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Control Algorithms for the Optimization of Energy Storage Systems Management in Urban Transport Systems

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Abstract

The increasing number of passengers per hour in urban railway transport systems requires higher power from propulsion systems. If the grid is not adequate to satisfy the increasing power demand, undesired voltage drops can occur affecting the correct operation of the system. It is possible to re-think the system utilizing additional devices to sustain the grid. It is then necessary to realize intermediate stations to sustain the grid providing power to the vehicles. The sustain stations can be realized utilizing energy storage systems based on Supercaps charged by the grid or by Photovoltaic (PV) plants.

The main problem in the integration of PV-Supercaps-Railway System is the control of the power converters installed between PV and Supercaps and between Supercaps and the railway system. In the paper is proposed a control algorithm for a Step-up DC-DC converter utilized as interface between PV and Supercaps, and between Supercaps and Railway system. The algorithm has been set up and validated in simulation, the results are reported and discussed in the last part of the paper.

Keywords: urban transport, energy storage system, photovoltaic.

INTRODUCTION

The new concept tram vehicles are destined to increase the number of passengers per hour, their propulsion systems must be consequently dimensioned for this new target of urban mobility. In particular, the electrical drives for the trams have to be over-dimensioned. If the grid is not adequate to satisfy the increasing power demand, undesired voltage drops can occur affecting the correct operation of the tramway system. It is not practically possible to re-build the grid but there are techniques and technologies that make possible to renew the grids utilizing additional devices to sustain the grid. It is then necessary to realize a certain number of intermediate stations to sustain the grid. These stations provide power to the vehicles reducing the peak power demanded to the grid.

The sustain stations can be realized utilizing energy storage systems based on Supercapacitors charged by the feeding grid or by photovoltaic plants. The realization of these stations requires some design steps consisting essentially in:

- Definition of Supercaps modules necessary for the energy need;
- Definition of the rated characteristics of bidirectional power converters necessary for the power flow management;
- Set up of control algorithms for the optimized management of the storage systems;
- Sizing of PV panels for the storage of the electric energy demand, taking into account the annual average radiation.

The correct and complete dimensioning of the single stations can be realized after completing a preliminary study to:

- Evaluate the power request as a function of the frequency of the trams operating on the lines;
- Know the power request of the tram vehicles along the track;
- Verify by experimental prototypes the behavior of the auxiliary elements introduced in the system.

General criteria for the design of sustain stations must take into account the specific traffic conditions and is then necessary to consider a real case-study to validate the results.

In urban electrical transport the energy storage systems utilized in light metro, tramway, trolleybus can be located on-board or in substations [1-3]. The main reason why the storage system is located on-board is the opportunity to recover energy, specifically the kinetic energy, by means of the regenerative braking of the convoy [4-6]. The electrical energy, stored in braking operation, is then utilized in acceleration phase.

The use of energy given by the storage system reduces the average energy absorbed by the vehicle from the grid. The on-board storage systems can be then directly connected to the propulsion drive allowing a higher efficiency in the energy recovery because the losses in the electrical connections are obviously minimized. In this case the energy exchange is limited to the single convoy.

The energy storage systems located in the stations are destined to the energy recovery too. In this case the trains approaching the station transfer part of their kinetic energy which is utilized for the following trains departures. The efficiency of the energy exchange is lower than the case of on-board storage systems because of the longer distances and, consequently, longer electrical connections.

The energy storage systems can also be utilized to sustain the voltage of the contact lines of tram and trolleybus net, introducing economic benefits especially in case new generation convoy are utilized.

In these case the storage system operates mainly as sustain: electrical energy is absorbed when there is no vehicle transit, and contribute to feed the train successively in case the power request could determine unacceptable voltage drops that can compromise the normal operation conditions.

Considering the high availability of sunny surfaces all along the railway and in the stations, it can be convenient to think of a PV system to produce energy that can be stored in Supercapacitors and utilized to shave the power peaks in train departures [7-16].

The main problem in the integration of PV-Supercaps-Railway System is the control of the power converters installed between PV and Supercaps and between Supercaps and the railway system. In this paper is proposed a control algorithm for a Step-up DC-DC converter utilized as interface between PV and Supercaps, and between Supercaps and Railway system [17-20]. The algorithm has been set up and validated through simulation, the results are reported and discussed in the last part of the paper.

METHODS

In a railway urban system where are integrated PV panels and supercap-based storage systems is necessary a converter to adapt the PV plant output voltage to the one necessary in recharge phase [21-26]. The converter utilized as interface between PV panels and a storage system based on supercaps is a typical Chopper buck.

Recently, in applications where are requested reduced volumes and high voltage variations is preferred to utilize DC-DC converters – DAB (Dual Active Bridge) with a medium frequency transformer to boost the voltage. In our case there is no need to reduce particularly the volumes increasing consequently the converter cost, the utilized converter is then a traditional buck converter. The buck converter control acts on the output voltage and inductance current of the chopper.

By means of a charging strategy, set up for the storage system, is determined the reference value of the output voltage of the chopper, and through a PI control is obtained the reference current of the inductance. The block scheme is shown in fig. 1. The saturation blocks impose limits on the reference current in the inductance and Duty Cycle. The Chopper structure and control have been implemented in Simulink.

The goal of the control is the recharge of supercapacitors during the day. The $V_{out,ref}$ is calculated in order to assure that the current flow in the supercaps and the current recharge limits are respected. Basing on the saturation value imposed on the current and on the duty cycle; the PI regulator are tuned assuming that the proportional constant produces the block saturation when the input error is equal to the 80%, while the integral constant is manually tuned.

The algorithm for the control of the converter acting as an interface between the storage system and the train is an evolution of the above introduced algorithm. The reference input voltage is the voltage of the catenary that feeds the convoy. The converter is a buck converter. Figure 2 shows the block scheme of the proposed control algorithm.

The variable to be controlled is the catenary voltage. This value is of great importance for the correct operation of the whole transport system, especially in acceleration and deceleration of the tram vehicles, the high current absorbed determines high voltage drops in the grid affecting negatively on the correct operation of the railway traction chain (particularly the effects are on the inverter and traction motor, reducing the available power). Comparing the reference and measured values is obtained the power reference value which is utilized in the control strategy as represented in the block scheme of fig. 3.

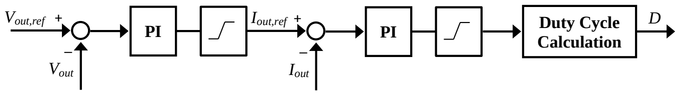

Figure 1: Block scheme of the control strategy for the chopper interfacing PV plant and Supercaps

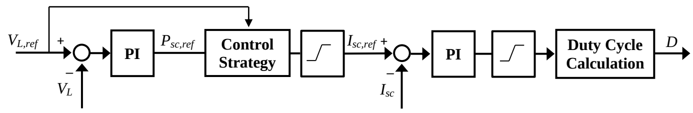

Figure 2: Block scheme of the control strategy for the chopper interfacing Storage System and Catenary

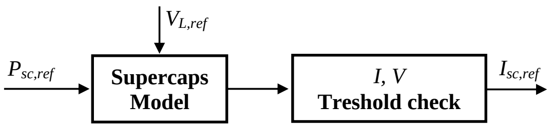

Figure 3: Implemented control strategy

The supercaps are modelled as a RC circuit; from this model and using the reference voltage $V_{L,ref}$, it is possible to compute the reference value of supercaps discharge current; in order to respect the supercaps voltage threshold, the following equation must be solved:

$$P_{sc,ref} = \frac{C}{2}\frac{dv_{sc}^2}{dt} - RC^2\left(\frac{dv_{sc}}{dt}\right)^2$$

where C is the capacitance of the storage system, R is the internal resistance of supercaps and v_{sc} is the output voltage of the systems.

If the value of v_{sc} is comprised in the range of the maximum and minimum allowable value of voltage for the supercapacitors and the $I_{sc,ref}$ is below the maximum value, the new reference value of the current is found. It is necessary to respect also a minimum threshold value for the v_{sc} in order to kept constant the efficiency of the supercapacitors.

After determining the reference discharge current of supercaps (in this case the supercaps are charged by the PV plant and the charging current is monitored by controlling the chopper on the PV plant side), the current error is evaluated by a PI and the duty-cycle of the chopper is calculated. All the PI are regulated by means of Ziegler-Nichols method.

The control techniques have been validated by means of simulations performed considering the case of a tramway of Naples (Italy) and using the software Matlab© and Simulink©. The considered tramway track, which is shown in Fig. 4, is approximately 1.8 km long and has five stops placed 300 m apart. The total time needed to pass over this track is about 300 s. A yellow circle in Fig. 4 indicates the presence of one shelter, while the green circles correspond to two shelters. The green circles are also positioned at the initial and final stops of the track. At each shelter, it is possible to install PV panels with the characteristics reported in Table 1 [27].

The maximum power generated by a plant assembled on a single shelter is about 1 kWp. Considering the total number of shelters, it is possible to install 12 kWp of PV panels along the entire track. The electrical power generated by this power plant can be utilized by connecting the PV panels directly to the low-voltage power system through an inverter to exchange electrical energy with the power system, or by linking the panels to a storage system based on SCs and using the energy during the tramway operation [27].

Table 1: Electrical data of photovoltaic panels

Quantity	**Values**
Maximum Power	212 W
Open circuit Voltage	36.2 V
Short circuit Current	7.93 A
Module efficiency	16.1 %

RESULTS AND DISCUSSION

The analysis of the integration of power converters utilized in the system including PV generation-storage-tramway with reference to the part of track between the stations Poggioreale Emiciclo and Piazza Nazionale (Fig. 4), has been done optimizing the system in the way to take the maximum advantage from the energy generated by the PV panels located on the shelters, particularly in acceleration phase of the convoy operating in the considered track.

As above mentioned there are 12 shelters along the track, and their dimensions allow to install 12 PV plants of 1 kWp on each one. The tram is a “SIRIO” model, in Fig. 5 are reported some technical specifications, equipped with two motors of 106 kW, a maximum speed of 70 km/h and the maximum absorbed current is 378 A.

Figure 5 shows the chopper output current obtained implementing in Simulink the proposed control, assuming an input voltage 300V, a load variation 500 W (rated load 6 kW) during the charge of supercap with a reference output voltage costantly 600 V (Fig. 3). Figure 7 shows the charge current in case of reference voltage ramp variation. Both simulations validated the correct operation of the control, with a step variation of small entity, in case the output reference voltage should follow a fixed trend obtained by means of the control strategy.

The algorithm for the control of the converter acting as an interface between the storage system and the train is an evolution of the above introduced algorithm. The reference input voltage is the voltage of the catenary that feeds the convoy. The converter is a buck converter. Figure 2 shows the block scheme of the proposed control algorithm.

Figure 4: Map of possible installation of photovoltaic power plant in a part of Naples tramway

TECHNICAL SPECIFICATIONS
Years of construction: 2004-2007
Number of vehicles built: 22
Manufacturer AnsaldoBreda
Wheel arrangement Bo+2
Motor power: 2x 106 kW
Maximal speed: 70 km/h
Dimensions
Length 20.200 mm
Width 2.300 mm
Height 3.414 mm
Floor height at entrances 350 mm
Passenger capacity
31 Seated
124 Standing (6 pers./m²)
155 Total capacity

Figure 5: Tram AnsaldoBreda SIRIO operating in Naples (Italy) tramway

The variable to be controlled is the catenary voltage. This value is of great importance for the correct operation of the whole transport system, especially in acceleration and deceleration of the tram vehicles, the high current absorbed determines high voltage drops in the grid affecting negatively on the correct operation of the railway traction chain (particularly the effects are on the inverter and traction motor, reducing the available power). Comparing the reference and measured value is obtained the power reference value which is utilized in the control strategy as represented in the block scheme of fig. 3.

After determining the reference discharge current of supercaps (in this case the supercaps are charged by the PV plant and the charging current is monitored by controlling the chopper on the PV plant side), the current error is evaluated by a PI and the duty-cycle of the chopper is calculated.

The simulations have been done considering a real track of the tramway net of Naples city (Italy), between Poggioreale and Piazza Nazionale stops. The absorbed electric power is reported in fig. 9.

The energy stored in the supercaps has been calculated [27], the PV installed on the tramway shelters contribute for 12 kWp, and the reduction of energy absorbed by the tram after introducing the control algorithm implementation is evidenced in fig. 10. Figure 11 shows the voltage of the catenary obtained by implementing in simulation the control algorithms. Looking at the voltage it is possible to verify that the values are in the range 600V-900V, according to the values guaranteed by the Tramway Company.

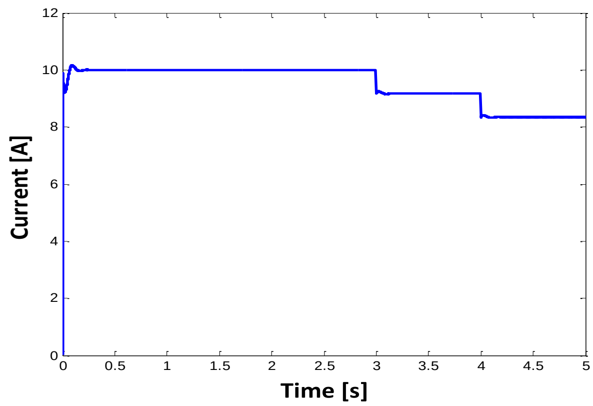

Figure 6: Chopper output current:
case of two step variation (500W) of the load

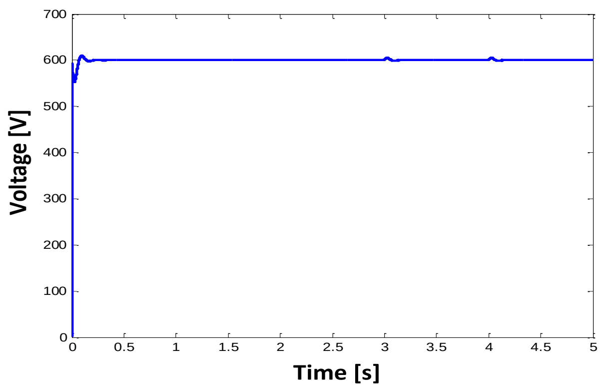

Figure 7: Chopper output voltage:
case of two step variation (500W) of the load

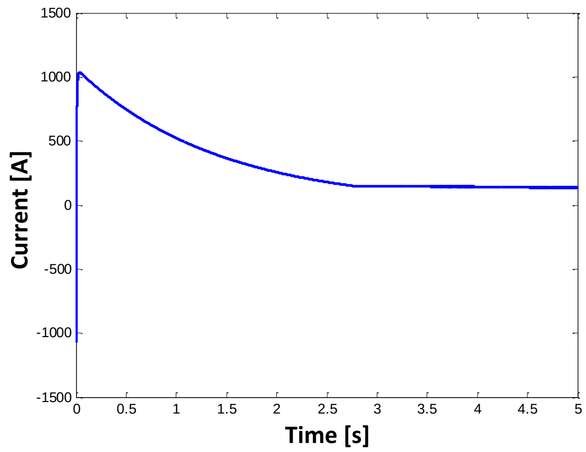

Figure 8: Chopper output current:
case of ramp variation of the output voltage reference

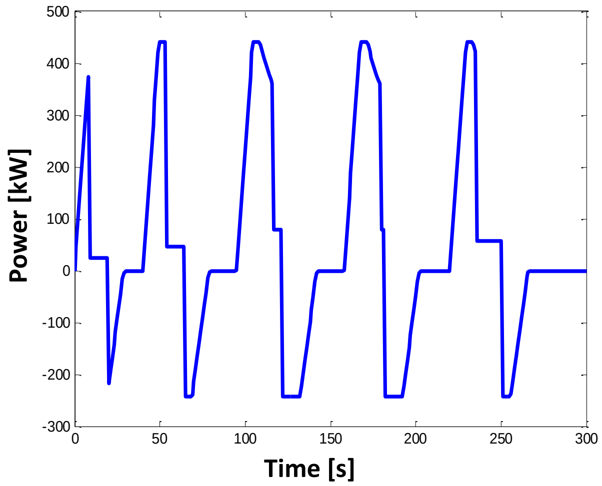

Figure 9: Power absorbed by the tram (travel time 300 s)

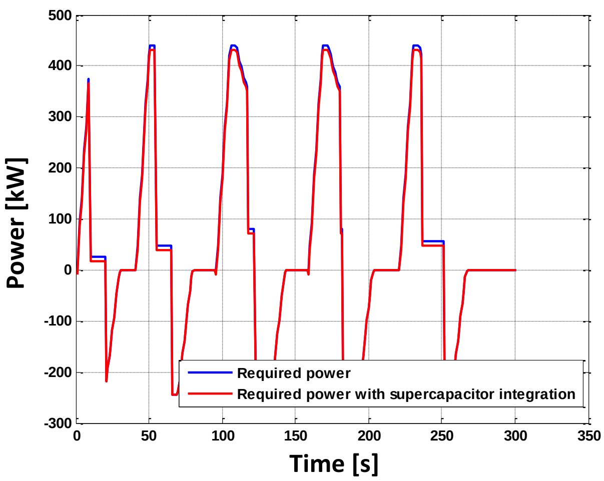

Figure 10: Power in case of integration of stored energy and PV plant

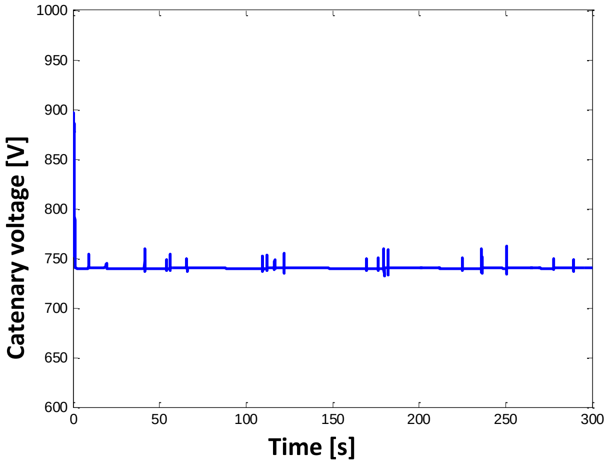

Figure. 11. Catenary voltage in integration of stored energy and PV plant

CONCLUSION

The urban railway transport system at high passenger capacity require requires new concept vehicles that are utilized to increase the number of passengers per hour. The propulsion systems must be consequently of higher power. In this paper has been considered a tramway and the problems introduced in the supply grid by the increased power demand have been analysed proposing the realization of intermediate stations to sustain the grid. These stations provide power to the vehicles reducing the peak power demanded to the grid. The sustain stations can be realized utilizing energy storage systems based on Supercapacitors charged by the feeding grid or by photovoltaic plants.

In the paper has been analyzed the integration, in railway urban transport, of energy storage systems based on Supercapacitors, photovoltaic plant, and railway system. The main problem in the integration of PV-Supercaps-Railway System is the control of the power converters installed between PV and Supercaps and between Supercaps and the railway system. In the paper is proposed a control algorithm for a Step-up DC-DC converter utilized as interface between PV and Supercaps, and between Supercaps and Railway system.

Control strategies for converter utilized as interface in the integration of PV plants, supercap-based storage systems, and tram have been set up and validated in simulation by Matlab and Simulink implementation. The simulations have been done considering a real track of the tramway net of Naples (Italy). The results of the simulation evidenced the reduction of energy absorbed by the tram after introducing the control algorithm implementation, moreover the voltage of the catenary obtained by implementing in simulation the control algorithms remains in the range 600V-900V, according to the values expected by the Tramway Company.

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