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Stationary and on-board storage systems to enhance energy and cost efficiency of tramways

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HIGHLIGHTS

- One important bonus of tramways comes from the reversibility of electric drives.
- Braking energy of trams can be recovered in storage systems.
- High power lithium batteries and supercapacitors have been considered.
- Storage systems can be installed on-board or along the supply network.
- A simulation tool has been realised to achieve a cost/benefit analysis.

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ABSTRACT

Nowadays road transportation contributes in a large amount to the urban pollution and greenhouse gas emissions. One solution in urban environment, also in order to mitigate the effects of traffic jams, is the use of tramways.

The most important bonus comes from the inherent reversibility of electric drives: energy can be sent back to the electricity source, while braking the vehicle. This can be done installing some storage device on-board trains, or in one or more points of the supply network. This paper analyses and compares the following variants:

- Stationary high-power lithium batteries.
- Stationary supercapacitors.
- High-power lithium batteries on-board trains.
- Supercapacitors on-board trains.

When the storage system is constituted by a supercapacitor stack, it is mandatory to interpose between it and the line a DC/DC converter. On the contrary, the presence of the converter can be avoided, in case of lithium battery pack. This paper will make an evaluation of all these configurations, in a realistic case study, together with a cost/benefit analysis.

1. Introduction

The use of underground railroads and tramways has been recently rediscovered to reduce urban pollution and greenhouse gas emissions. In particular, aspects such as the lower moved mass per passenger and the higher well-to-wheel efficiency of the path between the primary energy source (e.g. a fossil fuel) and the wheels, in comparison to the standard gasoline or diesel cars, may show significant, beneficial effects.

Another important bonus of electric propulsion comes from the inherent reversibility of electric drives, that allow to send back the energy towards the electricity source, while braking the tram. This can be done installing the storage system on-board trains (*on-board storage*), or in one or more points of the supply network, typically in the vicinity of the substation (*stationary storage*). The first case has the disadvantage that the storage system must be replicated several times, since it has to be installed in all reversible trains, as well as the higher space occupation and the additional mass involved by this installation. In the second case, the main disadvantage is that

Abbreviations: ESS, electric substation; LFP, lithium iron phosphate; NMC, nickel manganese cobalt; OCV, open circuit voltage; RESS, rechargeable energy storage system; SOC, state of charge.

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energy must flow through the contact line before reaching the stationary storage system and this causes energy loss and catenary voltage rise. When a train is far from the point in which the storage system is installed, the consequent voltage rise can require the train control to reduce the current conveyed to the line, to avoid excessive overvoltage. This might severely limit the amount of energy globally recovered during braking actions on the tram or underground railway. On the contrary, when two or more trains are very close to the stationary storage system, the latter requires to be properly oversized to manage the total amount of the braking currents. In literature, an overview about strategies and technologies to manage the braking energy in urban railroad systems is detailed in Refs. [1,2].

Furthermore, storage systems with several variants can be taken into account. Since the reduced braking times, the most frequently proposed solution takes advantage of supercapacitors, as described in Refs. [3,4]. From the other side, the recently developed high power lithium batteries make them more interesting and economically feasible than they used to be.

However, supercapacitors typically require the presence of the DC/DC converter, since the charge/discharge processes imply rather large voltage variations. When, on the contrary, storage system is constituted by a lithium battery, two variants can be considered: with and without DC/DC converter. The first one has the advantage to guarantee much more flexibility in the sizing of the storage system, limiting also the stress for the battery and deviation respect to the predefined state-of-charge (SOC). The latter has the advantage of the lower cost, although power fluxes and battery state-of-charge (SOC) cannot be explicitly controlled.

It must additionally be specified that the presence of the storage system on-board can also allow the tramway to operate autonomously, without the grid connection. Several other solutions equipped with sophisticated hybrid power train solutions, aimed to extend the range during driving in absence of the grid, are actually under investigation [5,6].

This paper, by means of a simulation model, makes a comparison of all the variants, in a realistic case study. Some detailed conclusions will be drawn from the analysis, mainly in terms of energy saving, sizing and cost evaluation for the considered storage systems.

2. The system under study

The basic structure of the system under study is a traction line, fed by electrical substations, with trams that start, accelerate, run, and brake. The frequent brake applications cause a large amount of kinetic energy to be zeroed, either by converting it into heat or, much better, by converting it back into electricity and using it for some useful task.

The most natural way to reuse this energy is either to send it back into other trains that need it or to store into some storage means. The situation is depicted in Fig. 1 and Fig. 2. In Fig. 1 the braking energy from train A is sent into train B, while in Fig. 2 it is partly sent into B, partly stored in the storage system located around ESS2. The next paragraphs present the main characteristics of the system under study, considering electric substations, network, trams.

The energy flows analysis requires a simulation tool able to simulate the network equations, the vehicle dynamic equations, the driver, and different running phases, such as acceleration, constant speed run, coasting and braking. The model has been developed in Modelica language [7–9]. A simplified version, containing only four substations and four trams, is shown in Fig. 3. As visible, the main subsystems are the electrical substations, the contact line, the trams and the storage system (in figure only one stationary storage system

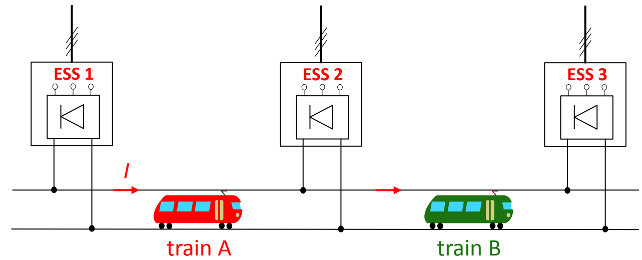

Fig. 1. A simplified representation of the traction line. Train A is braking and B is partially absorbing the recovered braking energy.

in correspondence to ESS3 is displayed). The blue lines represent electric wires, while the dark blue and the pink ones represent a bus signal that transfer information as the position, direction and velocity of the trams to the subsystem simulating the contact line. Further details about Modelica language characteristics and modelling technique used are reported in Ref. [10].

2.1. Electrical substations and contact line

Tramline feeding substations are typically based on diode bridges. Very common is the situation in which two three-phase bridges are present, fed by different windings of three-winding transformers: if the two windings are star and delta connected, and the number of secondary turns are suitably chosen, in this case each substation operates as a twelve-pulse DC source. Since it is out of the scope of this study to evaluate effects of harmonics, only the DC component of this source is of interest, and therefore for any substation the well-known DC equivalent of Fig. 4 is used, in which R_{fict} is a fictitious resistor that simulates the voltage drop due to the commutation phenomenon [11]. The main characteristics of the ESSs are summarized in Table 1.

Since during simulation trains move along the line, the contact line is a time-varying system. The line resistance between a train and the subsequent one varies over time; moreover, when a train moves from a section to another, the very topology of the contact line is changed. It is possible to analyse the contact line in reference to the scheme reported in Fig. 5, related to bilateral power conditions. Indeed, the line resistance can be modelled as variable linearly along the line, according to the following expressions:

$$R_1 = (1-\delta)R_{tot}$$
$$R_2 = \delta R_{tot} \qquad (1)$$
$$\delta = \frac{(P_2 - x)}{L_{12}}$$

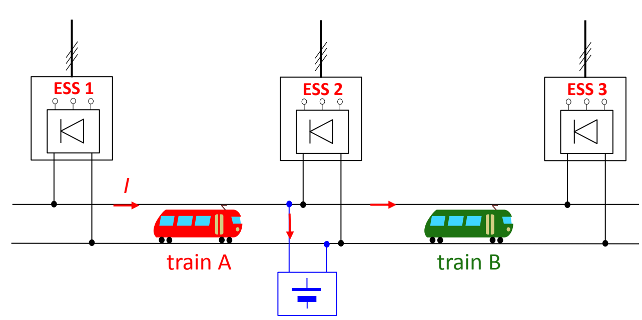

Fig. 2. A simplified representation of the traction line. Train A is braking and a storage system helps train B in absorbing the recovered braking energy.