Improvement of the Energy Recovery of Traction Electrical Drives using Supercapacitors

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Abstract— **In the paper the possibility of improving the energy recovered during the braking of railway vehicles and reduction of power peaks during accelerating are discussed. The energy available from the regenerative braking of the motor is stored into supercapacitor sets placed on board and reused subsequently for the acceleration of the train. This auxiliary storage system allows the reduction of the losses on the line, because the power peaks are shaved by supercapacitors and, hence, the rms power supplied is reduced. In addition, also the energy consumption of the train can be reduced respect to traditional convoys, especially if the characteristic duty-cycle presents many accelerations and braking periods as the case of subways trains. The set of supercapacitors needs the use of an intermediate dc/dc converter in order to harmonize the voltage with that of the dc-link of the drive and control the power flows of the supercapacitors. The mathematical model of the whole system and the control strategy of energy management are presented.**

The actual possibilities of the energy recovery are shown by means of numeric simulations and expressed in percentage respect to the energy drawn during accelerations. The control strategy has been experimentally validated on a scale system made of an asynchronous drive supplied by a dc source and a set of supercapacitors as auxiliary storage device.

Index Terms—**Supercapacitors, traction drives, energy recovery**

I. INTRODUCTION

The increase of the specific power demand by present-day railway traction vehicles implies to find reliable technical solution in order to reduce the energy consumption. The typical journey i.e. of subway trains, light rail vehicles (tram) is made of accelerations, coasting and braking periods. In particular, the largest part of the energy drawn by the train is ascribed to the acceleration, because of the reduced distance between two subsequent stations. Modern electrical drives for traction motors benefit from the possibility of regenerative braking [1] and the advantages related to the saving of energy has been already demonstrated attempting to inject the energy into the supplying line [2, 3].

The exchange of power flows between the vehicles and the catenary is not always allowed. It depends on if the catenary is capable of storing the amount of energy comes from more vehicles at same time. At present the main dc/dc energy substations of the catenaries are not bidirectional in the power. Indeed, the ac/dc power rectifiers have cheap diodes. As result the recovery energy can be only used if there are in the neighborhood other convoys to be supplied, otherwise line over-voltage phenomena can occurs.

At present, to avoid the over-voltage, the braking is usually rheostatic and the energy is dissipated on ballast resistors present on board.

So the recovery of the kinetic energy of the trains is subjected to the traffic conditions and dependent on phenomena not easily predictable. Such an energy management does not require any significant increase in the complexity of existing infrastructures, but the energy actually recovered is not greater than 10% of that drawn during accelerations [2].

Nevertheless different technical solutions are reliable [4,5]: use of storage devices on board of rail vehicles; use of storage devices on substation of rail vehicles; use of bidirectional electrical drives in substation.

At the present the main storage devices available are the electrochemical batteries, the electrochemical capacitors or supercapacitors, and the flywheels. The characteristics of these different devices can be compared referring to their specific energies and specific power, respectively expressed in Wh/kg and W/kg. For the use on board, only electrochemical batteries and supercapacitors seem to have practical applications, even though they present complementary characteristics. The batteries present high energy density and relatively low power density, with discharges time ranging from ten of minutes to hours. The supercapacitors have energy density (6Wh/kg) lower than that of batteries but higher power density (6kW/kg), with discharge times ranging from ten of seconds to minutes. This aspect points out that supercapacitors are suitable for supplying power peaks. In addition, their cycle life is about 106 cycles of charge discharge because the principle of the energy storage is based on electrostatic processes. So supercapacitors are, hence, the most suitable devices for the application on railway vehicles.

The first solution has been adopted by Bombardier transportation on prototype vehicle in Mannheim [7]. The prototype is a modern Light Rail Vehicle and the storage device is a stack of supercapacitors with energy content of 1kWh with a mass of 450 kg. The devices have been mounted on roof of vehicle. This solution has several advantages in terms of increase energy efficiency of the whole system, reduction of power peak demand during acceleration operations, reduction of infrastructure losses, and line voltage stabilization. The main disadvantages are the increase of train mass (approximately 2%); additional space due to energy storage container and bidirectional step/up converter, and high density supercapacitors cost.

About the second solution, the energy management of single substation has to be coordinated in real time with others on the basis of the power demand requested by vehicles traffic. So a hierarchized power control permits to reduce the power peak demand of each substation but without reduction of current line losses and line voltage stabilization. In latest case additional space and weight are not binding.

The last solution can be adopted just for new substations where it can be represented the cheaper solution. Nevertheless this implies an energy management on AC side of the substations. This is not always permitted by energy committing.

However the optimal solution (tradeoff between technical and economic) must be searched for on the basis of single rail services in terms of type of rail vehicles (LRV Tram, Metro, ecc…) and type of infrastructure (substation, catenary, track).

Nevertheless the considerations about the improvement of the energy recovery when there are supercapacitors on board on railway vehicles appear to be missing in the technical literature up to now published. For this reason, the author has been first presented the model of the whole system (electrical drive with induction motors, the contact line and the supercapacitors) by means of their equivalent electrical circuit and a control strategy. Numerical simulations of the electrical drive of Metropolitan Vehicles equipped on board of supercapacitors set have been presented in order to show the capability to supply power peaks and the quantification of the energy recovery referred to a standard duty cycle of the rail vehicle.

At the end experimental results on scale system are presented in order to validate the proposed control strategy.

II. MATHEMATICAL MODEL

Standard traction drives are supplied by the catenary by means of pantographs. The catenary can be supplied either in dc or in ac with different voltage levels, depending on the country where the railway is located. In case of dc lines, the catenary is directly connected to the inverters with filter capacitors, whereas in case of ac lines there is also a rectifier stage in cascade. Therefore the traction drive is always supplied by a dc line. The line is modeled considering its equivalent circuit at the pantograph terminals. For simplicity, the line has constant voltage, v_d, constant resistance, rd, and constant inductance, l_d. The supercapacitors are modeled by their equivalent series electrical circuit with a series of their capacitance, C_{sc}, and resistance, r_{sc}. The supercapacitors set operates in dc current and is connected to the dc link of the drive. However, since the supercapacitor voltage changes with their state of charge, it is necessary an intermediate dc/dc converter capable of harmonizing voltages and regulating power flows of supercapacitors. This converter has to boost the voltage of supercapacitors and be bidirectional for cycling them. The system configuration is represented by the equivalent electrical circuit shown in fig.1.

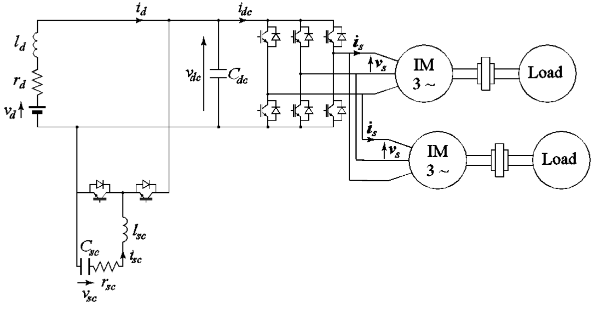


Fig. 1 – Outline of the equivalent electrical circuit of the system

From this circuit and considering the switches ideal, the mathematical model of the system can be derived as follows:

$$\begin{cases} v_d = r_d i_d + l_d \dfrac{di_d}{dt} + v_{dc} \ ; \\ i_d + i_{sc}\, d(t) = i_{dc} + C_{dc} \dfrac{dv_{dc}}{dt} \ ; \\ v_{sc} = r_{sc} i_{sc} + l_{sc} \dfrac{di_{sc}}{dt} + v_{dc} d(t) \ ; \\ i_{sc} = -C_{sc} \dfrac{dv_{sc}}{dt} \ ; \\ \boldsymbol{v}_s = \dfrac{2}{3} m(t) v_{dc} e^{jn(t)} \ ; \\ i_{dc} = \Re e\left\{ m(t) \boldsymbol{i}_s\, e^{-jn(t)} \right\} \ ; \\ \boldsymbol{v}_s = r_s\, \boldsymbol{i}_s + l_s \dfrac{d\boldsymbol{i}_s}{dt} + \dfrac{d}{dt} L_m \left(\boldsymbol{i}_s + \boldsymbol{i}'_r\, e^{jp\theta_r} \right) \ ; \\ 0 = r'_r\, \boldsymbol{i}'_r + l'_r \dfrac{d\boldsymbol{i}'_r}{dt} + \dfrac{d}{dt} L_m \left(\boldsymbol{i}_s\, e^{-jp\theta_r} + \boldsymbol{i}'_r \right) \ ; \\ J \dfrac{d\omega_r}{dt} = \dfrac{3}{2} \Im m \left\{ \boldsymbol{i}_s\, \breve{\boldsymbol{i}}'_r\, e^{-jp\theta_r} \right\} - T_r \ ; \\ \dfrac{d\theta_r}{dt} = \omega_r \end{cases} \tag{1}$$

where the meaning of the parameters is given at the end of the paper, *d*(*t*) is the switching function of the dc/dc converter, *m*(*t*) and *n*(*t*) are the switching functions of the inverter in case of SVM modulation. These functions are equal to 0 or 1 at the instant *t*, depending on the state of the switches and diodes.

III. CONTROL STRATEGY

The control strategy aims to minimize the power peaks of the catenary and to stabilize the line voltage. The idea is to hold a constant reference value for the line current during braking and accelerating operations in order to prevent current peaks. In addition the control unit has to regulate the level of charge of supercapacitors. This level has to be set in order that the supercapacitors can supply extra power demands and can reserve a storage capability for braking energy. Only the exceeding energy is, hence, given back into the catenary or dissipated into brake resistor.

The main difficulties of this strategy are basically due to the proper determination of the line current set-point. A current too low involves the full charge of the supercapacitors before the end of the braking process and the recovery of the remaining energy with increasing of catenary voltage and current losses; a current set-point too high implies an insufficient utilisation of the storing capacity of the supercapacitors and non-optimal average charge-discharge efficiency. The optimal current set-point has to be determined depending on the state of charge of the supercapacitors and the amount of energy to be recovered during the braking process. However, it is very difficult to estimate correctly the amount of energy because it depends strictly on the velocity profile of the vehicle.

After a load peak, the control unit has to provide to recharge partially the supercapacitor until a voltage set-point value. This value has to be a compromise between the necessities of energy enough for covering load peaks and the necessities of capacity enough for energy recovery. A simple criterion is to regulate the voltage set-point as a decreasing function of the vehicle velocity, which is directly related to the kinetic energy of the moving mass. For a low velocity, it is more logical to expect an accelerating than a braking; in addiction, only a little amount of energy is available in a braking process. Therefore, an optimised control strategy has to set a high level of charge of the supercapacitors. On the contrary, for higher velocity it is more logical to expect a braking and then it is more suitable to reserve capacity for the energy recovery. For example, if the remaining capacity is set to be proportional to the whole kinetic energy available, the voltage set-point is:

$$\frac{1}{2}C\left(V_{s,\max}^2 - V_{sp}^2\right)=\frac{1}{2}k\,m\,v^2 \Rightarrow V_{sp}=\sqrt{V_{s,\max}^2 - k\frac{m}{C}v^2} \quad (2)$$

where V_{sp}, and $V_{s,max}$ are respectively the set-point and maximum voltage of supercapacitors set, v is the vehicle velocity and k is a constant.

The second aspect of the control strategy is the regulation of the supercapacitors power flows in order to keep constant the line current. It is possible to define on the plane (i_b, v_s) the working area of the control strategy, as it is shown in fig.2. Then, the working operations are defined by the minimum and maximum threshold of the supercapacitor voltage, i.e. $V_{s,min} \le v_s \le V_{s,max}$. Outside this zone the supercapacitors set is disconnected from the dc-bus. The upper and lower limits of supercapacitors set voltage, $V_{s,max}$ and $V_{s,min}$, have to be chosen on the basis of the amount of energy demand during acceleration and braking operations. In particular, they define the maximum energy recovered and provided to the line during load cycle. Control automatically comes back in the working area, as soon as the motor current is lower than the reference line current and $v_s < V_{s,min}$, or the motor current is greater than the reference line current and $v_s > V_{s,max}$. In the range $V_{s,min} \le v_s \le V_{s,max}$, control guarantees that supercapacitors set is not charged over the upper threshold and discharged under the lower threshold. Finally, the line current limit defines the charge and discharge areas. In particular, when the load current is greater than the reference current, the supercapacitors set supports the catenary supplying the peak power demand of the motor. If the motor current is lower than reference, the catenary charges the supercapacitors. The final state of charge of supercapacitors is defined by the voltage level expressed by the relation (2) between the supercapacitors set voltage and the vehicle speed. In addition the control system verifies also other condition like: the supercapacitors set current has to be lower than the maximum current of dc-dc converter. If an over-current occurs, the control system switches to a current control of supercapacitors set.

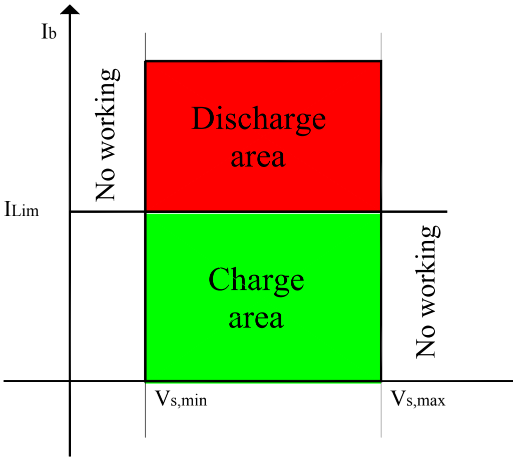


Fig.2 – working area of control strategy

IV. NUMERICAL RESULTS

The behavior of the railway vehicles equipped with supercapacitors on board has been simulated by means of the mathematical model previously presented. The induction motors are controlled by a field oriented control with feedback of the speed and indirect method of estimation of the rotor flux position. The main parameters of the motor are reported in Tab.I. The control strategy keeps constant the rotor flux up to the base speed, n_b correspondent to a train speed of 50 km/h. For speed greater than the base speed, the flux is decreased in order to keep constant the output power delivered by the motor.

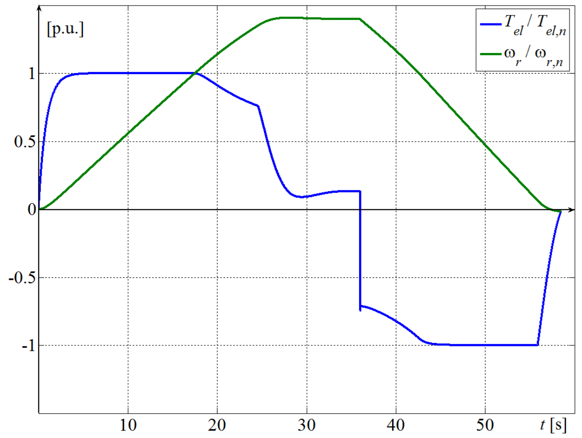
TABLE I. MAIN PARAMETERS OF THE TRACTION MOTORS

P_n [kW]	V_n [kV]	n_b [rad/s]	r_s [Ω]	r'_r [Ω]	l_s [mH]	l'_r [mH]	L_m [mH]	J_m [kgm^2]
300	1.5	153	0.13	0.09	1.81	2.62	72.8	3.9

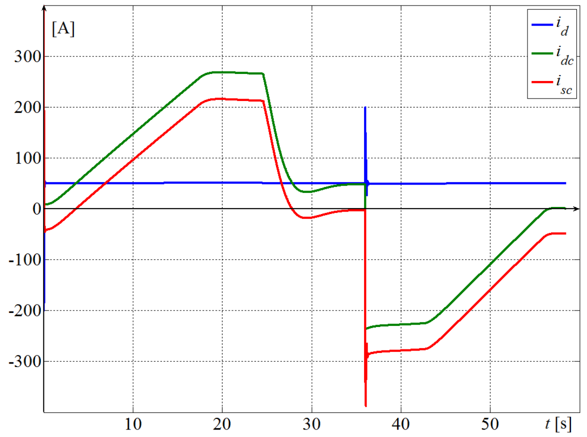
The following parameters of the system have been considered for the simulation: the translating mass of the train, referred to a single wheel set of the bogie, is equal to 46000 kg; the maximum speed of the train is 70 km/h; the rated torque of each induction motor is 2000 Nm; the line voltage of the dc catenary is equal to 2.4 kV.

The supercapacitors set has been sized taking into account the energy which can be actually recovered from regenerative braking. At the speed of 70 km/h, the kinetic energy of the train, referred to a single wheel set of the boogie, is about 2.4kWh. is made of 5 modules connected in series and 2 strings in parallel. The single module is characterized by a rated operating voltage of 390 V with an energy available of 282 Wh and maximum current of 950 A, referred to the half of the operating voltage. The features of the modules are referred to a HTM390 module produced by Maxwell, see Tab.II. The size of the supercapacitors set takes into account the maximum available kinetic energy of the train and the maximum power requested by the electrical drive during the electrical braking operations. The motion resistance takes into account the friction force due to the air and the wheel rail contact.

In the simulation, the train starts from standstill, accelerates up to 70 km/h, cruise for few seconds and stops with regenerative braking. The results of the simulation are shown in fig. 3. The speed and the torque developed by each motor are shown in fig.3a. The set of supercapacitors helps the contact line in the supplying of the drive during the acceleration. The control of the dc/dc converter implies that supercapacitors discharge themselves and limit the line current (fig. 3b).



(a)



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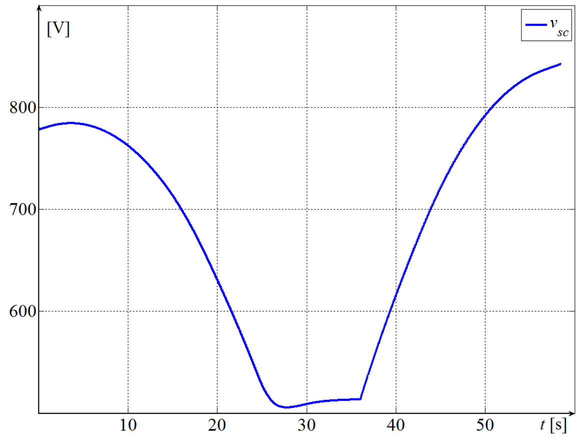

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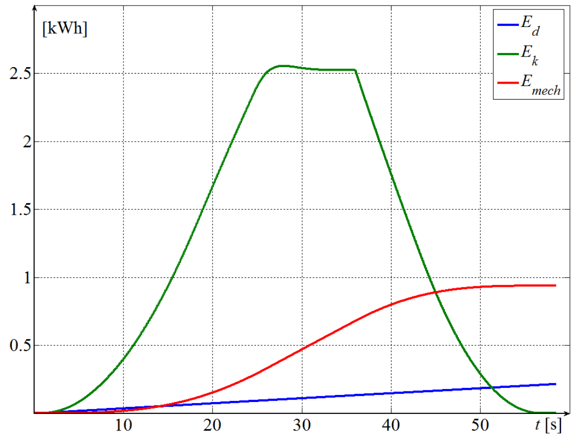


(d)

Fig.3 - numerical results for a traction cycle: motor torque and speed (a), currents supplied by the catenary, the supercapacitors and the dc-side of the inverter (b), supercapacitors set voltage (c), and diagram of energies (d).

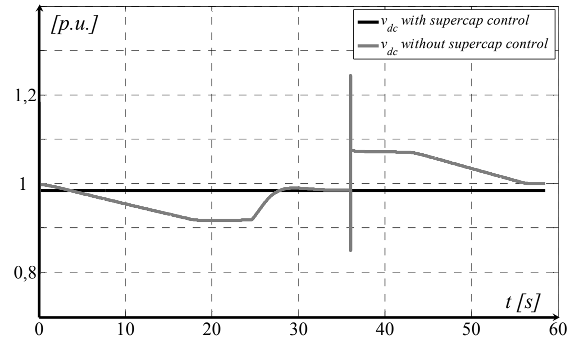


Fig.4 – dc line voltage with and in absence of supercapacitor control

TABLE II.
FEATURES FOR HTM390 MAXWELL SUPERCAPACITOR MODULE

V_n [V]	390
C [F]	17.8
R [mΩ]	65
I_{max} [A]	950
E [Wh]	282
W [kg]	165
V[mm^3]	1200x629x288

This limit current is set in order that the line supply only the average power to the drive. During the braking, the kinetic energy of the train is recovered and stored into the supercapacitors. In fact, the state of charge of supercapacitors increases because their voltage increases when the braking starts, as fig. 3c shows. In fig. 3d are finally shown the energies involved. The energy supplied by the line increases linearly, since v_d is constant and i_d is almost constant. This means that the rms power supplied by the line is considerably reduced because the peaks are supplied by supercapacitors. The reduction of the line current peak is equal to 80%, as shown in fig.3b. This implies that the droop line voltage V_{dc} is reduced compared to case of absence of the supercapacitors bank. In fact voltage droop without supercapacitors is lower than 10%, instead with the supercapacitors bank is lower

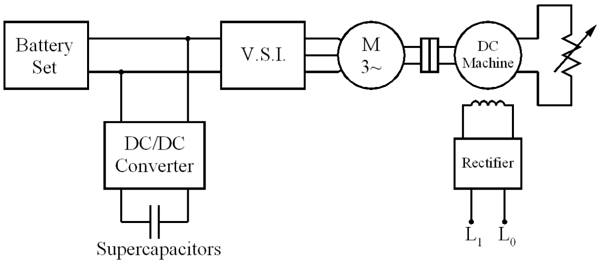


Fig. 5 – Block diagram of the test bench used for experimental tests

than 2% as shown in fig.4. The diagram of fig.4 has been carried out with line resistance and inductance equal to $r_d = 0.75\ \Omega$, and $l_d = 10\ \mu H$.

V. EXPERIMENTAL RESULTS

In order to verify the effectiveness of the suggested control technique a sample drive supplied by batteries and supercapacitors has been set-up. Since the impossibility to reproduce into laboratory the moving mass and the power of real rail vehicle, the electromechanical drive has been scaled in the power (1:30). The test-bench used for experimental tests is shown in fig.5. The mechanical load consists of a rotating inertia and a separately-excited dc generator of 25 *kW*, which simulates the behaviour of the vehicle in terms of torque required at the axis of the motor in different operating conditions. The dc generator supplies an adjustable passive dc load. Since the output power of dc machine depends on the square of the speed, it is possible to simulate the wind friction on the vehicles keeping constant the excitation voltage.

The supercapacitors set are connected in parallel with the battery by means of a three leg full bridge dc/dc converter of 20 *kVA*. The maximum current allowed by the converter on the supercapacitors side is 150 *A*. The dc bus supplies the traction drive constituted by a three-phase voltage source inverter and an induction motor of 11 *kW*. The supercapacitors set consists of two modules in series, each one with a rated voltage of 42 *V* and capacitance of a 67 *F*. The battery is lead-acid type for traction applications and has 33 elements of 65 *Ah* connected in series, reaching a rated bus voltage of 396 *V*. The battery set wants to simulate the dc source of the catenary.

The remote control of the inverter allows different loads by selecting the motor speed and acceleration.

The performed tests aim to evaluate the contribution of supercapacitors during accelerations of the vehicle and their recovering capability during braking operations. For this reason the supercapacitors voltages, the battery currents and the load currents have been measured by a data acquisition board. The cycle considered has been shown in fig.6.

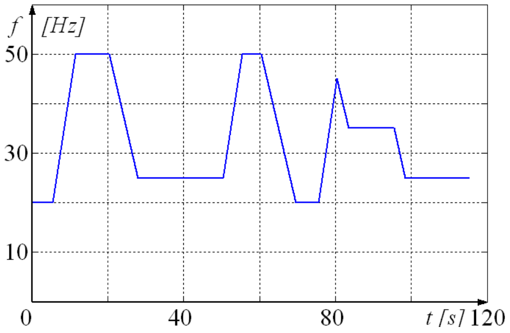
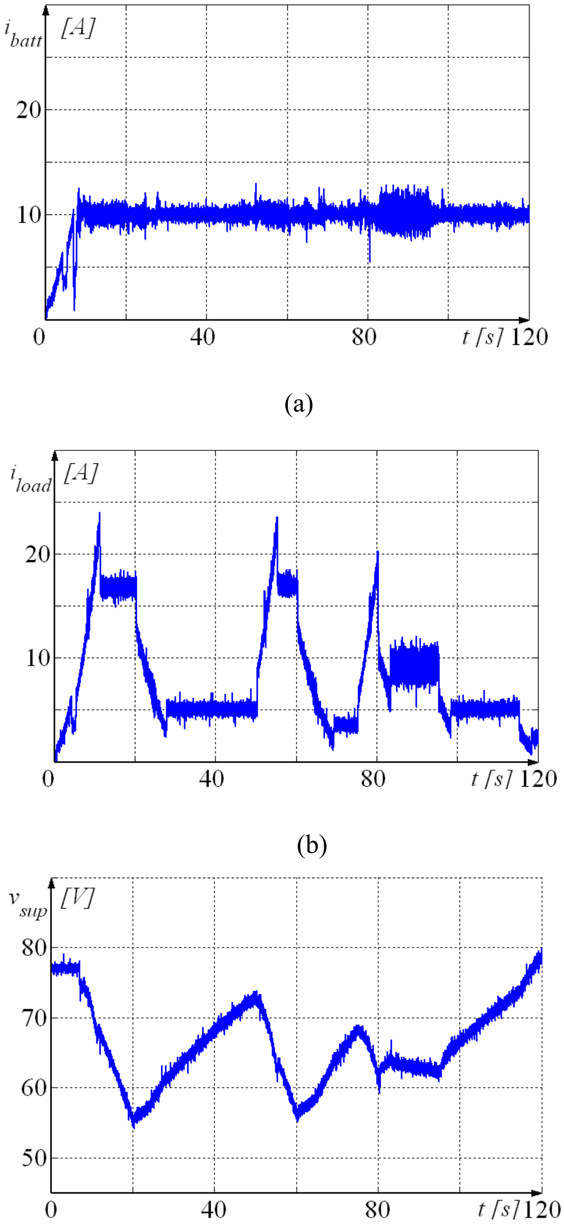


Fig.6 – speed - cycle

The first test has been performed when the rail vehicle is supplied by the battery pack and supercapacitors set. The cycle consists of three load peaks of different length and amplitude. Battery current, load current and supercapacitors set voltage have been depicted on figs.7. The initial state of charge of batteries (S.O.C.) has been set equal to 100%. The control essentially holds constant the battery current to a value equal to 10 *A*, also when the current load demand is two times greater than the reference value, as shown by figs.7a and 7b. These results points out of the efficiency of the control strategy when the supercapacitors voltage is inside its working area ($V_{s,min} = 40\ v \le v_s \le V_{s,max} = 80\ v$).



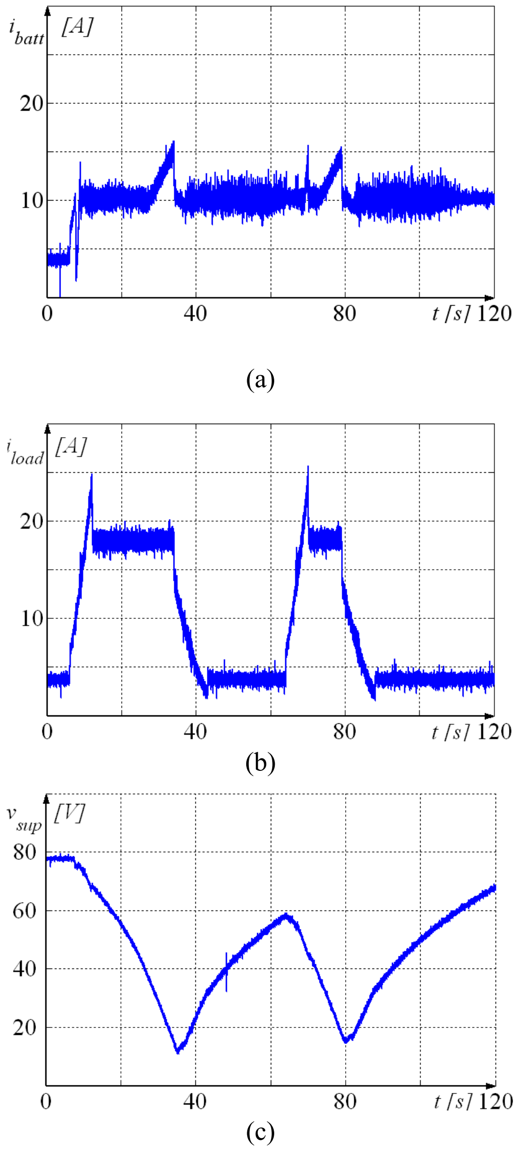
(a)

(b)

(c)

Fig.7 – Battery current (a), load current (b) and supercapacitors set voltage (c)

In addition, it is shown that during low load operations the battery-pack charges the supercapacitors with a constant current.



(a)

(b)

(c)

Fig.8 – Battery current (a), Load current (b) and supercapacitor voltage (c)

A second cycle has been considered with average current requested by the load higher than the battery set-point (10 A), see fig.8b. In this case the supercapacitors voltage reaches and crosses over the minimum value (V_{min} = 40 V), as shown in fig.8c, with consequence increases of battery current during load peak, as shown in fig.8a.

VI. CONCLUSION

The paper has shown why and how the use on board of supercapacitors bank represents a solution technically effective and feasible to recovery energy on board and to reduce the line power peak demands during the accelerating operations.

The use of supercapacitors on board allows to reduce the line current over the 50% (examined case 80%) which causes a reduction of the line voltage drop. It is obvious that supercapacitors storage devices on board of traction vehicles stabilize the catenary voltage. It can be confirmed by comparison of catenary voltages with and without use of supercapacitors in diagram of the fig.4.

These improvements can lead to reduction of infrastructure losses, of committing power and energy cost allowing i.e. an increasing of the distance between substations for the planned new lines; reducing of time intervals between following trains at existing lines; acceptance of longer trains on existing lines.

List of symbols used

i_d	current supplied by the line
i_{dc}	input current of the inverter
$\mathbf{i}'_r$	space vector of the rotor current of the motor referred to the stator winding
$\mathbf{i}_s$	space vector of the stator current of the motor
i_{sc}	supercapacitor current
l_d	equivalent input inductance of the line
l'_r	rotor leakage inductance referred to the stator winding
l_s	stator leakage inductance
l_{sc}	boost inductance of the dc/dc converter
p	pole pair number
r_d	equivalent input resistance of the line
r_{sc}	equivalent series resistance of supercapacitors
r'_r	rotor winding resistance referred to the stator winding
r_s	stator winding resistance
v_d	equivalent input voltage of the line
v_{dc}	input voltage of the inverter
$\mathbf{v}_s$	space vector of the motor voltage v_{sc} supercapacitor voltage
C_{dc}	input capacitance of the inverter
C_{sc}	supercapacitor capacitance
J	rotating inertia
L_m	mutual inductance of the motor
T_r	resistant torque
θ_r	rotor angular position
ω_r	rotor angular speed

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