Metro Trains Equipped Onboard with Supercapacitors: a Control Technique for Energy Saving

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***Abstract*--The paper suggests a control technique for improving energy saving in metropolitan trains equipped by onboard supercapacitors. On the basis of the typical duty-cycle of a metro-train, the supercapacitor system has been sized with reference to an energetic criterion that tries to limit overhead line current and, consequently, voltage drop at the train pantograph. The control algorithm is then based on a changeover scheme that properly manage the charge and discharge of supercapacitors in order to keep constant the line current during acceleration, coasting and braking of the train. Experimental results on a scale model, reproducing forces and inertias of a real railroad vehicle, validate completely both the sizing procedure and the control technique proposed.**

***Index Terms*--Energy conversion, energy management, rail transportation, supercapacitors.**

I. INTRODUCTION

In the last years people mobility has increased more and more in urban centres, implying the necessity of rapid transit improvement in terms of passenger capacity and number of journeys. These requirements have been satisfied by the introduction of new vehicles, that draw higher power peaks and greater energy consumption than traditional ones. However, the fast developing of transportation systems has not been always followed by a corresponding modification of the power supply and overhead lines. The present loads running on railway lines are therefore responsible of a consistent growing of power losses and amounts of the electrical energy supplied by the electrical substations (ESS). Moreover, greater currents drawn by trains during accelerations imply greater voltage drops on the overhead line, that further affect negatively their safe starting. The reduction of the energy consumption should be achieved if the kinetic energy of the trains were recovered as much as possible. Actually the braking is already made in regenerative mode so that the kinetic energy is converted into electrical energy, but the recovery possibilities are limited to the exceptional case where another train is starting at the same time [1].

Starting from these considerations, it is evident that rapid transit systems could benefit from the use of inverting substations [2,3] or energy storage devices [4,5]. The first solution, however, implies the modification of all ESS existent on the track. The second solution instead can be actuated without substantial change of the present supply system, because storage devices can be located both in the substations and in the stations. Storage devices store the electrical energy available from train braking and supply it again for helping trains when they start. Therefore the main advantages are the reduction of the energy consumption due to the improvement of the energy regenerative braking and the reduction of the power peaks supplied by ESS because part of the power is supplied directly by the storage device [6,7].

At present, onboard and wayside energy storage devices seem to be the best technical solutions [8,9]. On board storage devices are in the most suitable location for flattening the power demand of the train both in acceleration and in braking, due to the smallest distance covered by the energy travelling to and from the traction electrical drive. However, they need a suitable redesign of coaches for their allocation onboard and imply an increase of train weight. This disadvantage is not present in wayside storage devices that can be placed in the stations along the line, even though a lower energetic efficiency should be expected for the greater distances covered by the energy.

The starts and stops of metropolitan and suburban trains have typical duration of several seconds and require high electrical power. Among different storage devices, supercapacitors and flywheels are therefore the best candidates for the application in railway systems [10-12], because they have high power densities (5-10 kW/kg) and then can quickly charge and discharge. Moreover, the very high number of charge-discharge cycles guarantees a lifetime comparable to that of the other devices of the plant. Supercapacitors are suitable both for onboard and wayside application, because energy is stored via electrostatic processes, whereas flywheels are not good onboard due to gyroscopic effects. Usually, electrochemical batteries are not suitable for railway application because of their longer recharge time, that leads to very high weights and volumes of the stack [13].

Although energy storage devices has been largely studied in the technical literature referring to electric cars, the application of railway systems has not been completely exploited yet. Some experimental tests have been carried out on a prototype of suburban train equipped with onboard supercapacitors evidencing an energy saving of approximately 30% [14-15]. The results of the study have been extended to metropolitan trains only using rough theoretical considerations. The main problems arising from the experimentation are due to the assembly and management of large scale prototypes of railway vehicles. In such a case, scale models can be more easier handled for testing and simulating the operating conditions of a real train. They are also useful for the evaluation and validation of control strategies for the energy management of storage devices both in case of onboard and wayside application. Therefore authors designed and built a laboratory scale model with the aim of reproducing not only the forces and the inertia of a metropolitan train, but also its typical mechanical transmission. This paper focuses on energy saving capabilities of energy storage systems. Therefore the scale model has been equipped with onboard supercapacitors and its power electronics converter. The whole system has been used for the validation of a control strategy for the energy management of supercapacitors. The validation has been carried out by analysing the energy saving and the reduction of power peaks obtained with the proposed control.

II. SIZING OF ONBOARD SUPERCAPACITORS FOR METROPOLITAN TRAINS

The electrical energy needed by trains is transmitted at a distance from the ESS by means of overhead lines. Electric trains that collect their current from overhead lines use a device such as pantographs. The line can be supplied either in dc or in ac with different rated voltages. In case of dc supply, the traction inverter is connected directly to the line via filter capacitors; in case of ac supply, the inverter is connected by means of a rectifier. In any case, onboard supercapacitors are connected to the dc-link of the traction inverter as depicted by Fig. 1. The traction inverter feeds two three-phase induction motors mounted on the same bogie.

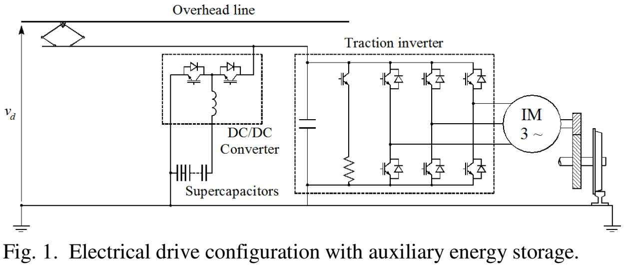

Fig. 1. Electrical drive configuration with auxiliary energy storage.

In this paper, the rated voltage of the overhead contact line is 1.5 kV in direct current. The train running on the track is a typical wagon for a rapid transit system. It includes three identical units, each one made of two powered vehicles having a full load translating mass $m_t = 46\,300$ kg. The maximum train speed is 75 km/h. The train acceleration and deceleration rates are respectively $a = 1$ m/s^2 and $d = 1$ m/s^2. The power required during coasting is about 10% of the maximum power required during the acceleration. The mean efficiencies of the mechanical transmission, electric motor and inverter are respectively $\eta_{mech} = 0.93$, $\eta_{em} = 0.91$ and $\eta_{inv} = 0.95$.

The typical duty-cycle of the train is made of an acceleration up to its maximum speed, a coasting of about 10 seconds and a braking until the stopping. On the basis of the characteristic values of this train, the power supplied by the overhead line is shown in Fig. 2.

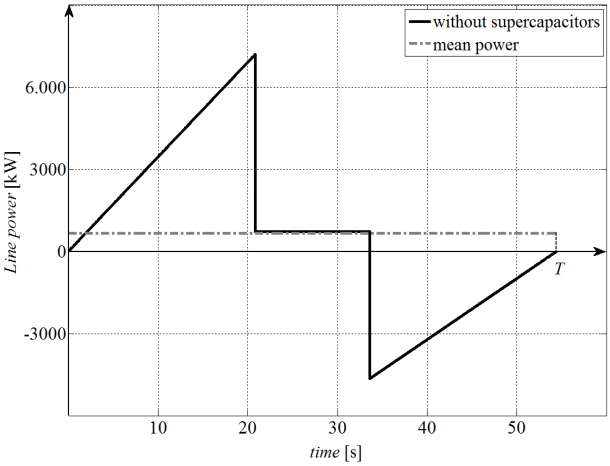

Fig. 2. Power supplied by the line for a typical duty-cycle of the train

The peak and the mean powers of the line are given by:

$$P_{Line,\max} = 6 \times \frac{m_t\, a\, v_t}{\eta_{mech}\, \eta_{em}\, \eta_{inv}} = 7\,198 \text{ kW} . \qquad (1)$$

$$P_{Line,mean} = \frac{1}{T}\int_0^T p_{Line}(t)\, dt = 655 \text{ kW} . \qquad (2)$$

If the line current was constant, the power delivered by the line would be also constant. The power, that is the difference between the actual power requested by the train and the line power, should be supplied by supercapacitors. As said before, they are connected to the dc-link of the traction inverter by means of a dc/dc converter. The controller of this converter manage the energy flows between supercapacitors and the traction inverter; the maximum amplification voltage between dc-link and supercapacitor bus-bars is 3.

For the energetic autonomy of the train, the power of the line should be at least equal to $P_{Line,mean}$. However, the efficiencies of the DC-DC converter, η_{dcdc}, and of the supercapacitors, η_{sc}, imply that this power should be greater than $P_{Line,mean}$. The actual power of the line, P_{Line}, can be easily evaluated by the consideration that the supercapacitor energy function, given by:

$$e_{sc}(t) = \int_0^t \left\{ \frac{\left[p_{Line}(t) - P_{Line}\right]^+}{\eta_{dcdc}\eta_{sc}} + \eta_{dcdc}\eta_{sc}\left[p_{Line}(t) - P_{Line}\right]^- \right\} dt \qquad (3)$$

where:

$$
\begin{aligned}
\left[p_{Line}(t)-P_{Line}\right]^{+} &= \frac{p_{Line}(t)-P_{Line}+\left|p_{Line}(t)-P_{Line}\right|}{2}\\
\left[p_{Line}(t)-P_{Line}\right]^{-} &= \frac{p_{Line}(t)-P_{Line}-\left|p_{Line}(t)-P_{Line}\right|}{2}
\end{aligned}
\qquad (4)
$$

at the end of the cycle has to be equal to zero, i.e. $e_{sc}(T) = 0$. If $\eta_{dcdc} = 0.95$ and $\eta_{sc} = 0.90$, the resolution of (3) yields $P_{Line} = 1\ 027$ kW. Once the actual value of the line power has been determined, the capacity of supercapacitors can be easily evaluated by:

$$
Q_{sc} = \max\left[e_{sc}(t)\right] - \min\left[e_{sc}(t)\right] = 17.9\ \text{kWh}\,. \qquad (5)
$$

Using the supercapacitor modules of Tab. I, the energy given by (5) can be stored by interconnecting at least 177 modules, which means 30 modules per each powered car.

TABLE I
MAIN CHARACTERISTICS OF SUPERCAPACITOR MODULES

Rated voltage [V]	125
Capacitance [F]	63
DC series resistance [mΩ]	18
Max current [A]	750
Energy available (75% SOC) [Wh]	101.7
Module weight [kg]	165
Module size [mm]	1200x629x288

Since the maximum boost ratio of the DC/DC converter is 3 and the line rated voltage is 1500 V, the minimum voltage of supercapacitor set should be not less than 500 V. The minimum voltage of a supercapacitor is obtained when the module is considered conventionally discharged, i.e. when the voltage is equal to the half of the rated voltage. Therefore, the minimum number of modules that have to be connected in series for the application considered is $N_s = 8$, because $8 \times 125 \div 2 = 500 = 1500 \div 3$. From energetic point of view, the supercapacitor set for each wagon if then made of $N_p = 4$ strings in parallel, each one made of eight modules in series. However, it is necessary to check if this stack is capable of accepting the electrical power coming from the DC-DC converter during train braking. The maximum power peak to be recovered by the supercapacitors installed in each car is:

$$
P_{sc,\max} = \frac{1}{6}\left(m_t\, d\, v_t\, \eta_{mech}\, \eta_{em}\, \eta_{inv} + P_{line}\right)\eta_{dcdc} = 899\ \text{kW} \qquad (6)
$$

This power has to flow in supercapacitors at the start of the braking, i.e. when the modules are fully discharged and supercapacitor voltage is the half of the rated one. Therefore, the maximum current flowing in each module is equal to:

$$
I_{m,\max} = \frac{P_{sc,\max}}{N_p\, N_s\, \dfrac{V_{m,n}}{2}} = 450\ \text{A}\,, \qquad (4)
$$

where $V_{m,n} = 125$ V according to Tab. I. Since the max current of each module is 750 A, the sizing is correct also with reference to supercapacitor powers.

III. CONTROL STRATEGY

The main target of the control strategy is the reduction of the power peaks supplied by the catenary, with consequent stabilization of the line voltage. The line current is maintained constant, also when the train accelerates and brakes, using the supercapacitors. They should be capable of supplying an extra power during accelerations and storing the energy available from train braking.

The main difficulty of this strategy is basically the proper on-line determination of the current set-point. A current too low involves the full discharge of the supercapacitors before the end of the acceleration, with consequent increasing of catenary current and losses; a current set-point too high implies an insufficient utilisation of the storing capacity of the supercapacitors. 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 speed profile of the vehicle.

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_d, v_{sc}) the working area of the controller, as it is shown in fig.3. Then, the working operations are defined by the lower and upper bounds of the supercapacitors voltage, i.e. $v_{sc,min} \le v_{sc} \le v_{sc,max}$. Outside this zone supercapacitors are disconnected from the dc-bus. The upper and lower limits of supercapacitors voltage, $v_{sc,min}$ and $v_{sc,max}$, 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. The controller automatically comes back in the working area, as soon as the actual line current is lower than the set-point and $v_{sc} < v_{sc,min}$, or is greater than the set-point and $v_{sc} > v_{sc,max}$. In the range $v_{sc,min} \le v_{sc} \le v_{sc,max}$, the control guarantees that supercapacitors are not charged over the upper threshold and discharged under the lower threshold.

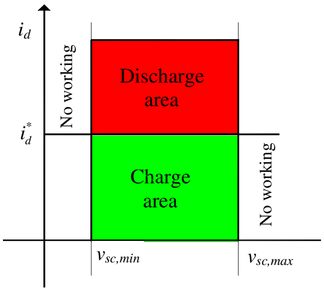

Fig.3. Working area of control strategy

Therefore the line current set-point defines the charge and discharge areas. In particular, when the line current is greater than the set-point, supercapacitors supply the extra power required by the motor and support the catenary. If the line current is lower than that reference, the catenary charges the supercapacitors.

If the duty-cycle of the train is repetitive and supercapacitors store the kinetic energy of the train, the energy supplied in a cycle by the catenary is equal to the losses of the system. Therefore the line current set-point can be selected as the total energy lost divided by the line voltage and by the period of the cycle.

In case the duty-cycles of the train are not determined, the choice of the line current set-point can be cumbersome. A simple criterion could be to regulate the voltage set-point of supercapacitors as a decreasing function of the vehicle speed, which is directly related to the kinetic energy of the moving mass. For a low speed, it is more logical to expect an acceleration rather than a braking; in addiction, the kinetic energy available at low speed is very low. Therefore, an optimised control strategy has to set a high level of charge of the supercapacitors. On the contrary, for higher speed it is more logical to expect a braking and then it is more suitable to have available 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 can be selected on the basis of the following criterion:

$$\frac{1}{2}C\left(v_{sc,\max}^{2}-v_{sc}^{2\,*}\right)=\frac{1}{2}k\,m_{v}\,v^{2}\Rightarrow v_{sc}{}^{*}=\sqrt{v_{sc,\max}^{2}-k\frac{m_{v}}{C}v^{2}} \quad (5)$$

where $v_{sc}{}^{*}$ and $v_{sc,max}$ are respectively the set-point and maximum voltage of supercapacitors, v is the train speed and m_v is translating mass and k is a constant which takes into account the effect of friction.

IV. EXPERIMENTAL VALIDATION

In order to verify experimentally the effectiveness of the suggested control strategy, a single metro line has been simulated in the Electrical Machines Laboratory of the Department of Electrical Engineering of the University of Naples Federico II. Because of the impossibility to reproduce into laboratory the moving mass and the power of vehicle on real dc track line, an electromechanical simulator has been set-up and scaled opportunely with respect to the train power [16].

A. *Electromechanical Simulator*

The electrical substation, the double track of catenary and power train of vehicle have been simulated. The primary feeder is composed of variable auto-transformer with a diode unidirectional rectifier. The rectified voltage is equal to 435 Volt. A proper variable resistor is placed, R1, in order to simulate the variations of the double track line resistance according to the vehicles movement.

The electrical drive of the simulator consists of a voltage source inverter and an induction motor of rated powers 20 kVA and 5.5 kW respectively, simulating the power train of the metro train. The stationary storage system is realized by supercapacitor modules interfaced with dc traction line by means of a three-leg full bridge 20 kVA dc/dc converter. The maximum allowable current at the supercapacitors side is 150 A. The supercapacitors set are composed by three modules in series, each one with a rated voltage of 42 V and capacitance of 67 F.

The remote control of the inverter allows to emulate different load conditions, by suitably selection of the motor speed and its acceleration. The schematic diagram of electrical power plant simulated in Laboratory is shown in Fig. 4.

The unit control is based on two independent Digital Signal Processor boards. The first one is used for the implementation of the vector control of induction motor, whereas the second one is devoted to the power management of supercapacitor storage device. This is based on the Texas Instruments platform TMS320VC33, that offers up to 4 analogous inputs, 4 analogous outputs, 4 digital inputs and 4 digital outputs. The sampling time is 400 μs. The data acquisition system consists of two voltage and current transducers, one encoder of 2000 pulses/rotation and a National Instrument board with eight inputs channel. The dynamic mechanical load is simulated by means of a mechanical scale model, reproducing typical train forces and inertias of a metropolitan train. The simulator is mainly composed of a mechanical transmission unit (motor, gearbox, wheel-set), located on a mobile frame, and four wheels set on a rigid axle. The transmission and the mobile frame lean on a couple of wheels by means of a wheel-set, which represents a pair of driving wheels of the light street car. In order to obtain different friction forces between the pairs of contacting wheels, it has been added a mass fixed on the mobile frame.

The flywheels represent the inertia of translating masses, which is directly related to the mass of the real train. A side view of scale model is reported in Fig. 5. In Tab. II the main electrical characteristics of the electromechanical simulator are reported.

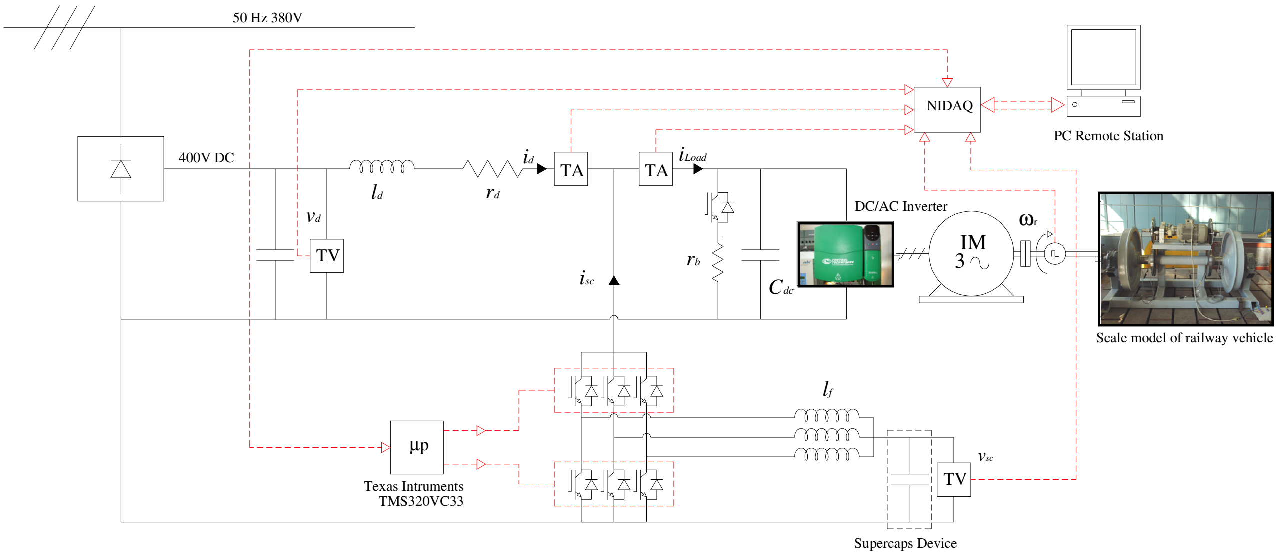

Fig.4. Lab test-bench

A. Experimental results

The performed test is focused to evaluate the storage ability both during accelerations of the vehicle in terms of voltage stabilization and energy saving. At this aim, line and load currents, dc link and supercapacitor voltages have been collected by a data acquisition board. The speed cycle considered has been shown in Fig.6a.

TABLE II
ELECTRICAL PARAMETERS OF THE SIMULATOR

	Unit	Quantity
Line		
Track total resistance	[Ω]	3
Rated dc Voltage	[V]	435
Drive		
Rated Power of Induction Motor	[kW]	5.5
Power of Voltage Source Inverter	[kW]	22
Storage System		
dc/dc Power Converter Max Current referred to supercap	[kVA] [A]	20 150
Capacitance	[F]	22.3
Rated Voltage	[V]	126
Number of modules in series	-	3
Mechanical		
Equivalent inertia	[kgm^2]	3.28
Maximum angular speed	[rpm]	600

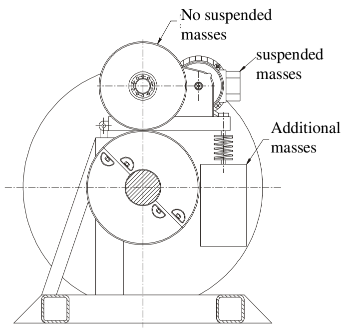

Fig. 5. Side view of the scale model

The simulated vehicle starts from standstill, accelerates up to 22 km/h (equivalent to a motor speed $\omega_r = 600$ rpm), has a coasting phase of about eleven seconds and it stops with braking in ten seconds. During acceleration, the load current increases up to 14 A (Fig. 6c) and the dc-bus voltage drops down (from 415 V to 370 V) as depicted in Fig. 5d. Since the storage unit-control is not active (the supercapacitors voltage stack is kept charged to 105 V), the line current i_d is equal to load current as shown in Fig. 6b. During the braking operation, since the ac/dc diode rectifier is unidirectional, the energy coming from the drive charges the dc-link capacitor, involving the increase of dc-bus voltage depicted in Fig. 6d. When the braking resistance of VSI is switched on, the voltage is limited to 750 V.

The same load cycle has been repeated starting from $t \cong 42$ s, when the storage unit control is active. The reference line current is set to 5 A. At beginning the motor does not rotate, so the supercapacitor voltage slightly increases (Fig. 6e). Then, during the acceleration the supercapacitors discharge themselves and the voltage decreases from 106 V to 90 V. The average line current and dc-bus voltage are held respectively constant to 5 A and 400 V. During steady-state, the supercapacitors are re-charged form the line. The charge continues during the regenerative braking too. In fact the load current becomes negative (peak of −5A) for about five seconds and the supercapacitors voltage increases quickly up to 100 V. It can be noticed that during the braking the line over voltage is avoided since the dc-bus voltage is held to 400 V.

The control essentially holds constant the average line current to a value equal to 5 A, during all cycle also when the current load demand is greater than the reference value, as shown by Figs. 6b and c. At the end of the cycle the supercapacitors is recharged up to 105 V.

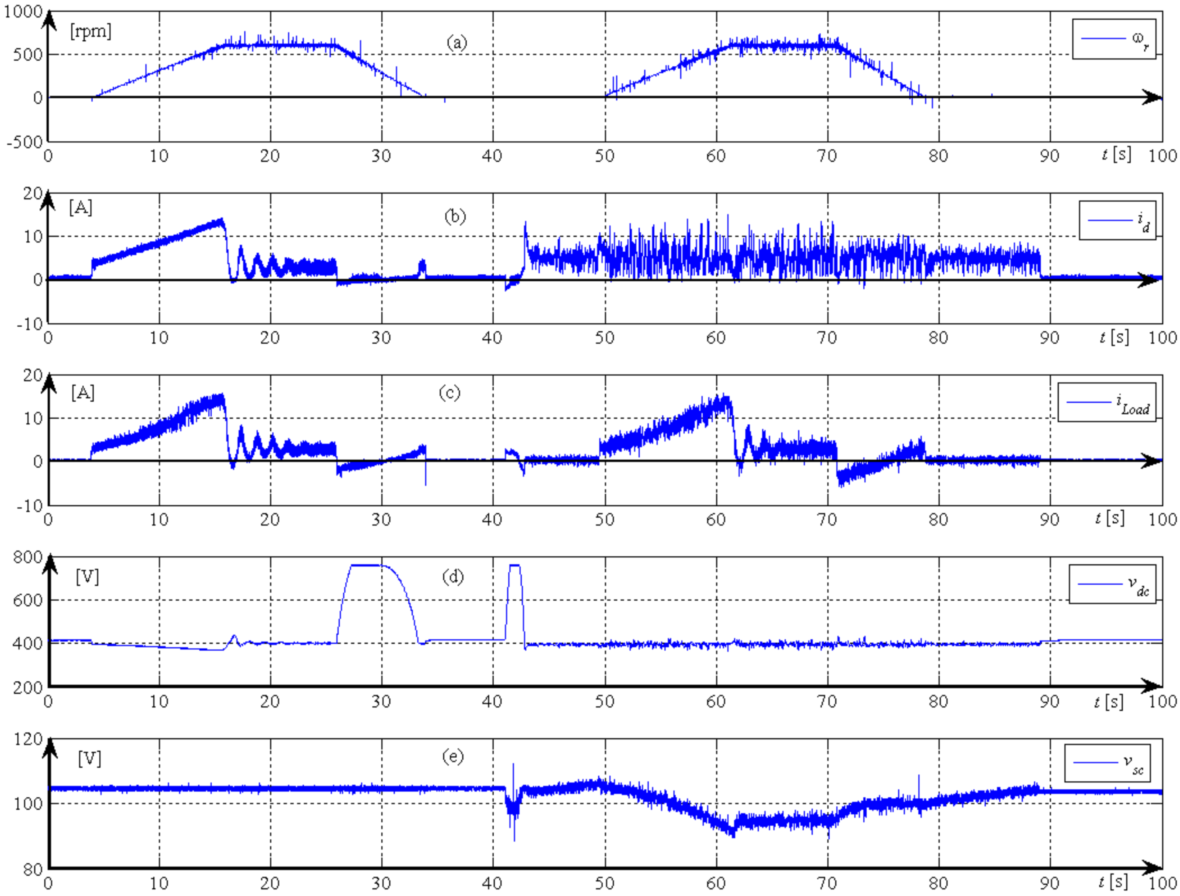

Fig. 6. Motor angular speed (a), line current (b), load current (c), dc-link voltage (d), and supercapacitor voltage (e)

V. CONCLUSIONS

The use on board of supercapacitors unit represents a solution technically effective and feasible for the reduction of power peak demand up to 50%, with consequence reduction of line drop voltage up to 1% and recovering energy on board during braking operations up to 30%. These improvements can lead to reduction of power demand on the infrastructure allowing an increase of the distance between substations for the planned new lines and the reduction of time intervals between consecutive trains in existing lines. Moreover the onboard energy storage allows an autonomous operation, i.e. moving the vehicle to the next station in case of lost of power. Another benefit could be the additional power of supercapacitors used to boost the vehicle when the catenary power is limited. However, the use of onboard supercapacitors involves also disadvantages like increases of train mass by approximately 10% and the necessity of additional space to accommodate the energy storage containers. In the examined case, the supercapacitors banks can be placed on the roof of each wagon for a total length of 18 m and a width of 1.2 m for each powered vehicle.

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