Development of Energy Optimization Strategies for Catenary-Free Tramways

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Abstract. The current development trend in the railway field has led to an ever-increasing interest for the energetic optimization of railway systems. A strong attention is paid to the mutual interactions between the loads presented by railway vehicles and the electrical infrastructure, including all the sub-systems related to distribution and smart energy management, such as energy storage systems. The use of regenerative braking, already widespread in tramway field, may represent one of the most promising methods to increase energy efficiency, combined with regenerative braking with storage systems of various types (Energy Storage Systems - ESS), placed on the vehicle or along the line. With the aim of correctly estimating energy performances, it is necessary to develop predictive models of entire railway systems. The objective of the present research activity was to develop an energy optimization strategy for a tram system, considering a city line in Florence. Particularly, a model of the tramway line and of the vehicle were developed with the use of simulation tools such as MATLAB-Simulink and MATLAB-Simscape. An optimization was carried out to determine the correct energy management and the use of regenerative braking, as well as the possibility to run the entire line (or portions of it) without the over-head line. The results show that recovered energy produced in the braking phase and a correct energy management can reduce the emissions produced, saving energy about 40% for each line configuration and obtain architectural improvement.

Keywords: Affordable and Clean Energy · Sustainable cities and communities · Railway · Energetic Optimization · Simulation · Energy Storage Systems

1 Introduction

Transport is a major source of air pollution and greenhouse gas emissions [1]. Transitioning to more sustainable modes of transport, and optimizing them, can play a key role in achieving this goal. Modern railway vehicles, during the braking phase, can convert mechanical energy into electricity. The current trend is to allow the reuse or accumulation of the energy produced (regenerative braking), contrary to that was done previously, where the energy was dissipated in special rheostats (dissipative braking). There are some main ways of using the energy produced during braking:

- Energy cooperation between different vehicles;

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- Use of ESS positioned on board the vehicle;
- Use of stationary ESS integrated into the infrastructure;
- Conversion and re-introduction into the electricity grid outside the line;
- Combination of the above modes.

Regenerative braking systems have been already introduced in urban type vehicles, like metro and tram vehicles whose running is characterized by several and continuous accelerations and decelerations. Literature shows some research focused on the optimization of the timetables to maximise the energy cooperation between nearby vehicles. In this way the energy obtained from the regenerative braking of a decelerating train is used by another accelerating train. The electricity generated is returned to the catenary supply line, leading to a high level of uncertainty as there is no guarantee that a train will accelerate at the same time and in the vicinity where the energy is available. However, this methodology, combined with the optimization of the speed profiles between the stations, allowed to obtain up to 14% of energy savings [2, 3]. This approach enables for an integrated optimization, which results in better energy savings than using individual optimization of the timetables and speed profiles of the vehicles. Another significant example was conducted on Beijing subway [4, 5]. Energy Storage Systems (ESS) can be mounted on the vehicle or be stationary. The use of ESS can reduce the peak demand for electricity. In fact, they can be used as "peak shaving", i.e. to store energy when demand is low and release it when the demand for electricity is greater [6]. In the research conducted, lithium ion (Li-ion) batteries have been used. These accumulators have become very popular in recent years for powering electric vehicles and small electronic devices [7], thanks to their high energy density, high charge efficiency and a long life [8, 9]. Examples of ESS implementations on board a vehicle are the Brussels and Madrid metro lines and the Mannheim tramway, reducing the energy required by up to 25%. These systems allow reducing losses and the stabilization of the energy supply line voltage, but their efficiency depends on the characteristics of the vehicle, which can affect the amount of energy produced (during braking) and consumed (during acceleration) [10]. Stationary systems, on the other hand, allow to power more than one vehicle and help reduce brownout problems that could damage vehicle equipment [11, 12]. They usually consist of a battery connected to the power line through a power control unit. This solution allows energy savings of up to 30%. There are some commercial products such as "Sitras SES" (Static Energy Storage) from Siemens [13], or "EnerGstor" from Bombardier [14]. The last approach to reuse the regenerative braking energy is the use of reversible substations that takes advantage of regenerated energy to be fed into the AC line upstream of the substation itself [15]. Even though reversible substations are designed to have the capability to feed regenerative braking energy to the upstream grid, if maximum regenerative energy recovery is aimed for, priority should be given to energy exchange between trains on the DC side of the grid electric. The possibility of powering the vehicles using only on-board batteries allows to overcome architectural constraints typical of historic city centres, removing the over-head line. The solutions, for the installation of this kind of systems, differ on the basis of the ESS recharging method:

- Solutions with recharge at the stations while stopped there;

- Solutions with recharge while passing under the traditional contact line on short parts of line. In this case there are sections with catenary and others without it;
- Solutions based on continuous power supply systems alternative to the catenary, such as by means of magnetic induction.

In this paper, the results shown before were used to optimize a tramway line in Florence. The aim was to find solutions for the use of new ESS and the possibility of running sections without the over-head catenary line. At the same time, an energy optimization was carried out. The implementation of the solutions obtained in this work could allow the reduction of energy consumption and the emissions of pollutants, to achieve the goal of "Sustainable cities and communities" provided by the Sustainable Development Goals (SDG).

2 System Modelling

The research carried out in the present paper, proposes a flexible modelling to simulate the electrical and mechanical behaviour of a railway vehicle on any line. The main objectives of this work were:

- Efficient energy management achieved through regenerative braking of vehicle;
- The use of ESS (stationary and on board) to optimize the regenerative braking;
- The modelling of an innovative system partially or totally without catenary;
- Energy optimization of the examined tramway system.

For the implementation of functional models for the purposes of the research work, MATLAB - Simulink software was used, allowing to simulate the interaction between complex systems, such as mechanical and electrical. The activity started from a previously developed model which considered a high-speed railway vehicle (ETR 1000) [16]. Initially, the existing tram system was represented and then the stationary and on-board ESS were implemented, testing the possibility of running parts of the section (or the entire line) without the use of the catenary. The ESS were also sized to be able to travel on various line configurations that alternate sections with and without a catenary. Finally, the vehicle speed profiles were evaluated to optimize the vehicle timetables. The system model has been divided into two sub-model: the first one described the longitudinal dynamics of the vehicle (mechanical), while the second one represented all the elements necessary for the vehicle power supply (electrical). The two sub-models communicated in real time using Simulink. The simulation, and its optimization, have been carried out considering both a single and a multi-vehicle system, with trams moving in two directions. The mechanical model took as input the voltage in a given point of the line from the electrical sub-model and communicated the electrical energy request of the vehicle to the supply line and to the batteries. The goal was to respect the timetable of the vehicle but, at the same time, optimize the regenerative braking. This model allowed to determine the position and speed of the rolling stock instant by instant, starting from its ideal speed profile (obtained by experimental tests conducted on the line and provided by the vehicle manufacturer), considering traction and braking forces, forward and accidental resistance forces, adherence and comfort passengers limits. A virtual driver, modelled using a PID control, allowed to determine the difference between the ideal speed and the real one, and consequently to accelerate or decelerate the vehicle. As regards the acceleration and deceleration efforts, the traction and braking curves of the vehicle have been implemented in the mechanical model, in order to avoid sliding. The resistant forces, i.e. the aerodynamic ones, those related to the wheel-rail contact, those due to the slope and to the curvature of the track, have been also considered (Fig. 1).

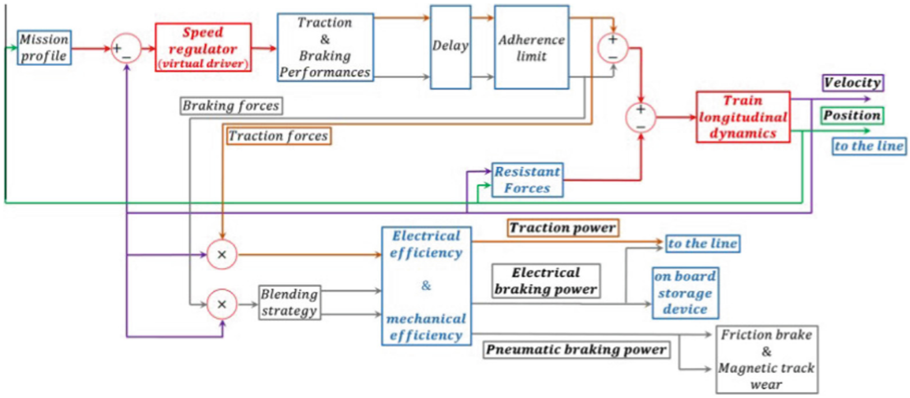

Fig. 1. Architecture of the vehicle mechanical model.

The acceleration has been calculated by the ratio between the resultant of the forces and the equivalent total mass of the vehicle (Considering also the contribution of rotating masses of elements such as axles, motors and transmission components). By integrating twice over time, both the speed and the position, necessary to calculate the electrical power requested, has been obtained. The auxiliary power required to power all the on-board devices has been added to the power thus obtained. In the braking phase, on the other hand, the electric and hydraulic braking forces has been obtained, with which the regenerated electric power has been calculated, considering the efficiency of the system. The output of the mechanical model represented the input of the electrical one. The electrical sub-model was developed using Simscape. The electrical substations, the stationary and vehicle ESS, the catenary line and the feeder system have been modelled. The input were the position and the power required from the vehicle, while the output was the voltage applied to the vehicle. The communication between parts in Simulink and in Simscape has been realized by proper conversion blocks between the two languages. The obtained system was strongly time-varying due to the dependence of the electrical variables on the mechanical ones and vice versa. For the power supply of the line, a physical sub-model has been developed to represent the electrical substations in a simplified way. The catenary line was then modelled to simulate the change in electrical resistance of the power cable, as a function of the vehicle position. This consideration allowed to determine the supply voltage of the tram and the absorbed current. The feeder system, used along the Florence tramway line, was also modelled (Fig. 2).

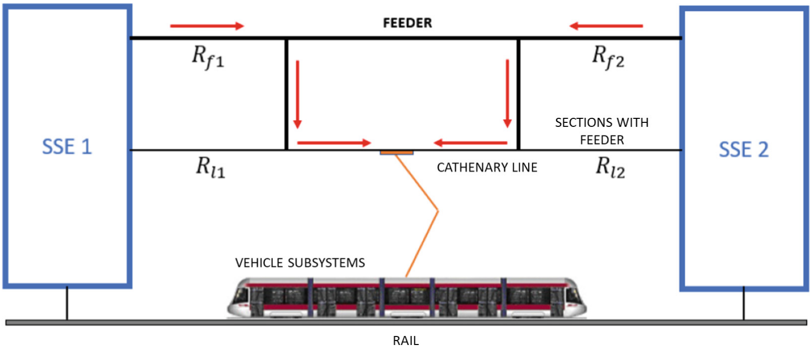

Fig. 2. Diagram of power substations, overhead line with feeder and vehicle subsystems.

For the modelling of the ESS, lithium batteries were considered, because evaluated as the most promising for the applications under study. The modelling of the electrical part considered the possibility of installing stationary and on-board batteries. In the first case, the batteries were placed in parallel respect to the substations, in order to limit the space required for them. In the second case, a parallel connection was made between the battery and the ideal current generator which represents the energy requirements of the vehicle, placing proper switches to connect the battery to the rest of the model. All the parts mentioned above are shown in Fig. 3. The presented module allowed to fully represent a section between two electrical substations. Repeating it in series or in parallel, it is possible to represent even very complex lines. The modularity of the model also allowed the representation of the unpowered sections, disconnecting the catenary line and operating, in proper way, the switches for connecting the batteries. In addition, the model can include several vehicles circulating on the line. The vehicles are represented with distinct mechanical sub-models to impose different timetables or different vehicles.

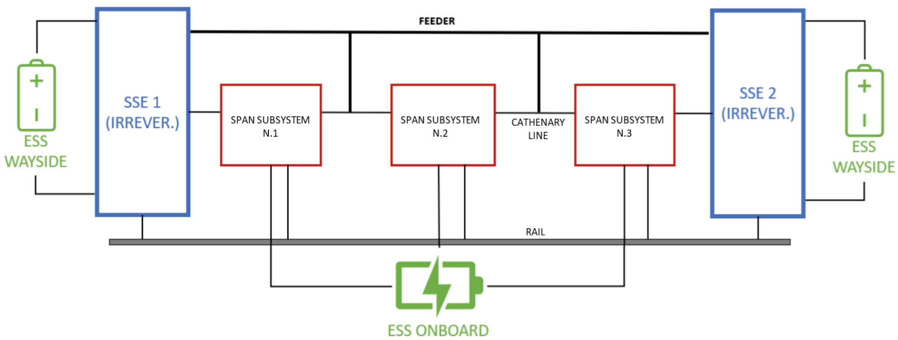

Fig. 3. Diagram of the configuration of a module between two substations.

3 Test Case and Results

The main technical data of the vehicle has been obtained from the manufacturer. This data contains the speed profiles, traction and braking mechanical characteristic, tare weight and maximum weight, axle load and accelerations in the entire line. Furthermore, there is also the technical datasheet of the four motors present on the tram with the relative voltage, current, power, number of poles and rotation speed.

The considered route is a Florence line and the energy supply system was based on five irreversible substations positioned along the section. The original system did not contain any ESS to take advantage of regenerative braking. The energy produced during the braking phases by the vehicles was always dissipated in rheostats placed on the rolling stock. The research conducted assessed the possibility of reusing the energy obtained from regenerative braking implementing stationary and on-board ESS. The possibility of running the line (or portions of it) without the catenary was also tested, taking advantage of the innovative retrofit proposed by the manufacturer for the vehicle. To obtain this goal, the original configuration was initially modelled, to be used as a comparison with the other proposals. The use of reversible substations was not considered for the high complexity and costs of this solution.

In the present work, four configurations have been considered with sections where the vehicle is powered by the over-head line and sections without it, where the vehicle uses only the on-board ESS. The line was divided into three parts in correspondence of two power substations. In this way the modification of the electrical supply line could be relatively easy, reducing the costs of the proposal (Table 1).

Table 1. Characteristics of the tested configurations.

Configurations	Section 1	Section 2	Section 3
Configuration 1	Catenary Free	Catenary	Catenary
Configuration 2	Catenary Free	Catenary	Catenary Free
Configuration 3	Catenary	Catenary Free	Catenary Free
Configuration 4	Catenary Free	Catenary Free	Catenary Free

For each configuration, the stationary and on-board ESSs have been sized, respecting the constraints that allowed to make the most of the batteries and ensure their long life. From the simulations carried out, it was possible to obtain the state of charge of the batteries (SOC) and the speed profile of the vehicles. In all the configurations, the regenerative braking made it possible to recover part of the mechanical energy, even if the battery still tended to discharge. When, on the other hand, the vehicle was connected to the power supply line, the ESSs tended to recharge. In the last configuration, it was considered to recharge the batteries at the beginning and at the end of the line, since the energy obtained through the regenerative braking was not sufficient to maintain the required SOC. This configuration turned out to be the most onerous, for the use of on-board batteries since there was neither a power line nor stationary ESS. In any case, thanks to the use of the electrical energy produced by regenerative braking, a reduction of the energy required to operate the vehicle on the considered line was obtained (Fig. 4).

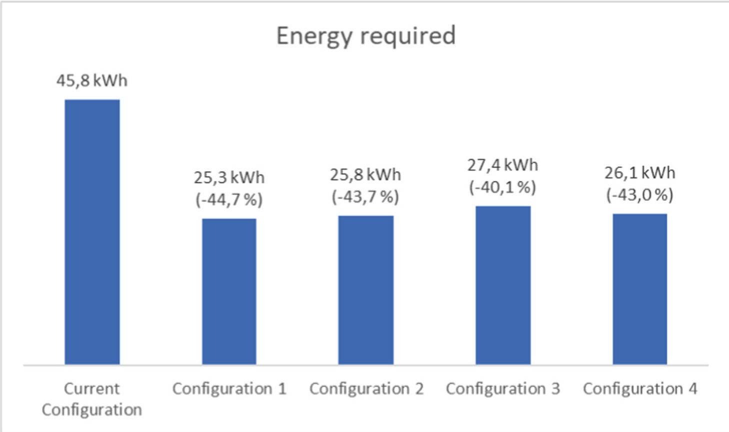

Fig. 4. Comparison between the proposed configurations and the original case.

4 Conclusion and Further Developments

In this research a flexible model has been developed to describe, instant by instant, the mechanical behaviour of a light rail vehicle and the electrical behaviour of its energy supply line. The model has been divided into two parts. The mechanical one can analyse the longitudinal dynamic of the vehicle, while the electrical one can determine the energy requirement during the utilization. The developed model has been used to evaluate four different configurations where the vehicles can run connected to the catenary line or without it, thanks to the energy provided by the on-board ESS. The stationary and on-board ESSs have been sized and an optimization has been carried out to make the most of the batteries considered. The regenerative braking connected with the usage of ESS can provide an increased energy efficiency, but also architectural improvement in city centres. All the configurations can lead to saving up to 44% of energy required during the operation of the vehicle on the considered line.

As future developments, specific costs and benefits obtained with the solution and the model exposed will be evaluated. In particular, it will be interesting to evaluate the possibility to use the proposed model to retrofit or to design new tramway lines. In addition, the model could also be used to design new tram vehicle to use in catenary free lines.

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