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THE ENERGY SAVING SYSTEM WITH THE CAF URBOS 3 OF URBAN PUBLIC TRANSPORT IN BELGRADE

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Key words: *On-board energy, CAF Urbos 3*

Abstract: *The power consumption of a tram is characterized by distinct peaks combined with a low average value. Using an on- board energy storage, the overhead line peak power and energy consumption can be reduced. The storage device introduces a degree of freedom for control of the power flow. To incorporate the freedom an energy management is required. The design of the energy management can be seen as a multi-objective optimization problem with the objectives "minimize line peak power" and "minimize energy consumption". As common to most multiobjective optimization problems it is not possible to minimize both objectives at the same time. This paper describes new on board energy storage systems applied in the urban electrified public transport in Belgrade (R. Serbia).*

INTRODUCTION

The urban electrified public transport in Belgrade, employ the low voltage DC systems at 600 V, which are usually the most economic. In this case, the pantograph connects directly the contact line to the power inverters of the train by means of filter capacitors. The average distance between substations is very limited for example, in a subway at 600 V with heavy traffic, it can be of the order of 1.5 km, with minimum values of 1.3 km.

The urban electrified public transport in Belgrade, employ the low voltage DC systems at 600 V. Tram system is a 1000 mm gauge network that in 2016 had 10 routes running on 43.5 kilometres of (at least mostly double) track in the city of Belgrade, the capital of Serbia. It is operated with around 200 trams, including 30 the electrical multiple unit train manufactured by CAF S.A. (Construcciones y Auxiliar de Ferrocarriles) named CAF Urbos 3 (see Fig. 1).

The main parametars of the CAF Urbos 3 are: Architecture- Mc-S-R-S-Mc, Rated power- 560 kW, Tram length: 31380 mm, Tram width- 2400 mm, Tram height- 3350 mm, Number of passengers: 261, Max. speed- 70 km/h, Acceleration -(0-35 km/h): 1.2 m/s^2, Traction power - 750V, Emergency brake deceleration rate – 2,8 m/s^2.

Urban transit network of Belgrade with the CAF Urbos 3 applied mobile energy storage system (or so called on-board energy storage systems), which consists of onboard energy storage systems usually located on the vehicle roof. Every system works independently, and the recovered energy is directly sent to the storage system placed on the tram. When the vehicle accelerates, energy is used in priority from the energy storage systems (EES) to propel the tram [1,2]. This principle is illustrated in Fig. 2.

Fig. 1 Picture of CAF Urbos 3 electrical multiple units operating on of Belgrade Urban Line

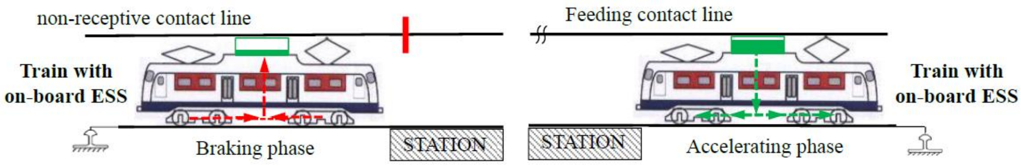

Fig. 2 Schematic operation of on-board energy storage system for urban rail vehicles (modified from [1])

The Rapid charge accumulator (ACR System) developed by CAF Urbos 3 is an on-board energy storage system based on the use of supercapacitors which enables trams to run between stops without catenaries, as well as to save energy through the full regeneration of braking energy. The supercapacitors are charged in 20 seconds while the train is stopped at a station. The system can store both the braking energy and the energy received from the network during the journey. The Rapid charge accumulator has a working autonomy without catenaries of around 1.200 metres, depending on the capacity installed and the characteristics of each tramline. This system is compatible with other technologies and suitable for use on rolling stock of any type and manufacturer, and on new or existing facilities and infrastructure.

On-board Energy Storage System installed on the CAF Urbos 3 tram is based on Rapid charge accumulator (ACR) as shown on Fig. 3 [1,2].

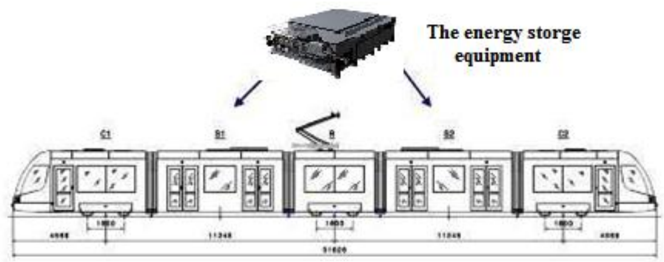

Fig. 3 The energy storge modules are fitted on the train connected in parallel with the patograph

SIMULATION MODEL FOR THE ON-BOARD ENERGY STORAGE SYSTEM

With the on-board storage element on the CAF Urbos 3, the necessary electrical drive power can be provided by the storage element as shown in Fig. 4.

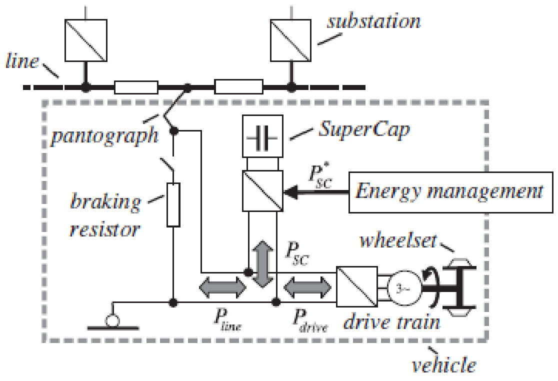

Fig. 4 CAF Urbps 3 with ACR system

Many parameters influence the design of a supercapacitive **energy storage system** for the CAF Urbos 3. Features such as tram weight, passenger load, maximum speed, driving cycle, altitude differences and supercapacitor characteristics need to be studied to determine the energy storage system in terms of energy capacity. To evaluate the effects of all these parameters, a backwards looking simulation tool has been developed in Matlab/Simulink with the objective of determining the power flow at tram level, line voltage and current, and power drawn from substations with and without on-board supercapacitors. Fig. 5 shows a detail of the tram model inside the simulation program [1,2].

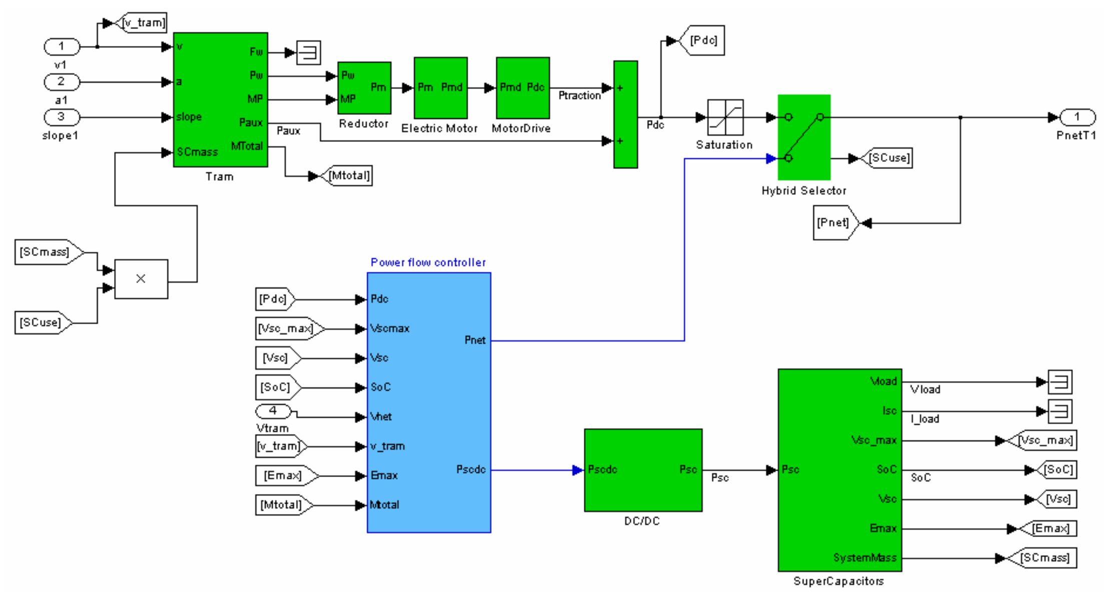

Fig. 5 Detail of tram model in simulation program

Starting from a predefined speed cycle, it calculates both the traction and braking power requested by the tram. Then, according to the requested power at the DC bus level, a power controller (blue), determines the amount of power to be provided by the supercapacitors and the remaining power to be provided from the net.

SIMULATION RESULTS WITH ACR SYSTEM

The simulated tram starts from standstill, accelerates up to v_t= 65 km/h, cruises for about eleven seconds and brakes for sixteen seconds until it stops. The whole cycle has been simulated for one stop for a total covered distance of 570 m . During the starting phase

($\Delta t \cong 24s$), the reference speed has been set to $v_{t,ref}$ = 65 km/h and the vehicle linearly accelerates with a maximum traction effort set to $F_{t,max}$= 340 N.

The Rapid charge accumulator (ACR) system are pre-charged to $V_{SC,\max}$= 135 V. The behavior of the traction drive equipped with ACR system is evident from the compared analysis of Fig. 6 a) and Fig. 6 c). In particular, this last one shows that ACR reference current, $i_{SC,ref}$, change in sign according to vehicle acceleration. In fact, actual SC current, , $i_{SC,ref}$ reaches its maximum of 19.5 A at the maximum speed and falls to zero at the end of the acceleration. During the braking, a similar behavior can be observed with the opposite current sign whose maximum results -33.6 A. The ACR current is reflected in the current supplied by the substation and that drawn by the dc-bus of the traction vehicle, i_t, shown in Fig. 6 a). The "peak shaving" action due to the contribution of ACR system is highlighted by the diagram of the substation current, i_{sub}, that in correspondence of t= 24 s, presents a peak equal to $i_{sub,peak}$= 12.4 A, significantly smoothed respect to one of the vehicle current, which is obviously the same as for the case of dissipative braking ($i^{(BR)}_{sub,peak} = 17A$), with consequent current peak reduction by 27.1 %.

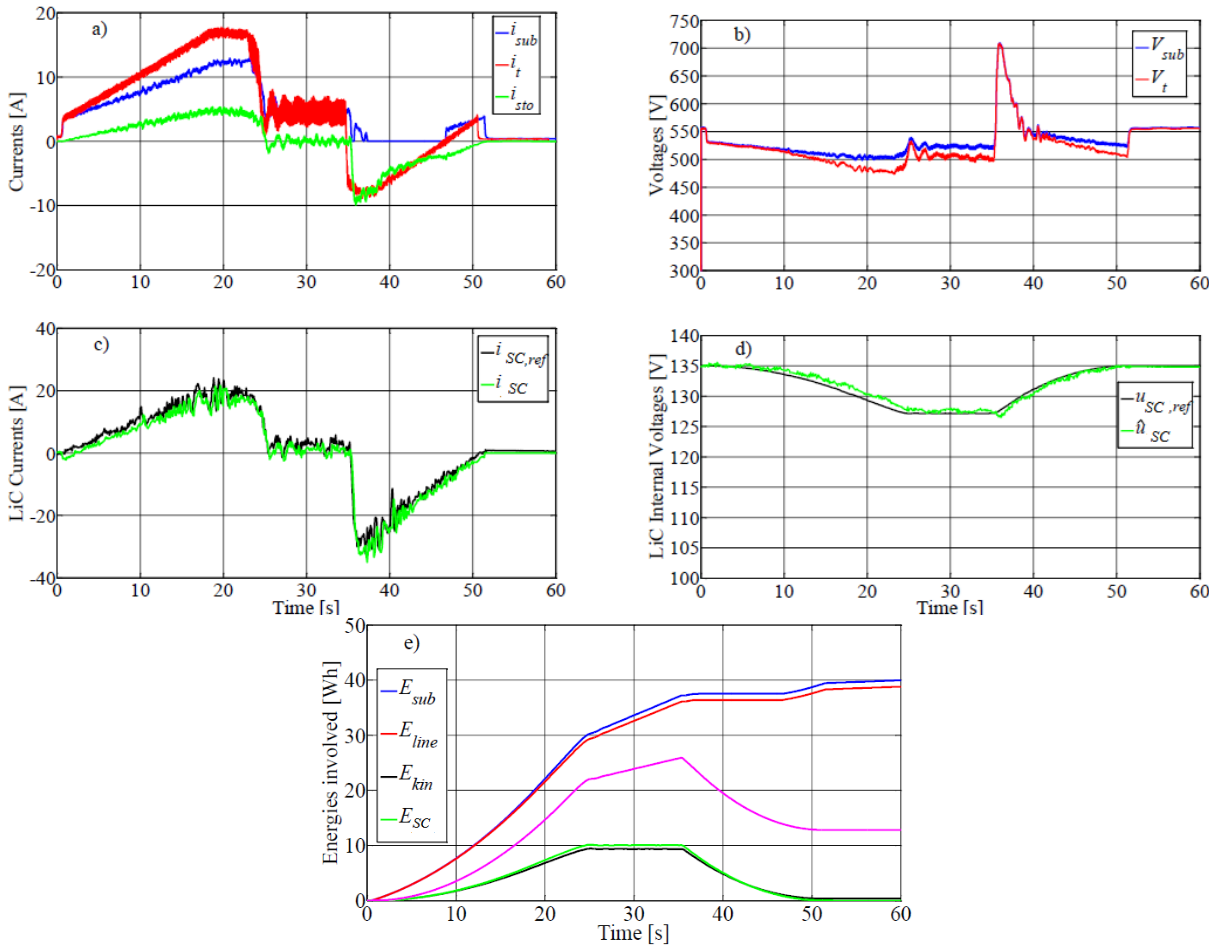

Fig. 6 On-board with ACR system simulation results: a) Line, tram and storage currents; b) Substation and tram voltages; c) SC actual current and its reference; d) ACR internal estimated voltage and its reference; e) Energies involved in the traction cycle

In agreement with the suggested control strategy, ACR system reach the minimum voltage of 127 V when the simulated vehicle travels at the maximum speed.

During the braking, the kinetic energy is converted into electrical energy by the electrical traction drive, as it can be seen since i_t is negative. In this phase, ACR stores the electrical energy available and is recharged to its initial state of charge value since the ACR internal voltage reference is directly related to the actual vehicle kinetic energy E_{kin}, as it is evident from Fig. 6 e). This effect can be also highlighted in Fig. 6 d) by the increasing of ACR voltage when the braking starts.

As it is evident from the figure, the agreement between estimated ($\hat{u}_{LiC}$) and reference ACR voltage is very good for all the cycle, confirming the effectiveness of the speed tracker control proposed.

The impact of the energy storage system on the simulated railway DC electrified line is shown in Fig. 6 b). The voltage drop on the line, which occurs at t= 24 s, is significantly reduced ($\Delta V_{t,\max} = 52V$) respect to the no-load substation voltage $V_{sub,0}$ = 535 V) by the presence of ACR for the whole duration of the acceleration.

COMPARISON FOR WITHOUT AND WITH THE ACR SYSTEM INSTALLATION

In order to better assess the differences and characteristics of the tested control strategies and also for remarking the benefit of installing the ACR storage by evaluating the system performances in terms of energy efficiency improvement and voltage drops compensation, some specific performance indexes have been defined. The Table 1 shows the defined indexes by comparing all the aforementioned test results without and with the ACR system

Table 1

Index	Without ACR system	With the ACR system
Energy saving $es\% = \left(1 - \frac{E_{sub}}{E_{sub}^{(BR)}}\right) \cdot 100$	-*	16,5
Max Voltage drop $\Delta V_{t,\max\%} = \left(1 - \frac{V_{t,\min}}{V_{sub,0}}\right) \cdot 100$	13,8**	9,91
Substation peak current reduction $r_{isub,peak\%} = \left(1 - \frac{i_{sub,peak}}{i_{sub,peak}^{(Br)}}\right) \cdot 100$	-***	27,1

*Base value for the comparison $E_{sub}^{(BR)}$ =**47.8** Wh,

** Base value for the comparison $\Delta V_{t,\max}^{(BR)}$ =**75.0** V with $V_{t,0}$ = $V_{sub,0}$ = 535 V,

*** Base value for the comparison $i_{sub,peak}^{(BR)}$ =**17.0** A.

As it is clearly highlighted, on equal traction cycles, the on-board ACR strategy assures the highest value of *es%* (**16.5** %). This is mainly obtained thanks to the capability of the ACR technique to make null the energy wasted in the on-board braking rheostat. This is not a surprise, since the actual energy stored in the ACR system, E_{SC}, is instantly related to the actual kinetic energy of the vehicle, E_{kin}. The ACR strategy also gives satisfactory results with regard to maximum line voltage drop, $\Delta V_{t,max\%}$, and substation peak current reduction, $r_{isub,peak\%}$, which corresponds to the **9.91** % of $V_{sub,0}$, (53 V) and the **27.1** % of $i_{sub,peak}^{(BR)}$, (12.4 A).

The Fig. 7 shows the trend of the energy saving in function of the maximum cruise speed and different total distance covered, assuming the regenerative braking energy share coefficient: β = 1.

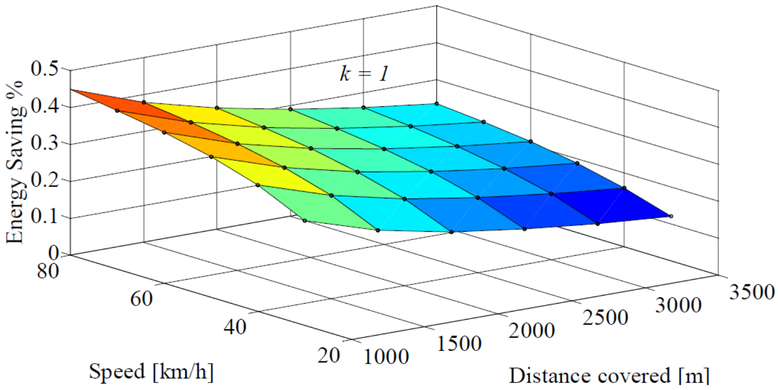

Fig. 10 Trend of energy saving in function of the maximum vehicle speed and the total distance covered, with β=1

CONCLUSION

On board energy storage systems applied in the urban electrified public transport in Belgrade (R. Serbia) is still in a prototype state. Some open technical and commercial tasks have to be solved, but they seem to be uncritical. Nevertheless applications will not be done without any risk share between operator and vehicle manufacturer. Therefore it is to early to introduce energy storage in a bigger portion of new trams, but at least new vehicles should be prepared for the future. That means that vehicles for intensive usage - with a high energy saving potential - should be equipped with electrical traction equipment.

In spite of the mature technology of trams, many improvements concerning energy saving are still possible. The very different types of operation call for different methods of energy optimization. While the improvement of vehicle technology takes time and cost in general, the greatest effects will arise from a systematic and operational approach of the railway system based on sophisticated train control and management systems. As described in this research, the energy storage devices have reached a level of reliability that is necessary for transport application. Their benefits cover energy saving as well as improved system performance, together with possible reductions of greenhouse gas emission. In particular, intelligent control and management of auxiliary component can result in drastic reduction of energy consumption during catenary-free operation of the trams. Local technical optimizations will result in smaller overall effects, most of which are attributable to the very mature level of technology that has been reached today.

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СИСТЕМА ЗА ЕНЕРГОСПЕСТЯВАНЕ В ГРАДСКИЯ ТРАНСПОРТ НА БЕЛГРАД ЧРЕЗ ПРИЛОЖЕНИЕ НА CAF URBOS 3

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Ключови думи: *консумирана енергия на борда на превозното средство, CAF Urbos 3*

Резюме: *Консумацията на енергия от трамваите се определя, както от височината на превозното средство, така и от средната стойност на цената за консумирана енергия. В случаите когато енергията, необходима за придвижване на трамваите се съхранява на борда на превозното средство, то тогава консумираната енергия от градската електромрежа ще бъде намалена. Приложението на устройство за съхранение на енергия на борда на првозното средство позволява да се контролира потока на електроенергията. За да се постигне това е необходимо да се осигури свобода на управление на електроенергията. Управлението на електроенергията е многоаспектен оптимизационен процес, който има за цел, както да намали консумацията на енергия от градската електропреносна мрежа, така и да намали енергопоглъщаемостта на превозното средство. Разбира се посочените две цели не могат да бъдат постигнати едновременно. Основната цел на настоящия доклад е да представи системи за съхранение на електроенергия на борда на превозните средства, които се използват при градския електротранспорт на гр. Белград.*