus on two major objectives: the removing of series resistances and the substitution of starting rheostats of classic drives by variable voltage regulators (choppers) realized with IGBT, that provide the current control in the regimes "running" and "braking".

In order to certify that the design was made correctly, the simulation of the working rates using the designed physical parameters has often been necessary [4], [6].

The selection of the optimum driving solution depends on many factors, including the equipment's conformity with respect to electric braking processes. The electric braking is available only at urban transportation vehicles with electric motors at wheels. The electric braking relies on the energetic reversibility of the traction electric machines. During the braking regimes the traction motors operate as electric generators, and the presence of the braking torque at wheels consists in providing the functioning of electric generators with loads. To meet this requirement (including the case of driving series d.c. motors), one of the following situations must be realized:

- the connection of some braking resistances at the generators' terminals (the case of resistive braking);
- the connection of the motors (now acting like electric generators) in series or parallel and the delivering of their electric energy directly toward the contact line (used to supply other public transportation vehicles) (the case of regenerative braking).

During the electric resistive or regenerative braking regime all the traction motors of the tram will operate as "electric generators". During motion, they are the only equipment that provide the conversion toward electric energy of the kinetic energy variation (caused by the tram speed decreasing).

II. ASPECTS RELATED TO THE ELECTRIC BRAKING

A. Resistive Braking

The traction motors from tram should perform a resistive braking providing that the variation of its kinetic energy ΔW_c is converted (by the tractions motors - that now operate like d.c. generators) into electric power that should be dissipated (as heat) along some braking rheostats R_f, conveniently ratted [2].

During the braking regime, the excitation of a d.c. motor can be handled in several ways. The most common modalities to perform the excitation winding supplying are:

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- the excitation is in series with the induced winding;
- the excitation is supplied separately
- the excitation is supplied separately and self-compensated.

The specific modality of exciting the d.c. generators (during braking) plays a major role with respect to the resistive braking quality and performances.

Due to the independence relative to the contact line, all the methods applied for the resistive braking take advantage on an increased safeness degree relative to the regenerative braking.

Because the contact line has no influence, all the models for the rheostatic braking provides an increased safeness degree relative to the regenerative braking. Still, owing to the technical and economical advantages, the rheostatic braking is not used as the only braking technique for the urban electric traction vehicles that use power electronics.

B. Regenerative Braking

During regenerative braking, instead of dissipating the braking energy as heat, this energy can be retransmitted (with appropriate parameters), in the contact line, from where it can be consumed as useful energy by other trams [2], [7].

Two conditions must be simultaneously accomplished:

1. Firstly, the traction circuit must be energetically reversible. As the traction motors are energetically reversible in an intrinsic manner, the only requirement concerns the electronic converters (if any), imposing that they must allow the bidirectional flow of current (respectively of electric power). Physically, the reversibility of traction motors is obtained when the induced “against electromotive voltage” E increases and overcomes the value of the voltage between terminals U_M and so E becomes capable to revert the sense of current through the induced winding $I=I_s$ (and consequently the sense of the power transfer though traction motor).

2. Secondly, because the braking electromagnetic torque:

$$M = C\, m \Phi I_S \tag{1}$$

of any d.c. traction motor is nonzero only if $I_S \neq 0$, the braking power/energy, returned to the contact line, must be instantaneously consumed. This condition requires the presence of a consumer connected to the contact line (LC).

This presence refers to:

- at least another tram, in the traction stage (placed on the same segment of the contact line) is operational. This condition requires the presence of a consumer connected to the contact line (Fig. 1);

- a neighboring d.c. reversible supplying substation capable to transfer the d.c. braking power toward the a.c. three-phase network where certain consumers should draw it instantaneously.

When none of the above conditions is accomplished, the regenerative braking is not possible and the resistive/ mechanical braking is performed instantaneously.

C. Hybrid Braking with Choppers

Although it presents many energy-related advantages, the regenerative braking with choppers presents certain major drawbacks at normal operation. It is advantageous only for autonomous electric vehicles, supplied by storage batteries [2].

When choppers are used, at non-autonomous vehicles supplied from the contact line (LC), a suitable solution consists in using a braking rheostat, R_f. This way one performs a hybrid solution, with regenerative and resistive braking [2]. A proper designing and realization of the electric braking at d.c. motors supplied through choppers might improve the reliability of the entire solution adopted at the driving using choppers – Fig. 2.

In principle at hybrid braking, the regenerative braking with choppers is supported by a resistive braking that becomes active automatically and takes over the difference of braking force (when the recovering modality is not operational or becomes weaker).

The rheostatic braking is accomplished through the adjusting of the braking resistance, R_f. If required, this can be subsequently divided into 2-3 stages that can be gradually removed (putted in short-circuit). The equivalent braking resistance, R_e, can be calculated with:

$$R_e = R_1 + (1 - a) R_f \tag{2}$$

where R_1 represents the total resistance of the windings of the excitation and respectively of the d.c. rotor, and R_f is the braking resistance.

The equivalent braking resistance can be continuously adjusted through the modification of the relative conduction duration $a = t_1 / T$ (“duty-cycle”), starting from the maximum value $R_{e(max)}$ (corresponding to a_{min}):

$$R_{e(\max)} = R_1 + (1 - a_{\min}) R_f \tag{3}$$

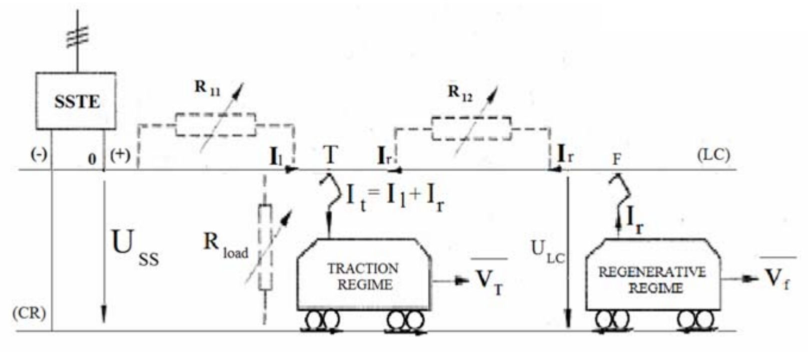

Figure 1. The consumer connected to the contact line instantly uses the braking power returned to the contact line

up to the minimum value $R_{e(min)}$ (corresponding to a_{max}):

$$R_{e(\min)} = R_1 + (1 - a_{maz}) R_f \qquad (4)$$

The limits for the adjustment of R_e are conditioned by the extreme values (a_{min} ; a_{max}) obtained for the relative conduction durations of the chopper used for the rheostatic braking [2].

The regenerative braking is possible only if:

$$I_a \geq 0,\ E \geq U_{LC} \qquad (5)$$

This is equivalent to:

$$n \geq n_0 \qquad (6)$$

where:

$$n_0 = U_{LC} / (k_e . \phi) \qquad (7)$$

Under n_0 the regenerative braking is no longer possible. The limit velocity, n_0 , can be adjusted only through the excitation regulation [2].

During each period, T, the recovered electric energy W is equal to the electromagnetic energy produced by the traction motor W_M, from wich the energy dissipated through the Joule effect within the windings is subtracted [2]:

$$W = W_M - W_J \qquad (8)$$

Because the general operational condition for the voltage-raising chopper requires that:

$$0 < U_2 - U_1 \qquad (9)$$

where U_1 is the supplying voltage of the braking chopper (after the line filter) and U_2 is the voltage across the motor terminals, including the voltage across the smoothing coil in the case of regenerative braking. Eq. (9) can be rewritten as:

$$0 \leq (k_e \cdot n \cdot \phi(I_2)) - R_2 \cdot I_2 \leq U_1 \qquad (10)$$

When this condition is fulfilled some problems can occur only at the maximum speed v_M (when the traction motor velocity is maximum and equal to n_M).

As usually at the maximum velocity for the chopper in use $a = a_{min}$, the accomplishing of (10) also involves both the weakening of the traction motor field ($\phi' \leq \phi$) and respectively the introduction of a buffer resistance R_t into the circuit of the rotor winding, such that:

$$0 \leq (k_e \cdot n \cdot \phi(I_2)) - (R_1 + R_2) \cdot I_2 \leq U_1 \qquad (11)$$

At the regenerative braking, once the velocity is decreased, firstly the resistor R_t will be removed (putted in „short-circuit") and secondly the d.c. motor (as d.c. generator) will be progressively got out from the „shunted" state.

If the „instant receptivity" of the LC contact line vanishes (this being mathematically equivalent to $i \to 0$), the instant value of u_1 (across the terminals of the filtering capacitor C_F) is rapidly increasing (overcoming the maximum addmitted limit for the contact line, U_{LC}). In the same time the mechanic braking at the wheels is vanishing too. From this moment (with a special control device), one must „suspend" the regenerative braking and simultaneously other braking systems should become active [2].

The quantity that performs a temporar „monitoring" of the degree of availability (or receptivity) of LC with respect to the recovered electric energy is quite the instant value of the voltage accross the capacitor terminals, $u_1(t)$.

Consequently, to guarantee that the regenerative braking is taking place one must accomplish the condition:

$$u_1 \leq U_{\max} \qquad (12)$$

where U_{max} represents the maximum admitted value of the voltage across the contact line. Otherwise other braking techniques must be used.

III. Technological Solution. Structure with Two Acceleration Choppers and one Resistive Braking Chopper

A. The Technological Solution Designed and Adopted

Both accelerators initially used on trams were substituted by choppers, each of them driving a bogie (for resistive acceleration/braking). Each chopper has its own circuit for intermediate voltage – Fig. 2. Therefore one must place on each of them a braking transistor. But this solution involves the use of two braking choppers and correspondingly two intermediate circuits. Because the operation of a braking chopper is temporarily (occurs only when there isn't any „starting - off" tram on the line), the adopted technical solution includes a single braking chopper as in Fig. 3.

The links between the electric schema of the chopper for the resistive braking from Fig. 3 and the other components from the force electric schema are as follows: 1 – the link with the choppers for running-braking; 10 – link with the braking resistance; 11 – link with the intermediate circuit.

For the "run forward" regime the switching P1 and P2 are closed. The current flows toward the following route: supplying line, motor, excitation, transistor, reverse diodes.

During the regime of regenerative braking the sense of the current through the excitation winding is maintained but the sense through the rotor's winding is reversed as the switches Z1 and Z2 are closed when P1 and P2 are opening. During this regime the power produced by the electric machine that became a generator is stored in the magnetic fields from a rotor winding and an auxiliary coil LM. In the following interval this stored energy, along with the supplementary one produced by generator is transmitted to the source and then the phenomena are repeated. The current flows along the following route: rotors, LM, excitation, T1 (T2), additional resistance, K2, D diode, source. The transistors T1 and T2 accomplish the transformation of the d.c. energy into another d.c. energy, changing the value of the source's voltage mean value. Through the variation of the relative duration of a voltage pulse one performs a variation of the angular velocity for constant excitation flux. When the running treadle is pressed, the running schematic is accomplished and the choppers transform the input voltage received from the

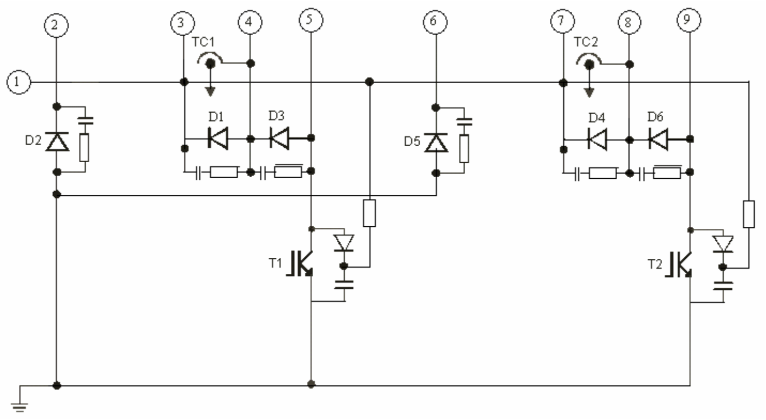

Figure 2. Electric schematic for choppers for running/braking

contact line into a voltage for the supplying of the group of motors from the bogies, and therefore the control of the current and torque is achieved. The driving system consists in 2 choppers operating in the regimes "running" and "regenerative braking" and a common chopper that provides the rheostatic (dynamic) braking when the contact network does not accept the recovered energy.

Each chopper serves one bogie, so the conditions are fulfilled for an independent operation. So, when a fault occurs the tram can retry toward the reparation post using a single bogie.

After selecting the type of running regime (forward/backward), the tram driver presses the running treadle and automatically the schematic corresponding to the selected regime is accomplished. The confirmations received by the microcontroller are processed and so the "START" signal is issued for both choppers. So the current through the motors is increased with a pre-established slope toward the prescribed value from the running treadle. Depending on the treadle position, the voltage from the supplying line is progressively transferred to the traction motors that develop the corresponding couple and the vehicle accelerates.

When the running treadle is released, a "launched running" regime is initiated automatically, with braking at minimum current, consequently to the realization of a braking schematic. When the braking treadle is pressed, the braking current is increased up to the prescribed value and the motor, operating as generator, delivers energy toward the contact. This energy should be consumed by other vehicles that operate in a "start off" regime.

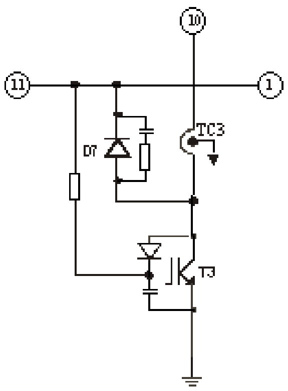

Figure 3. Electric schematic of chopper for resistive braking

When no consumer is connected to the supplying network and the regenerative braking cannot be accomplished, the energy stored by motor is dissipated as heat along a resistance R_f. In this case the current that should have had been directed toward the supplying network is redirected through the circuit closer K3 and through the chopper T3 along the resistance.

B. *The Control of IGBT Transistors*

Using the static switch one can control the connecting time (T_c) and respectively the disconnecting time ($T - T_c$) of the voltage U_d toward/from load.

The regulation of the load power can be accomplished through the control of the chopper that should operate in switching regime. One selected the solution with the connecting duration (T_c) variation, using the PWM technique.

The variation of T_c, while preserving the control period T (that is keeping a constant frequency), allows an optimum load current's smoothing.

The filling factor is gradually increased, until the current through the motor reaches a certain imposed percent from the starting or braking current, proportional to the percent from the pressing of the acceleration or braking treadle.

During braking, the PWM filling factor must increase fast, in order to strike the braking current. Afterward it enters into the control loop in order to keep the current to the prescribed value (through the braking treadle).

The peak value of the motor's current is also controlled to prevent it from overcoming the prescribed values. After the motor's current reaches the prescribed value using the pressed treadle, the current is kept to this value, decreasing the filling factor if the current tends to increase or decreasing it if the current tends to decrease. The decreasing of the filling factor is performed fast if the current's peak value approaches the maximum prescribed value or goes to zero if the current reaches this value.

If a fault current occurs, the pulses are stopped and the chopper becomes inactive. The chopper is reactivated automatically after a sequence in which the treadle is released, followed by another

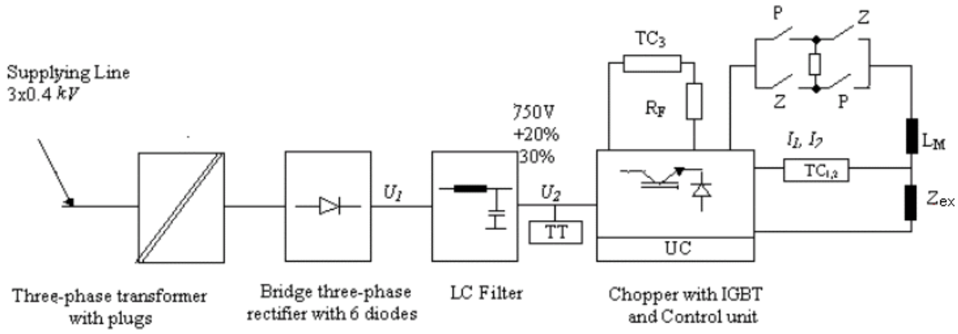

Figure 4. Electric schema for the test stand

treadle pressing. After a sequence of 3 fault signals, the chopper is completely stopped, and can be reactivated either after a revision and/or a special reactivation procedure. The ultimate alternative is the operation with a single IGBT.

At the braking, if the voltage overcomes the prescribed value U_2, T3 enters in conduction, supplying the motors with energy (generator regime) along the braking resistances. The control pulses filling factor increases if the voltage overcomes the value U_2, quite up to "the full wave" case. In braking regime, if T3 is controlled in full wave and the voltage in the intermediate circuit increases over U_3, the command for stopping the T1 and T2 pulses in fault regime is issued.

IV. Experimental Determination on Stand

The testing of various components of the driving equipment was performed on the test stand (Fig. 4). One validated the braking regimes within the driving system ensemble.

Compared to the real operation of the equipment on tram, the designed test schema presents some limitations, imposed by the conditions from the test stand [8]. The tests performed on the stand revealed aspects of resistive/regenerative brakings.

A Tests Concerning the Resistive Braking. Waveforms for the Voltage Along the Braking Transistor (CH II) and for the Current through the Braking Resistor (CH I)

Tests were performed for the input operational voltage with a peak-to-peak value of 450 V. The braking transistor enters in conduction along a resistive braking period when there are no consumers connected to the line and the voltage in the intermediate circuit tends to increase in a uncontrolled manner.

Therefore the control voltage of the braking transistor is the element that controls the discharging of the energy through the filtering capacitor along a braking resistance. To evaluate the efficiency of maintaining a maximum voltage across the capacitor one used 2 values for the voltage threshold: 420 V and respectively 720 V - as in Fig. 5.

B Tests on the Voltage Limitation with the Braking Transistor during the Regenerative Braking for Different Braking Stages

Two sets of tests were performed:

1. At the first test the supplying voltage was set to 800V and 2 braking stages were imposed: 12 A and respectively 60A.

For both braking stages during the regenerative braking the voltage was maintained at the constant value of 800 V.

2. At the second test (Fig. 6) the supplying voltage was set to 880V. The intermediate voltage is represented by CH II whilst the braking current by CH I. The same two braking stages were imposed: (12 A and 60A). Similarly, for both braking stages during the regenerative braking the voltage was maintained at the constant value of 880 V.

V. Experimental Determinations on a Tram Carrying the Tested Electric Driven System

In this section one presents experimental determinations on the current and voltage for the first chopper of acceleration/braking – the 4-th running stage (Fig. 7).

The waveform CH I corresponds to the current and reveals that, when the tram driver presses the acceleration treadle on the first stage, the current follows an ascending slope (200 A/sec), afterward being stabilized to a value of 100 A for 0.5 sec.

When the tram driver releases the acceleration treadle, the current falls to 0. Afterward the tram turns into a regime of „motor braking" that lasts 1.8 sec.

The oscillogram represents the current evolution when the brake treadle is pressed. The current for the 1-st stage (that lasts 0.2 sec.) is of 80 A with a slope of 160 A/sec. Afterward

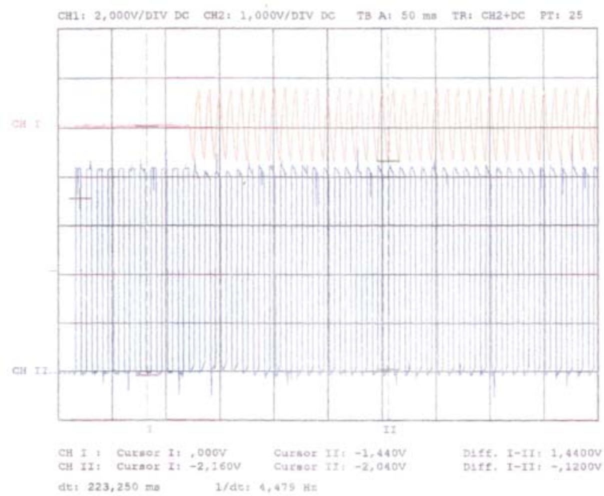

Figure 5. Voltage (CH II) and current (CH I) for the braking transistor at an input voltage of 720 V, at resistive braking

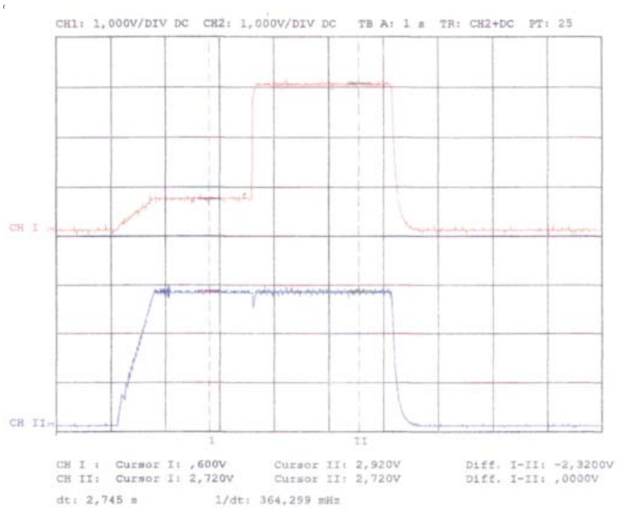

Figure 6. Voltage limitation with the braking transistor during regenerative braking. Braking stages of 12/16 A , supplying voltage of 880 V

the 2-nd stage of braking is reached and the current is stabilized to 130 A for 0.6 sec. The tram driver presses deeper the brake treadle and the tram turns into the 3-rd stage of braking (lasting 3 sec.). In this stage the current is of 160 A and the slope is 260 A/sec.

At the end of this period, the tram driver releases the brake treadle and the current in integrated with a negative slope, as a consequence of the filtering circuit's capacitor discharging.

The current is then set to a value of 30 A for 2.4 sec. due to the energy kept by the motor and afterward is falling to 0 A.

The voltage „jumps" when the running treadle is released, reaching a value of 820 V for 1.4 sec. This value is maintained during the „motor brake" process, and during the „strictly-speaking" braking process (1-st and 2-nd stage) the voltage is 840 V, all these phenomena developing during the regenerative braking.

In the 3-rd stage (regenerative braking), the voltage raises from 840 V to 870 V.

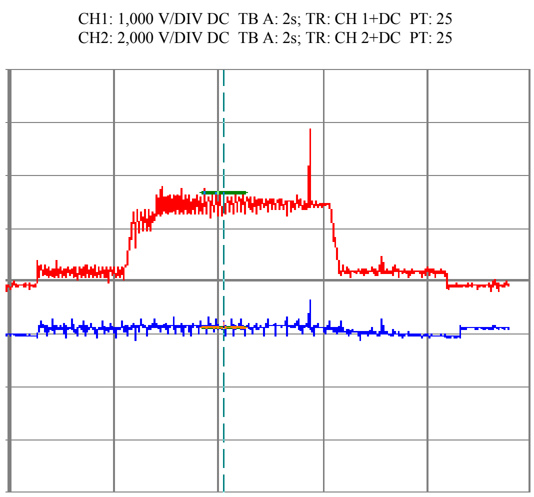

Figure 7. Current and voltage for the 1-st chopper in the 4-th braking stage

When the tram driver releases the brake treadle, the voltage falls to 800V , then further to 780 V and afterward comes back to its initial value of 820 V when the current reaches 0 A.

VI. Conclusion

The design with two choppers for regimes of acceleration/braking and one chopper for the resistive braking has proven to be the optimum solution from the technological point of view. The studies concerning the braking regimes for this study revealed that a hybrid solution should be the best solution for the electric braking processes.

The tests performed on the stand shown that for two distinct values of the braking current the supplying voltage is maintained at an almost constant level. This proves the efficiency of the regenerative braking for the adopted technological solution. The experiments made on the tram considering 4 stages of current reveal that the voltage from the supplying line is maintained at an almost constant level if at least one tram is connected to the line.

All experiments (on stand and on the tram connected to the line) demonstrated the solution correctness.

Experimental data gathered during a long period revealed that, providing that acceleration and braking choppers are used, one can recover a significant amount of energy (almost 10%) through the use of power electronics.

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