Abstract

An innovative subway has been proposed using supercapacitors as energy source. In this paper, are presented different possibilities to reduce on-board stored energy in order to downsize the on-board energy storage subsystem. Special attention is paid to the influence of a feeding rail extension or a downward slope at the beginning of the interstation on the on-board stored energy. A map is built to facilitate the selection of the solution which leads to reduce the on-board energy.

Keywords: on-board energy, energy storage, supercapacitor, ultracapacitor, subway, traction system, energy sizing, energy gain.

1 Introduction

Energy saving is a critical issue for the next decade. The development of new transportation systems takes a part in this challenge [1]-[2]. Because electric drives have better efficiency than internal combustion engine, electric vehicles and hybrid vehicles are developed to propose alternative solutions [2]-[4]. Trains, tramways and subways have been developed a long time ago, and they provide efficient systems for passenger transportation in urban cities. Classical subways are supplied by a DC bus (rail) all along the line. Using electric drives, their efficiency is generally very high. Moreover, regenerative braking can be used leading to re-injecting electrical through the DC bus [5]. This can be made under the assumption that there are other vehicles on the line that are able to absorb this energy. When it is not the case, all braking energy cannot be recovered and braking resistor and/or a mechanical brake are used as complement to dissipate energy [6].

New technologies can be introduced in these systems to increase their efficiency [7] such as supercapacitors [1], [8]-[9], new batteries [9] and flywheels [10]. In this way, the recovered energy can be stored and reused as needed for the next traction operation [11]-[14].

A new subway is developing to propose a more efficient subway traction system. This subway uses an on-board supercapacitors bank for autonomous operation [11]. The supercapacitor bank is charged at each station. When the subway accelerates, the supercapacitor bank is discharged. When the subway decelerates, the regenerative braking charges the supercapacitor bank. In this way, the energy saving is increased. However, a supercapacitor bank installed in the subway can increase the cost and the complexity of the vehicle.
The supercapacitors can respond to an important surge of power but cannot store as much energy as batteries; therefore, they are usually used as a power source [9]. Nevertheless, in this innovative subway they are also used as the main energy source. This means that the energy storage design will be larger and heavier than if it were used only as a power source.

The purpose of this paper is to propose different possibilities to reduce the on-board stored energy requirement in order to reduce the size of the on-board energy accumulator [12]. In the first part, a reference case and the procedure to evaluate the on-board energy needs are presented. In the second part, the influence of a feeding rail extension at the beginning of the interstation on the on-board stored energy requirement is studied. In the third part, the influence of a downward slope is studied. Finally in the last section, a map is established in order to choose the best solution to reduce the on-board energy requirement.

2 Evaluation of the on-board energy for the reference case

2.1 Reference case

The studied subway is made of three cars. Each car is composed of an energy storage subsystem with supercapacitors, and of a four-drive traction system. Between two stations, the on-board supercapacitors bank is the only source that supplies the vehicle (Figure 1).

When the subway accelerates the supercapacitors bank is discharged. When the subway decelerates, a part of the braking energy is recovered and charges the supercapacitors bank. When the vehicle is stopped in station, the on-board system is charged by an external supply. In this paper, the subway is studied between two stations and the recharge system in station is not considered.

The reference interstation track is at grade and 1000 m long. The chosen rolling conditions are the most stringent in terms of energy consumption: the vehicle rolls with a strong front wind and at its full load capacity. A feeding rail is used to recharge the on-board system while the vehicle arrives at the station and spans the length of a station (Figure 1). While the vehicle accelerates, the on-board supercapacitors bank is not solicited and the energy is directly taken on the feeding rail.

2.2 Evaluation of the on-board energy

2.2.1 Model and control

A model of the mechanical part of the subway and its control has been used to evaluate the on-board energy to be stored. In order to improve the organization of the simulation model, a graphical description, EMR (Energetic Macroscopic Representation), is used (Figure 2), (Appendix), [15]. EMR is based on the action-reaction principle for organizing the interconnection of sub-systems according to the physical causality (i.e. integral causality). This description highlights energetic properties of the system (energy accumulation, conversion and distribution). Moreover, an inversion-based control can be systematically deduced from EMR using specific inversion rules. The equations of the different blocks of the model and the control are not developed in this paper but are detailed in [16]. The torque and the acceleration limitations of the drive system are taken into account in the control to evaluate the maximum on-board energy. Indeed, the higher the system limitations are, the smaller the actual maximal on-board energy requirement is [16].

2.2.2 On-board energy

The traction energy $E_{\text{tract}}$, is calculated taking into account the traction force $F_{\text{tract}}$ and the vehicle velocity $v_{\text{sub}}$. It can be expressed as a sum of several energies to overcome the different resistive forces. When the vehicle accelerates on the feeding rail, this rail supplies an energy $E_{\text{rail}}$. This energy $E_{\text{rail}}$ doesn’t need to be stored on the vehicle. Therefore, the on-board energy $E_{\text{ob}}$ is defined as the difference between $E_{\text{tract}}$ and $E_{\text{rail}}$ (1), (2).

$$E_{\text{ob}} = E_{\text{tract}} - E_{\text{rail}}$$ (1)

$$E_{\text{tract}} = E_{\text{acc}} + E_{\text{stat}} + E_{\text{visc}} + E_{\text{aero}} + E_{\text{down}}$$ (2)

Where $E_{\text{acc}}$, $E_{\text{stat}}$, $E_{\text{visc}}$, $E_{\text{aero}}$, $E_{\text{down}}$ are respectively, the supplied energy to overcome the acceleration
force (which depends on the mass $M$ and of the acceleration $a_{sub}$ of the vehicle), the static friction force, the viscous friction force, the aerodynamic force and the downgrade force respective.

For the reference case, the energy $E_{rail}$ is equal to the supplied energy by the rail in station $E_{rail\_stat}$. Moreover, as the reference track is flat, the energy $E_{down}$ which is dependant of the slope is equal to zero (3).

$$\begin{cases} E_{rail} = E_{rail\_stat} \\ E_{down} = 0 \end{cases} \quad (3)$$

The on-board supercapacitors bank is sized from the maximum variation of the on-board energy $\Delta E_{ob\_max}$ which is the difference between the maximum on-board energy level $E_{ob\_max}$ and the minimum on-board energy level $E_{ob\_min}$ (4) (Figure 3).

$$\Delta E_{ob\_max} = E_{ob\_max} - E_{ob\_min} \quad (4)$$

For the reference case, the on-board energy $E_{ob\_ref}$ is equal to zero at the beginning of the interstation, as the vehicle is starting on the rail at station 1 (Figure 3, area 1). Then, it increases rapidly until the drive reaches it’s cruising velocity then continues to increase until it reaches its maximum on-board energy $E_{ob\_max}$ just before the deceleration phase ($E_{ob\_ref} = I$) (Figure 3, parts 2 and 3). When the vehicle decelerates, a part of the braking energy is recovered in the supercapacitors bank and $E_{ob\_ref}$ decreases until the vehicle reaches the feeding rail in station 2 (Figure 3, area 4). At this moment the braking energy is recovered through the feeding rail. The energy $E_{ob\_ref}$ keeps constant until the subway has come to a complete stop (Figure 3, area 5).

### 2.3 Possibilities of reduction

Different possibilities for reducing the energy variation $\Delta E_{ob\_max}$ are conceivable. The general idea consists in reducing the maximal energy $E_{ob\_max}$. So, the energy $E_{ob\_ref}$ has to be reduced before it reaches its maximum and in particular during the acceleration phase where the required energy is the most important.

![On-board energy diagram](image-url)

Figure 2: On-board energy calculation [16]
The supplied rail in station 1 contributes to reduce the maximum energy $E_{ob\_max}$, because the energy $E_{ob\_ref}$ is equal to zero at the beginning of the acceleration phase. A first possibility to be considered for reducing the energy is to extend the rail at the beginning of the interstation. The recovered energy also contributes to reduce the maximum energy $E_{ob\_max}$ during the braking phase [14]. A second possibility of energy reduction could consist in using recovered energy during the acceleration phase. It is possible if a downhill slope is added at the beginning of the interstation. These two possibilities for reducing the energy variation $\Delta E_{ob\_max}$ are developed in the following parts.

3 Influence of a feeding rail extension on the on-board energy

3.1 Studied case

At the end of the feeding rail in station, an extension is added at the beginning of the interstation (Figure 4). While the vehicle rolls on the feeding rail extension, the on-board supercapacitors bank is not used. One expects the energy variation $\Delta E_{ob\_test\_max}$ to be lower than the one of the reference case without rail extension $\Delta E_{ob\_ref\_max}$. For the studied case, the energy $E_{rail}$ is equal to the supplied energy by the rail in station $E_{rail\_stat}$ and by the rail extension $E_{rail\_ext}$ (5).

Moreover, as the studied track is flat, the energy $E_{down}$ is equal to zero (5).

\[ \begin{align*}
E_{rail} &= E_{rail\_stat} + E_{rail\_ext} \\
E_{down} &= 0
\end{align*} \]  

(5)

3.2 On-board energy gain

An on-board energy gain $G_{E\_ob}$ is introduced. It is the relative gain between the energy variations $\Delta E_{ob\_ref\_max}$ and $\Delta E_{ob\_test\_max}$ expressed in percentage (6).

\[ G_{E\_ob}(\%) = \frac{\Delta E_{ob\_test\_max} - \Delta E_{ob\_ref\_max}}{\Delta E_{ref\_max}} \times 100 \]  

(6)

The evolution of the energy gain $G_{E\_ob}$ with the length of the feeding rail extension $L_{rail\_ext}$ can be divided in four parts (Figure 5). During the acceleration phase, while the covered distance by the vehicle is higher or equal to the feeding rail extension length, the energy gain $G_{E\_ob}$ increases (Figure 5, part 1). Indeed, the feeding rail extension contributes to reduce the maximum energy $E_{ob\_test\_max}$ during the acceleration phase where the required energy is the most important (Figure 6, $L_{rail\_ext} = 250$ m). It is also the case during a part of the constant velocity phase (Figure 5, area 2).

![Figure 3: Reference case](image1)

![Figure 4: Feeding rail extension](image2)

![Figure 5: Energy gain thanks to feeding rail extension](image3)

![Figure 6: On-board energy for different feeding rail extension lengths](image4)
Then, the energy variation $\Delta E_{\text{ob max}}$ is equal to the recovered energy (Figure 6, $L_{\text{rail ext}} = 450 \, \text{m}$). The recovered energy is constant, therefore the energy gain $G_{E, \text{ob}}$ is constant (Figure 5, part 3). After, the energy gain $G_{E, \text{ob}}$ increases again when the vehicle begins to brake on the feeding rail in station 2 (Figure 5, part 4).

Indeed, the braking energy is recovered through this rail and the energy variation $\Delta E_{\text{ob max}}$ decreases (Figure 6, $L_{\text{rail ext}} = 850 \, \text{m}$). Finally, the vehicle rolls on the feeding rail extension during all its braking phase, the braking energy is completely recovered through this rail, therefore the energy gain $G_{E, \text{ob}}$ is equal to zero (Figure 5, part 5).

### 3.3 On-board energy sizing

This study shows that the energy variation $\Delta E_{\text{ob max}}$ can be reduced significantly when an extension feeding rail is added at the beginning of the station. For example, for a rail extension of 200 m, the energy gain is equal to 50%. It means that the energy to store on-board is reduced down to 50% in comparison with the reference case (without rail extension) (Figure 5).

However, for the studied track, it is not interesting to add an extension rail higher than 450 m because, the on-board energy gain $G_{E, \text{ob}}$ is constant. Moreover, a compromise has to be found. On the one hand, the addition of a feeding rail means an additional cost and maintenance. On the other hand, the reduction of the energy variation $\Delta E_{\text{ob max}}$ means a reduction of the on-board accumulator, avoiding so a bulky, heavy and costly storage subsystem.

### 4 Influence of a downward slope on the on-board energy

#### 4.1 Studied case

The track is adapted in order to launch the subway in its acceleration phase [12]. The studied track is composed of a downhill slope at the beginning of the interstation, then a flat part and an uphill slope at the end of the interstation. When the vehicle is rolling downhill, it losses potential energy. That energy is partially converted into kinetic energy and can be recovered. If the vehicle goes down during its acceleration phase, one expects the energy variation $\Delta E_{\text{ob max}}$ to be less important than the one of the reference case without slope $\Delta E_{\text{ob ref max}}$.

For the studied case, the extension rail is not considered and the energy $E_{\text{rail}}$ is equal to the supplied energy by the rail in station 1, $E_{\text{rail stat}}$. Moreover, as the studied track is not flat, the energy $E_{\text{down}}$ has to be considered (7). It is negative if the vehicle is in a downward slope (the slope $s$ is negative) and is positive if the vehicle is in an uphill slope (the slope $s$ is positive) (2).

$$E_{\text{down}} = \int_0^{\ell_{\text{sub}}} v_{\text{sub}}(t) g s(X_{\text{sub}}(t)) \, dt$$

Where $v_{\text{sub}}$ is the vehicle velocity, $g$ is the gravity and $X_{\text{sub}}$ the position of the subway.

#### 4.2 On-board energy gain

The evolution of the energy gain $G_{E, \text{ob}}$ with the slope length $L_{\text{slope}}$ can be divided in three parts (Figure 8). At the beginning of the acceleration phase, the subway is starting on the feeding rail at station 1; therefore the energy gain $G_{E, \text{ob}}$ is equal to zero (Figure 8, part 1). Then, while the distance covered by the vehicle during the acceleration phase is higher or equal to the length of the slope, the energy gain increases (Figure 8, part 2). Indeed, when the vehicle goes down, a part of its kinetic energy is recovered and contributes to reduce the maximal energy $E_{\text{ob max}}$ (Figure 9, $L_{\text{slope}} = 170 \, \text{m}$). It is also the case during a part of the constant velocity phase. After, the subway begins to slow down as soon as it reaches the uphill portion of the track slope. The energy supplied during the uphill slope becomes higher than the recovered energy (Figure 9, $L_{\text{slope}} = 450 \, \text{m}$). Consequently, the maximum energy $E_{\text{ob max}}$ increases, therefore the energy gain $G_{E, \text{ob}}$ decreases (Figure 8, part 3).

#### 4.3 On-board energy sizing

This study shows that the energy variation $\Delta E_{\text{ob max}}$ can be reduced significantly when there is a downward slope at the beginning of the station.
For example, for a length of the downward slope of 200 m, with a slope of 6%, the energy gain is equal to 25%. It means that the on-board energy to store is reduced of 25% in comparison with the reference case (without slope) (Figure 8).

5 Influence of a feeding rail extension and a particular track on the on-board energy

5.1 Studied case

The studied case combines both energy gain solutions presented previously. A feeding rail extension and a downward slope are added at the beginning of the interstation (Figure 10).

For the studied case, the energy $E_{\text{rail}}$ is equal to the supplied energy by the rail in station $E_{\text{rail,stat}}$ and by the rail extension $E_{\text{rail,ext}}$ (8). Moreover, as the studied track is not flat, the energy $E_{\text{down}}$ is also considered (8).

\[
\begin{align*}
E_{\text{rail}} &= E_{\text{rail,stat}} \\
E_{\text{down}} &= \int_0^t v_{\text{sub}}(t) M g p(x_{\text{sub}}(t)) dt
\end{align*}
\]

5.2 Energy gain map

In order to choose the best solution to reduce the on-board energy needs, a two dimensional map is constructed. It gives the energy gain $G_{E,ob}$ as a function of the rail extension length $L_{\text{rail,ext}}$ and as a function of the slope length $L_{\text{slope}}$ for a given slope $s$ (Figure 11).

Firstly, the $L_{\text{slope}}$ is fixed and the variation of the $G_{E,ob}$ with the $L_{\text{rail,ext}}$ is studied. Secondly, the $L_{\text{rail,ext}}$ is fixed and the variation of the $G_{E,ob}$ with the $L_{\text{slope}}$ is studied. Finally the variation of the $G_{E,ob}$ is studied when the $L_{\text{rail,ext}}$ and the $L_{\text{slope}}$ varies (Figure 11). For the studied case, the slope $s$ is considered equal to 6%. For a given $L_{\text{slope}}$, for example 150 m, without rail extension, the $G_{E,ob}$ is equal to 20% (Figure 12). If a rail extension $L_{\text{rail,ext}}$ is added, the $G_{E,ob}$ increases ($G_{E,ob,P1} < G_{E,ob,P2} < G_{E,ob,P3}$).

Considering the point $P_2$, as an example, the extension rail is equal to 200 m and the $G_{E,ob}$ varies from 20% to 60%. This study shows that it is not interesting to add a slope length higher than 175 m because beyond that the $G_{E,ob}$ decreases.

This map can be divided in different areas. Every area can be characterized by the sign of the derivative of the length slope $L_{\text{slope}}$ in relation with the rail extension $L_{\text{rail,ext}}$. The different cases are summarized in Table 1. The most interesting area is the one where this derivative is negative, identified by the greyed area (Figure 11). Indeed, in this area if the $L_{\text{rail,ext}}$ increases or if the $L_{\text{slope}}$ increases, the $G_{E,ob}$ always increases.

For example, for a rail extension $L_{\text{rail,ext}}$ of 200 m and a slope length $L_{\text{slope}}$ of 150 m, the $G_{E,ob}$ is reduced of 60%.

6 Conclusion

An innovative subway without feeding rail is under development.
An on-board energy storage system using supercapacitors supplies the vehicle with energy between two stations. Different possibilities to reduce the on-board energy to be stored have been studied. The first solution consists in adding a feeding rail extension.
at the beginning of the interstation. The second solution consists in changing the track profile with a downward slope at the beginning of the interstation. For these two possibilities, the on-board energy to be stored can be reduced significantly, in particular during the acceleration phase. The third solution is a combination of both solutions. The energy gain map help to choose the optimal solution.

Appendix: Synoptic of Energetic Macroscopic Representation (EMR)

<table>
<thead>
<tr>
<th>Source of energy</th>
<th>Coupling device (energy distribution)</th>
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<tbody>
<tr>
<td>Mechanical converter (without energy accumulation)</td>
<td>Control block without controller</td>
</tr>
<tr>
<td>Element with energy accumulation</td>
<td>Control block with controller</td>
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</tbody>
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References


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