

# Technologies for optimal management of regenerative braking energy in urban rail systems

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*Abstract– With the increase in energy demand and the need for clean and sustainable development, energy storage and conversion technologies have become one of the topics of greatest interest to the global communities of science and technology. Among them, electrochemical devices such as batteries, fuel cells and supercapacitors are of great importance. Specifically, supercapacitors have several advantages, such as fast charging, large number of charge-discharge cycles and a wide operating temperature range, which have enabled a wide application in hybrid and electric vehicles. Supercapacitors have proved to be very useful devices in transport systems, since they allow different degrees of energy savings in their operation, while contribute to a lower emission of greenhouse gases. On the other hand, an electric rail system is the most efficient and environmentally friendly way to transport people in the urban and interurban environment. Today, the optimization of energy consumption of the train is a major concern, so that rail systems have begun to consider regenerative braking technologies, which allow trains to use the energy generated in braking operations and to use it for other purposes, that is, to satisfy the on-board energy demand, provide traction to other trains on the same route or even reinject the energy to the electric power network that provides the railroad. This document presents a global vision of the strategies and technologies currently available for the recovery and management of braking energy in the urban railway, which includes the optimization of schedules, on-board and stationary energy storage systems, and reversible substations.*

**Keywords-- Regenerative braking - Supercapacitors - Energy storage systems - Reversible substations - Energy efficiency.**

## I. INTRODUCTION

In traditional railway systems without energy storage capacity, most of the energy recovered in braking is used by another train that is simultaneously accelerating in the same electrical section as the braking train.

When there is no train accelerating at an effective distance, the excess energy is lost. The most common problem is that the catenary, or the third rail as the case may be, cannot recover the excess energy and return it to the network. When a train is braking and there is no other accelerating, the voltage on the catenary or third rail rises to a level where it is necessary to dissipate the regenerated energy as heat way in a braking resistor to prevent damage to electrical equipment. In railway systems such as the railway in Korea or the Medellín Metro, this condition is frequent, and a large part of the regenerated energy is not used. In the case of the Medellín Metro, it was estimated that the energy dissipated in heat is 1.3 GWh per year (2.4% of the traction energy). The gas

emissions of greenhouse effect associated with the production of electricity that is dissipated as heat in the trains, in Colombia, correspond to 130 tons of CO<sub>2</sub> equivalent per year.

A stationary energy storage system is a stationary system that can be installed at a specific location next to the railway line. The energy storage system captures and stores the braking energy of the train so that it can reuse that energy afterwards. With energy storage installed as part of the rail system, when the train brakes, the excess energy produced is captured by the energy storage and dispatched to the grid for use later, when the next train draws power from the line.

This work is a necessary preliminary study for the development of a research project that proposes to design energy storage systems to equip the electrified railways of the Buenos Aires Metropolitan Area (AMBA).

## II. ENERGY STORAGE SYSTEMS

An electric rail system is the most efficient and environmentally friendly way to transport people in the urban and interurban environment. Although the automotive industry has the greatest pressure to innovate quickly and deploy more environmentally friendly technologies, the rail industry is also feeling that pressure. The regulations surrounding carbon dioxide reductions encourage rail operators to electrify and adopt technologies that reduce emissions. As the rail industry moves in the direction of renewable energy, Europe is thinking of replacing traditional diesel trains with trains with fuel cells in non-electrified secondary sections [1], [2] and they are becoming increasingly electrified kilometers of tracks.

In electric rail systems, trains, trams and subways use electric power to move, which is provided by the region's electrical network (Fig. 1), therefore, the optimization of the energy consumption of the formations is a great concern.

The traditional braking systems create excessive friction because they use brake pads to reduce the speed of the train, with the consequent production of heat and noise, which are emitted to the environment. Its replacement by another braking system, in addition to using energy more efficiently, substantially reduces the noise and heat produced. In this sense, rail systems have begun to consider regenerative braking technologies, which allow trains to recover the energy generated in braking operations and use it for other purposes, that is, to satisfy the demand for energy on board, to provide traction to other trains that are running in the vicinity or, even, to reinject the energy to the electric power network that provides power to the railway [4]. There are measurements and calculations that show that up to 40% of the energy

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provided to an electric rail system can be recovered through the use of a regenerative braking system [5], [6]. Most of the current traction machines are reversible; therefore, regenerative braking can be used to return the kinetic energy of the train to the catenary as electrical energy. This can be done under the assumption that there are other vehicles in the line that can absorb this energy. If this is not the case, not all braking energy can be recovered, and a braking resistor is used as a complement to dissipate the energy.

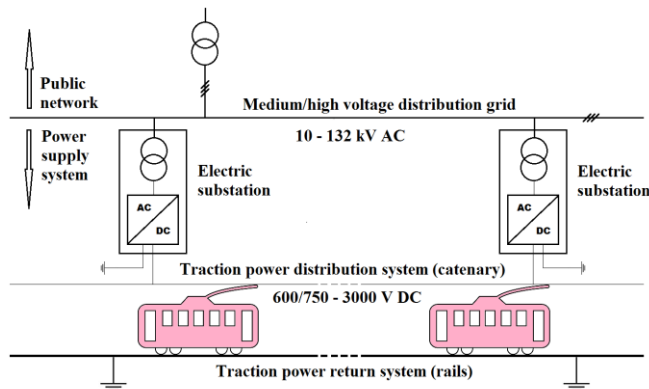


Fig. 1 Diagram of a typical DC power supply network for urban rail systems. Adapted from [3].

When vehicles are equipped with regenerative brakes, two possibilities appear: the recovered energy can be used by other trains -this is a typical solution in high density traction systems- or it can be stored in devices. In the last case, the energy storage device, which may be on board or located both in the substations and along the track, can be used for these purposes:

- energy saving.
- optimization of energy efficiency.
- stabilization of catenary voltage.
- power regulation [7].

Regarding about the first point, energy saving can be achieved by saving the energy generated by regenerative braking in a storage device and using it later, if necessary, which leads to a great reduction in energy consumption.

An optimization of the energetic efficiency can be reached basically by means of the reduction of the primary energy required for the electrical substations of the railway system.

Regarding about voltage stabilization, voltage drops in railway systems produce disadvantages in terms of the performance of traction motors. In general, an optimization of the voltage profile is obtained when regenerative braking occurs.

Finally, the storage systems are intrinsic candidates, for the operational behavior, to obtain a drastic reduction of the maximum powers required for the substations during the phases of acceleration and braking.

Then, energy storage systems (ESS) are introduced to increase efficiency in electric rail systems. For example, supercapacitors, new types of batteries and flywheels have been tested for this application [8]. Thereby, the recovered energy can be stored and reused for the next traction operation.

ESSs based on supercapacitors are ideal for this type of applications, where high power peaks are frequent [9], due to their capacity to capture them, due to their rapid response [10]. Its low internal resistance allows a high efficiency of the charge / discharge cycle, while its electrostatic nature allows a long service life [11] (in the order of one million cycles of loading and unloading [12]). ESSs based on supercapacitors provide:

- a solution to the challenges of electrification and efficient energy management.
- a reduction in the noise that trains make when they stop at a station.

There are two approaches to energy storage in rail networks that have significant advantages in cost savings and operational efficiency: the wayside or stationary energy storage and the on-board energy storage. Regardless of whether they are used for mobile or stationary applications, it can be said that ESSs usually consist of three main functions: the energy storage device itself, a power converter to make compatible the electrical input and output flows and a controller that manages the loading and unloading processes. Figure 2 illustrates the structure of the ESS.

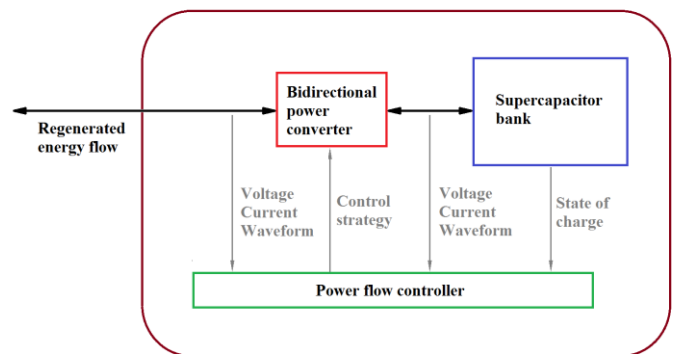


Fig. 2 Components of an ESS for railway systems. Adapted from [13].

#### A. On-board energy storage

The onboard energy storage system is installed in the train itself. Figure 3 shows the operation of a train equipped with an ESS on board:

- when the train leaves a station, the ESS provides the power to the electric machine that works in motor mode producing the acceleration of the vehicle.
- when approaching the next station, the train starts to brake and the electric machine changes its operation to generator mode, storing the energy recovered in the ESS.

c) while the train is stopped at a station, the ESS continues charging taking power from the network.

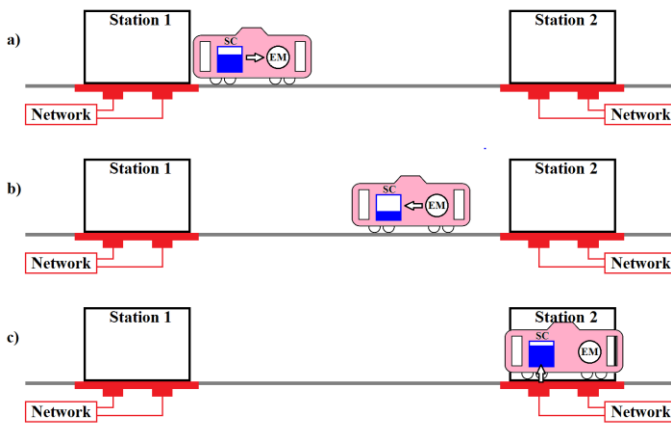


Fig. 3 Operation of a train with ESS on board. Adapted from [14].

The advantages of onboard energy storage are [13]:

- Cutting of the power peaks required from the network during the acceleration of trains, which reduces energy costs and minimize losses due to Joule effect in the supply line and in considerable benefits for the infrastructure, which may even allow the reduction of substations in a railway line.

- Limitation of voltage drops in the catenary, which could eventually allow a higher density of traffic without modifications in the existing infrastructure.

This is the best option for railway operators who want to save energy and protect the catenaries or electrical components on board regarding about voltage fluctuations.

- The train does not depend on the proximity to the substations to access the additional energy provided by the on-board storage system.

- It is used in hybrid trains to reduce fuel consumption through the use of recovered energy and to bring the operation of the diesel engine to more efficient operation points.

- Diesel trains benefit even more from on-board energy storage, as it provides a reliable and compact engine starting system, which operates even at temperatures of  $-40^{\circ}\text{C}$ .

- It allows the operation of electric trains without catenary or third rail. Trains without catenary refer to trains that do not have overhead lines.

- An ESS on board can serve as a backup power source when electricity is not available. An ESS covers the energy gap in a highly efficient way, effectively eliminating short-term power interruptions. Once the train is back on an airline, the ESS is recharged from the external power line.

### B. Stationary energy storage

In traditional rail systems without energy storage capacity, most of the energy recovered in braking is used by another train that is accelerating in the same electrical section of the braking train. When there is no train accelerating to an effective distance, the excess of energy is lost. The problem is

that the catenary cannot recover the excess of energy and return it to the network. When a train brakes and there is no other one accelerating, the voltage of the catenary rises to a level where it is necessary to dissipate the regenerated energy in the form of heat in a braking resistor to protect the electrical equipment from damage. In railway systems such as the railroad in Korea [15] or the Metro in Medellín, this condition tends to be frequent, and a good part of the regenerated energy is not used. In the case of the Medellín Metro, it is estimated that the energy dissipated in heat is 1.3 GWh per year (2.4% of the traction energy). The emissions of greenhouse gases associated with the production of electricity that dissipates in heat in trains, in Colombia, correspond to 130 CO<sub>2</sub> equivalent tons per year [16].

A stationary ESS is a system that can be installed in a specific location adjacent to the railway line. With energy storage installed as part of the rail system, when the train brakes, the excess energy produced is captured by the energy storage and dispatched to the grid for use later when the next train draws power from the line. The ESS is normally placed in electrical substations or in specific places where the voltage variations of the contact line are more significant, that is, where braking and starting are repeated, for example near the stops.

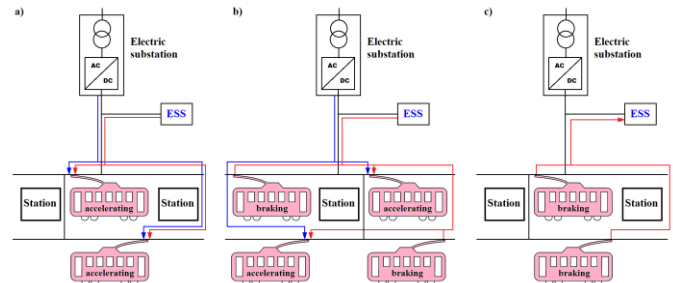


Fig. 4 Stationary ESS: energy flow in urban transit system.

Adapted from [15].

When the ESS is installed in an electrical substation, the energy flows as shown in Figure 4.

a) When most trains are accelerating, the power is provided by the network and the ESS.

b) In the case of equal number of trains that are braking and accelerating, part of the energy that the latter demand is provided by the energy regenerated by the former, and the rest, by the network and the ESS.

c) The ESS stores the excess energy when there is a majority of trains braking.

The energy storage system works in two ways: in the energy saving mode, it absorbs the energy generated by vehicles braking and stores it until the storage unit can power it back into the power supply system, later, when the vehicles accelerate. As a voltage stabilizer, its energy content is constantly maintained at a high level and is discharged when the system voltage falls below a specified limit, for example, if several formations are starting simultaneously, the catenary

voltage could fall enough to affect the performance of the train or tram.

When a train is braking and there is an energy consumption by nearby trains that are accelerating, the regenerated energy can be returned to the train's power system, an energy compensation phenomenon occurs, which stabilizes the voltage, contributing not to exceed the operational limits; it is then said that the network is highly receptive, defining receptivity as the fraction of energy that can be fully recovered using regenerative brakes [7]. When it is impossible to return energy to the system, due to the absence of compensation effect, the network is considered to be not very receptive [17].

Nowadays, due to the development of energy storage devices in conjunction with converters based on power electronics, it is possible to develop compensation equipment that allows improving the receptivity of the network, with the following benefits:

- Improvement in voltage stability: natural consequence of the compensation effect.
- Energy saving: the energy is not dissipated in resistances, but it is reused for traction.
- Better utilization of the infrastructure of the power system: when there is a flattening in the demand curve and an improvement in voltage regulation, the number of trains that can be supplied with energy with the same system increases, and eventually, before an expansion, the operating distance could be increased.
- Trains can reach the nearest station in the event of a power supply failure, which increases the safety of the system.

When compared to onboard devices, stationary systems have the advantage of having fewer restrictions in terms of weight and space required. In addition, stationary systems can recover energy from several braking vehicles at the same time and their implementation and maintenance do not affect operations. On the contrary, stationary systems are generally less efficient due to the transmission losses that take place in the network. This fact, which is directly related to the distance between the braking vehicles and the ESS, makes it essential to carry out a careful study to determine the optimal position of the storage devices along the line.

In general terms, the application of energy storage systems results in a reduction of approximately 20% of the cost of energy [18].

### III. REVERSIBLE SUBSTATIONS

Different options have been studied for the storage and subsequent reuse of the energy recovered during braking, both for the on-board and stationary alternatives. Another alternative is to use reversible substations (also known as bidirectional or inverter substations), which allow the direct return to the distribution network of the recovered energy that is not used in the railway system. This would be carried out by converters with capacity to transfer power from the catenary directly to the three-phase AC network. Storage options are

more expensive and larger than due to the energy storage components used. In addition, there are limitations associated with the lifetime of the storage components.

In DC networks, substations generally provide current only in one direction (power towards trains) and cannot conduct the electricity generated in the system back to the distribution network. On the contrary, reversible substations include an inverter that allows bidirectional operation. This means that excess regenerated energy can be used in the operator's network (lighting, escalators, offices, etc.) or eventually sold back to the energy supplier, depending on the legislation of each country or community [19].

Although the main objective of reversible substations is to improve the responsiveness of the DC power system line, transferring the excess energy to the AC medium voltage distribution network that is naturally receptive, they must give priority to the natural exchange of energy regenerated between vehicles. In addition, reversible substations are required to minimize the level of harmonics, ensuring a good quality of power supply on the AC and DC sides. The maintenance of the output voltage in the traction and regeneration modes to reduce losses is another important function that the inverter substations must fulfill [20].

The main expected benefits of reversible traction substations are:

- regeneration of 99% of the braking energy always, while maintaining the priority to the natural exchange of energy between the trains; this will allow to eliminate the braking resistors, and thus reduce the mass of the train and the release of heat.
- regulation of its output voltage in the traction and regeneration modes to reduce losses and increase energy pickup of distant trains, and
- reduction of the level of harmonics and the improvement of the power factor on the AC side [21].

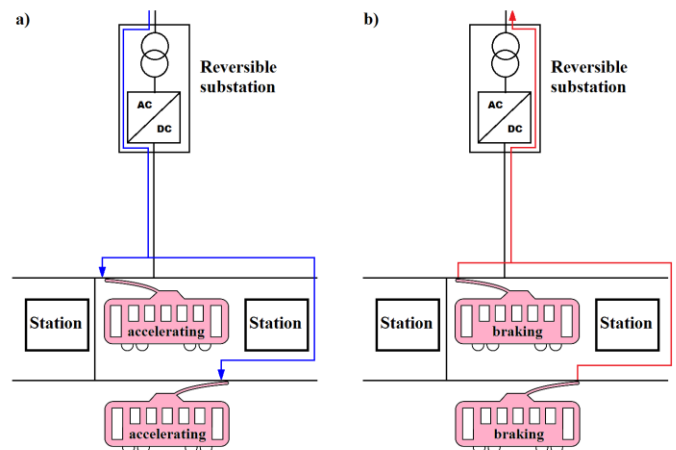


Fig. 5 Reversible substation: energy flow in urban transit system.

When the electrical substation is reversible, the energy flows as shown in Figure 5.

a) When most trains are accelerating, the power is provided by the network.

b) The energy comes back to the network when there is a majority of trains braking.

Compared with ESS, the recovery of braking energy through reversible substations can be considered a more efficient option, since they have less transformation losses. However, the resistive losses could be relatively high if an adjusted analysis is not carried out to select the most suitable locations. Other important advantages of reversible substations over ESS are as follows: they require reduced space; they have lower safety restrictions and do not require extensive maintenance. In addition, the implementation, maintenance and repair do not affect the operations in the rail system. On the contrary, the inverter substations do not allow operation without catenary of the vehicles and cannot be used for voltage stabilization or power peak reduction purposes.

#### IV. CONCLUSIONS

Supercapacitor-based energy storage systems provide a solution to the challenges of electrification and efficient energy management, while contribute to lower greenhouse gas emissions and reduce the noise that trains make when they stop at a station.

In general terms, the application of energy storage systems results in a reduction of approximately 20% in the cost of energy.

Current research and technological developments will allow in the near future, to have new energy storage systems, fuel cells and electric motors, which can be used in the replacement, increasingly, vehicles with internal combustion engines by vehicles of electric traction, either in pure or hybrid traction systems.

Reversible substations are a feasible and commercially available technology, although their economic viability depends to a large extent on the capacity to sell the excess of regenerated energy to public network operators at an adequate price.

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