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On the use of train braking energy regarding the electrical consumption optimization in railway station

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Abstract

Nowadays, many projects have been conducted in order to reduce CO_2 emissions, with the objective of reducing energy consumption. In the context of the urban railway area, the energy consumption is huge. It is respectively split into 70% for the traction and 30% for station consumers. Many works have already been carried out on traction systems, but very few of them were oriented towards the station energy problematic. This paper describes the project led by “Efficacity” Institute which concerns the use of the braking energy to manage and optimize the railway station energy consumption.

Efficacity investigates energetic concepts in order to store the braking energy of the trains with a stationary electrical saving system, and to reutilize it for the power supply of electric and thermal consumers or actuators in a railway station thanks to a microgrid. The idea is to store train braking energy in hybrid storage system (composed of batteries and super-capacitors cells) and to restate it judiciously at different moments of the day (during peak or low energy consumption hours) to various kind of station loads.

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1. Introduction

Efficacity is a research development institute specialized in the field of urban energy efficiency. The Efficacity Institute operates on the principle of action research:

- R&D work is carried out on the basis of a contractual program with the French National Research Agency (ANR) consisting of three research programs over the 2014–2016 period (linked to the 6 innovative projects);
- The Institute also supports public or private project owners seeking to develop innovations, experiments or demonstrators.

The project detailed in this paper is the “urban railway station” which aim to use all existing energy to reduce the daily energy consumption peak. Efficacity investigates energetic concepts in order to store the braking energy of the trains with a stationary electrical saving system, and to reutilize it for the power supply of electric and thermal consumers or actuators in a railway station thanks to a microgrid. The idea is to store train braking energy in hybrid storage system (composed of batteries and super-capacitors cells) and to restate it judiciously at different moments of the day (during peak or low energy consumption hours) to various kind of station loads.

2. Braking energy

Today, many projects are leaded to define how the braking energy can be used [F. Ciccarelli], [R. Teymourfar]. In this paper we focus on three recent projects which are close to the objectives of our work: OSIRIS, T2K and SEPTA.

2.1. Osiris

Osiris project [OSIRIS] started on the 1st of January and finished in December, 2014. Osiris has 17 project partners, including all major stakeholders: public transport operators, railway manufacturers and universities. Its aims at enabling a reduction of the overall energy consumption within Europe’s urban rail systems of 10% compared to current levels by 2020.

In order to fulfill the objective above, the following specific objectives was addressed:

- Define the overall needs and operational requirements allowing for the development of a global approach for the simulation, optimization and benchmarking of the energy consumption of urban rail systems (i.e., Light Rail, Metro, Suburban);
- Define a series of standardized duty cycles and key performance indicators for urban rail systems to allow for direct performance comparisons and benchmarking of technologies;
- Develop a holistic model framework assembling existing proprietary traction and power network simulation modules into a complete urban rail system model (i.e., the OSIRIS tool). It will include all the primary parameters that influence energy consumption, as well as their inter-dependencies. As part of the project, a model of thermal energy exchanges within trains, tunnels and stations will be developed as well;
- Employ optimization methodologies for the identification of efficient, reconciled strategies for realizing low energy consuming urban rail systems, based on the use of the OSIRIS tool;
- Propose a Technical Recommendation (TecRec – a sector-wide voluntary standard) for the use of onboard energy storage systems, addressing the issue of assessment and mitigation of safety risks for the customer and operation staff;
- Evaluate specific railway technologies, operational strategies and the economic/political framework for the future reduction of energy consumption in urban rail systems;
- Assess and compare the overall energy saving potential when applying new technologies or operational modes; and implementing them over both existing and new equipment.

- Demonstrate energy savings through the OSIRIS tool and a number of defined demonstration scenarios based on real use cases.

2.2. Ticket to Kyoto

Ticket to Kyoto (T2K) is a European project, which aimed at reducing CO_2 emissions in the public transport sector through more environmentally friendly behavior and improvements to transport-related infrastructure. The project ran over four years (2010 to 2014) with five main objectives:

- Achieving Quick Wins: The five partners have implemented easily achievable, short-term, energy-saving measures that require minimal investment, referred to as ‘Quick Wins’.
- Investing to reduce CO_2 emissions: More than half of the T2K budget was dedicated to investments to improve the energy efficiency of transport infrastructure. The investments focus on: saving energy in stations and other infrastructure; heat recovery; energy recovery from braking; and local energy production.
- Developing strategic CO_2 reduction plans for 2020: The partners built a common CO_2 foot printing method, defined common energy and climate indicators, and improved their energy monitoring. They also developed a standardized method to implement a CO_2 calculator in the five partner cities, with a view to informing users about CO_2 emissions produced when they use public transport. This work package was concluded by developing CO_2 reduction strategies until 2020.
- Optimizing policies and regulations for CO_2 reduction measures: Given the interactions between public transport companies and their stakeholders (local governments, operators, suppliers, and maintenance contractors), the partners developed a vision for improving the policy and legal context within which they operate. Benchmarking tools were also developed.
- Mobilizing people and industry: This last work package aimed to encourage T2K partners’ internal and external stakeholders to reduce their own energy use and carbon emissions through awareness-raising campaigns and events. Partners shared best practice on communication strategies to deliver these campaigns and events.

2.3. SEPTA

The Southeastern Pennsylvania Transportation Authority (SEPTA) is a metropolitan and regional transportation agency and authority. In 2012, SEPTA has developed an Energy Action Plan with the objective of making SEPTA more efficient while still preserving its substantial environmental benefits to the region. One of the three strategies categories was to implement operational strategies that achieve energy savings at no cost. One of the lost energy is the train braking energy. The problem for trains is that if there is not a nearby train accelerating to accept the regen, the energy is wasted – dissipating through the train’s resistor banks as heat. Replicating the hybrid technology would require a way to store the otherwise wasted energy.

The transit industry’s solution was the same as the automotive industry: a battery. SEPTA’s system happens to be comprised of several large batteries – produced by Saft Batteries, Inc. – and a controller – produced by ABB Envitech, Inc. – and is stored in an offsite (“wayside”) location, but it serves essentially the same purpose: to capture, store, and reuse regenerative braking energy. And, in the same way that SEPTA’s hybrid buses reduce fuel consumption, SEPTA anticipates that the battery will reduce its electric bills at the Letterly substation by 10 percent.

Through an energy storage and smart grid technology solution, SEPTA can:

- Recycle braking energy from trains powered by the Letterly Substation
- Optimize the use of their energy storage
- Decrease the payback period for their equipment
- Earn revenue from participation in the economic and regulation energy markets.

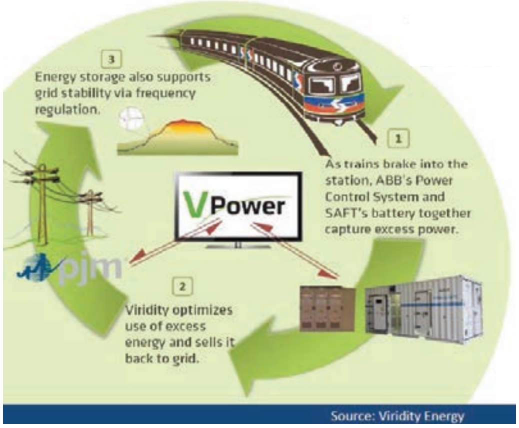

Fig. 1. How the SEPTA uses the train braking energy.

The most ground breaking feature of the project is not its potential for energy savings. Rather, it is the other ways the storage system will be simultaneously put to use. Through its partnership with Viridity Energy, SEPTA will participate in the “frequency regulation” market, which is managed by PJM Interconnection to keep the electric grid in a perpetual state of equilibrium. SEPTA’s battery will provide PJM with an on-call source of energy to help ensure grid stability. PJM will pay a premium for this service: SEPTA anticipates that frequency regulation and other demand response (load-shedding) programs could generate up to $250,000 per year in new revenue.

3. The electrical storage system adapted to the urban train station

So many investigations were made to reuse the lost braking energy for the railway electrical vehicle. There are no longer works made on the railway station potential consumer. In the literature we can find 4 methods to regenerate braking energy:

- Receptivity: the energy stay in the railway grid for the starting up of other vehicles.
- Restitute to the grid: with a reversible AC/DC the energy can be restituted to the medium voltage grid.
- Electrical storage: thanks to the technology constant evolution, today it is possible to store the braking energy.
- Warm: The lost energy is transformed to heat thanks to resistors.

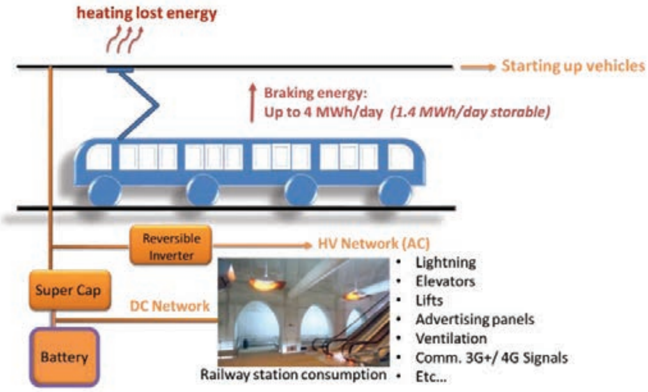

Fig. 2. Braking energy using.

Actually in the RATP (Parisian urban railway network), the braking energy is sent to other vehicles thanks to the good receptivity. The better receptivity can rise almost 96%. The 4% losses represents almost 4 MWh with a high transient current (600A maximum) and very short period (1s to 20s). With the power electronics limitations the energy usable is almost 1.5 MWh.

A storage system with a mix of super capacitors and batteries allows the using of the residual braking energy at a choosing daily time. The kind of grid (DC or AC) depends on the adaptation of the equipment. All main equipment works with a DC voltage but the input is dimensioned for an AC voltage. So it would be difficult to change all the already existing equipment but it can be interesting to forecast it for new stations concepts.

3.1. Daily consumption

Some measurements were made in a Parisian Metro station which allow to know the real consumption: almost 3 MWh. We can see in Fig. 3 the split of this consumption in main station equipment.

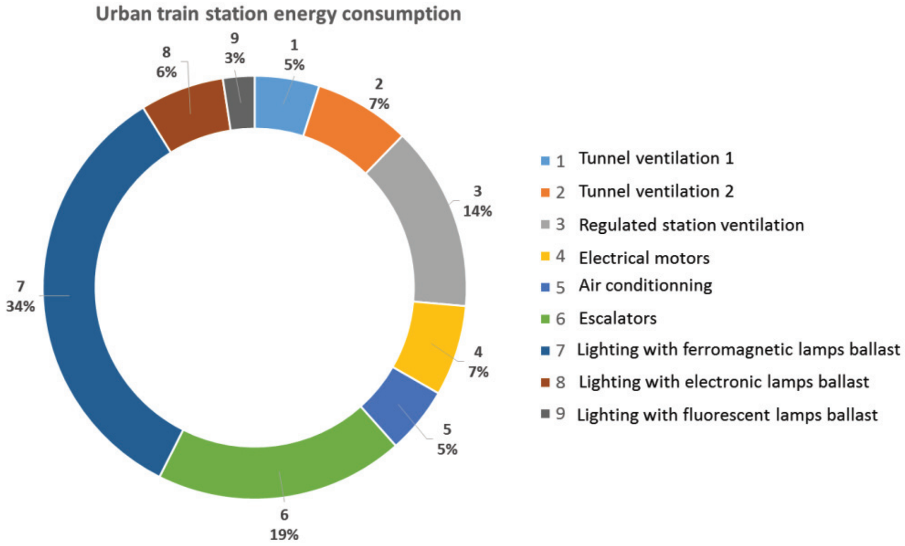

Fig. 3. A typical RATP station consumption for one day.

In Fig. 3 we can observe that the main load contributor of the station is the light. The Osiris project provides a quick solution to reduce this consumption by 50%: put LED light. Even if this load is reduced, its consumption may still be high.

We can also observe that the other main load is composed of an asynchronous electrical motors (escalators, lifts, HVAC: Heating Ventilating and Air Conditioning).

In Fig. 4 we can see that the most part of electrical consumption is the same for one day. It means we can save more energy by a good management of some equipment like HVAC.

In order to investigate the interaction of these main loads and the braking energy storage system, we developed a study case with an electrical model.

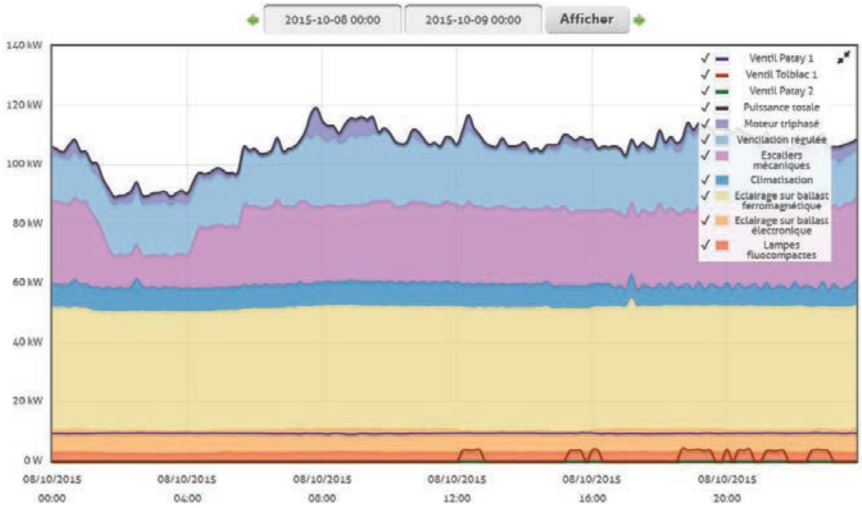

Fig. 4. A typical RATP station consumption for one day for each main equipment.

4. Study case

4.1. Station elements characteristics

In order to store energy for reducing daily peak consumption, the storage system has to be made with super capacitors for the braking energy regeneration and a battery for a long storage. These two components have to be associated in series. For this study, the supercapacitor is represented by a series resistor (278 Ω) and capacitor (19 F) sized for a 750 V voltage with a 3.4 F cells. The selected battery technology is Lithium ion for its fast charge (8C). The energy transmitted from the storage has to be controlled by a switch (Fig. 5).

Light and motors are two main station equipment. The light is equivalent to a resistor and the motor to a series inductor and resistor (the inductor for the magnetization load and the resistor representing the active power of the equipment).

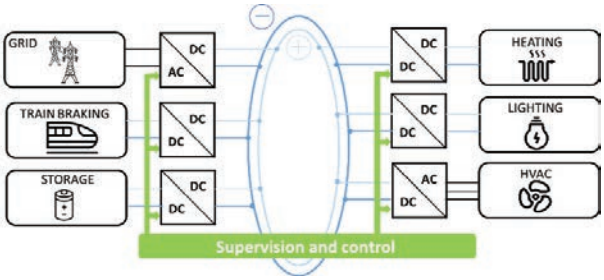

Fig. 5. Schematic of the case study with a HVAC equivalent load.

A heating component was added to this test to prevent the future need in station in case of a service development like pharmacy, medical consulting room, shopping gallery, etc…). The heating is represented in the model by a resistor load. The network is DC one in order to be free of the AC network transient effect and well adapted to the storage effects, which happen in DC mode. Moreover the control strategy for storage systems is easier to be implemented in a DC voltage mode. A study leaded by M. Iordach and S. Nasr for the OSIRIS project demonstrates that a DC network would be an appropriate solution for urban railway stations.

The schematic of the case study is represented in Fig. 6.

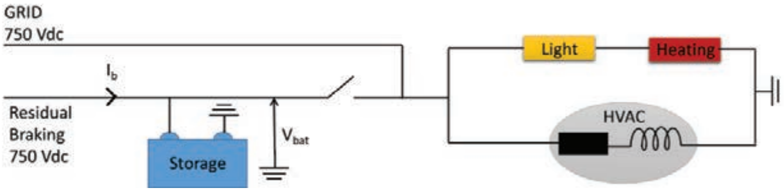

Fig. 6. Schematic of the case study with a HVAC equivalent load.

In this case study all the grid is fed by a 750 V dc voltage.

The simulation was carried out with Matlab SimPowerSystem® toolbox, with a total simulation duration of 500 s. We have to note that the duration time is too long to be able to represent the real asynchronous motor behavior with a PWM (Pulsed Width Modulation) converter control. Hence, this first study approach permits to observe the influence of the storage on the station equipment electrical evolution.

The second step of the case study will be the switch behavior study. At this step, the load power dissipation will be compound by a resistor (almost 50%) and asynchronous motors (almost 50%) as we can see in Fig 7.

The motor load control represents the HVAC one. Nowadays in underground railway stations, ventilation systems are often oversized and have an over electrical consumption. Thanks to measurements observations and the urban station electrical model, we will be able to adapt the ventilation size to the appropriated need and to optimize the HVAC control with the motor speed and airflow linear relation as follows:

$$P_{meca}\ (W) = Q(m^3/s).Hm\ (Pa) \tag{1}$$

$$P_{meca}\ (W) = Q(m^3/s).\left|P_{stat} + P_{dyn}\right|(Pa) \tag{2}$$

$$P_{meca}\ (W) = \Omega\ (rad/s).C_{meca}\ (N/m) \tag{3}$$

$$\boxed{Q(m^3/s) = \frac{\Omega\ (rad/s).C_{meca}\ (N/m)}{\left[P_{stat} + P_{dyn}\right](Pa)}} \tag{4}$$

where:
Q is the air flow (m^3/s) injected by the ventilation system, C_{meca} (N/m) the machine mechanical torque, P_{stat} and P_{dyn} respectively the static and dynamic air pressures (Pa), and Ω (rad/s) the rotational motor speed.

The speed control is made thanks to a pulse width modulation (PWM) ba sed on the frequency regulation.

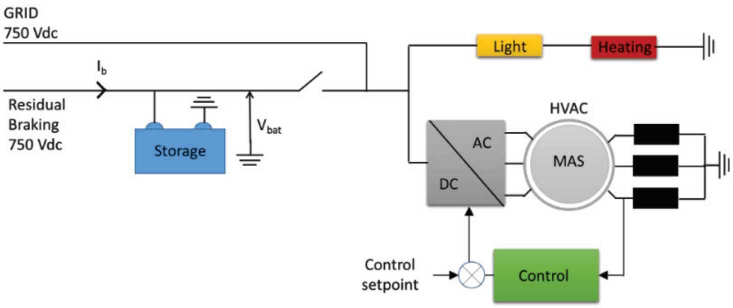

Fig. 7. Schematic of the case study with a controlled air flow.

In the next paragraph, we present results for the first step of the study in order to split each electrical phenomena and to determinate the simulation precision degree needed for the model development.

4.2. Grid electrical signal quality

In order to observe the good interconnection between the storage system and the main grid, we switch on the storage at 300s (the switch is here represented by an IGBT (Insulated Gate Bipolar Transistor) switch). Before this switch-on time, the battery (750V_{DC}, 300Ah) is only charging. After this time the battery is charging and discharging.

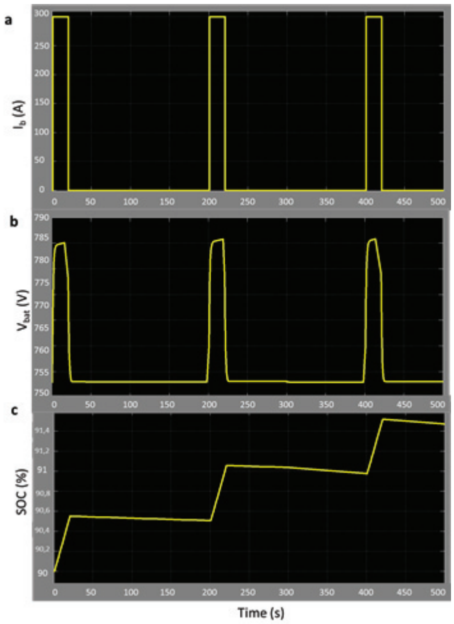

Fig. 8. (a) Braking regenerative current; (b) Storage voltage; (c) Storage State of Charge (SOC).

The braking energy signal is assimilated to a rectangle waveform with an amplitude of 300A and a duration of 20 s each 200s (Fig. 8 (a)).

We can observe that the SOC (State of Charge) of the battery rises at each braking phase, that means that the braking energy regeneration is well represented and taken into account in the electrical management (Fig. 8(c)).

We can also see a fluctuation of the storage voltage at each “braking instant” and after turning-on the switch. This is due to the current evolution. We can note that the SOC displays an insignificant change when the storage is directly connected to the station grid at braking time. This is due to the impedance balance: the impedance of loads are lower than the storage impedance. It is an interesting mode when we want to directly supply the station with the braking energy. If the need is to store the maximum of energy, we have to turn on the switch.

The load voltage and current stay stable at each time.

4.3. Regenerative signal impact on power electronic components

Power electronics have to be size to bear all transient phenomena. Hence, the study of the transient is necessary.

We can observe that the main grid and the storage currents are complementary (Fig. 9 (a) and (b)). At the storage grid switching on, we can see that the storage is enough to supply the station load when its SOC is near to 90%.

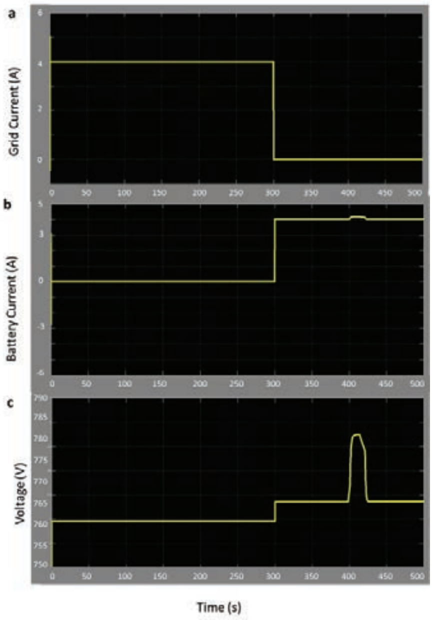

Fig. 9. (a) Main electrical grid current; (b) Storage output current; (c) Loads voltage.

We can also observe that the load voltage rise at the switching time and at each train brake. For this simulation, the voltage value doesn't disturb the equipment operational features. The solution to reduce this voltage gap is to oversize the battery capacity. Furthermore, it will allow a reduction of the charge cycles and will rise the life cycle.

5. Conclusion

In the urban railway area, the braking energy is a considerable energy source. Storing it and using it at daily consumption peak when the energy is partially produced by a coal power plant, will permit to participate at the minimization of carbon emissions and reduce the bill cost.

An urban station measurement campaign shows that the mean consumers are the light and electrical motors for elevators, lifts and HVAC application. We use these results to define a study case the nearest to a real station.

A study case representing the main station equipment and the braking energy management, demonstrates that the braking energy doesn't have a big influence on loads signal. So the hybrid storage with battery and super capacitor is enough to recover the residual train braking energy with a minimal effect on the overvoltage phenomena.

In order to be completed, this action has to be coupled to a thermal control. Thus, a mixing of a thermal and electrical grid will allow to reduce the global energy consumption with the regeneration of ALL the lost energies. The next step will be dedicated to develop an electro thermal micro grid.

This study case is the first step to a multi physical micro grid, which is a trampoline to the micro grid and the urban living of the future as reported by J. Jarass and D. Heinrichs. In the future, the micro grid will integrate many kind of energy resources and need to be managed thanks to an optimal demand response controller.

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