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Energy storage systems to exploit regenerative braking in DC railway systems: Different approaches to improve efficiency of modern high-speed trains

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ABSTRACT

The growing attention to environmental sustainability of transport systems made necessary to investigate the possibility of energy optimization even in sectors typically characterised by an already high level of sustainability, as in particular the railway system. One of the most promising opportunity is the optimization of the braking energy recovery, which has been already considered in tramway systems, while it is traditionally overlooked for high-speed railway systems. In this research work, the authors have developed two simulation models able to reproduce the behavior of high-speed trains when entering in a railway node, and to analyze the impact of regenerative braking in DC railway systems, including usage of energy storage systems. These models, developed respectively in the Matlab-Simscape environment and in the open source Modelica language, have been experimentally validated considering an Italian high-speed train. After validation, the authors have performed a feasibility analysis considering the use of stationary and on-board storage systems, also by taking into account capital costs of the investment and annual energy saving, to evaluate cost-effectiveness of the different solutions. The analysis has shown the possibility to improve the efficiency of high-speed railway systems, by improving braking energy recovery through the installation of such storage systems.

1. Introduction

Nowadays large part of railway vehicles is able to combine the standard pneumatic braking to an electrical braking system, made possible by the electric traction system. In this way, the kinetic energy of the train is converted in electrical energy, which can be handled in different ways. The first and simplest way to manage that energy is to dissipate it on a set of specifically developed resistors placed on-board trains; obviously, this solution comes along with some significant consequences, as example how to properly manage the heat thus generated. A second way is to perform the energy recovery: the electrical energy can be sent back to the contact line where it can be used by other trains during their traction phases, or stored in properly sized energy storage systems located along the feeding line or on-board the trains.

However, electrical braking allows significant advantages also in terms of maintenance costs: in fact, it allows to preserve friction materials of the mechanical brake (pads and discs) from excessive wear rates. This effect is significant in terms of environmental pollution, since mechanical brake particles count for a significant percentage of the air pollution due railway systems [1,2,3]. Also maintenance costs should be accurately evaluated, since the wear of braking pads depends on the percentage of train kinetic energy, which is mechanically dissipated. This aspect is detailed in UIC 541 rules [4,5], where a wear rate index defined as the ratio between the worn volume of tested friction material and the amount of dissipated energy for the testing and homologations of pneumatic braking systems are defined. Additional benefits should be obtained also in terms of protection of brake units from overheating, since electrical braking should be used also when extended braking phases occur. Moreover, the access to braking units for maintenance involves additional time and costs that have to be considered.

Regarding brake blending, i.e. the strategy to optimally apply the action of mechanical and electrical braking systems, several studies are shown in literature. In particular, blending of high-speed trains was the object of previous publications [6,7], which

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analyzed the influence of blending strategy on braking pads wear and on the braking system performance, taking into account the variation of the pads friction coefficient due to wear and hence vehicle safety issues. In fact, from the safety point of view, UIC rules [4,5] clearly specifies that emergency stop manoeuvre must be entirely ensured by mechanical braking devices, without usage of electrical braking: for this reason, an optimal management of electrical braking would not only allow energy savings but improve also the system safety.

When electrical braking is performed, two main ways to manage the generated power must be considered:

- Dissipative Braking: generated electrical energy is dissipated over an array of resistors typically controlled by a static converter.
- Regenerative Braking: generated electrical energy is available to be stored on board or redirect to the overhead line.

Regenerative braking is obviously the most interesting technology in terms of efficiency but poses severe limits to the way in which recovered energy is managed considering the following typical solutions which have been widely studied in [8,9] with a special attention to urban tramway systems [10]:

- Stationary/Infrastructure based Storage Systems. Main advantage is to avoid limitation regarding encumbrances. Main drawback regards additional losses, since energy flows move from the trains to the storage passing through the feeding line. This solution was also considered in literature, considering different storage technologies i.e. lithium batteries [11,12] or supercapacitors [13,14]. Energy storage systems are chosen and sized by considering their performance, aging and cost-effectiveness [15,16], also by considering the possibility to employ already aged batteries [17]. As additional problem to be considered, the presence of an appropriate short circuit protection system, as detailed in some existing safety rules specifically processed for DC systems [18].
- On-board storage systems, in which braking energy is stored on systems installed on-board train [19]. The main advantage is due reduction of losses, since energy transfer along the line is reduced or fully avoided. As drawbacks, additional encumbrances and weights on-board the vehicle, with a consequent reduction of available loading capacity of the train and with an increment of energy requests from the feeding electrical substations (ESSs), during the traction phases.
- Synchronized loads along the line: by optimizing railway timetables and signaling systems it is possible to synchronize the presence on the same line of both trains performing regenerative braking and loads represented by other compositions executing energy-consuming maneuvers (i.e. the traction phase). Thus, the need of energy storage devices is reduced since every time regenerative braking power is generated, there is one available load that can absorb it. This approach has been widely studied in many works and in light railways [20,21,22] it is just one of the possible technical solutions to take advantage of braking energy. On the other hand, in DC high-speed lines the use of braking energy by other synchronized loads within the same line is almost the only solution to exploit braking energy. This solution, although not expensive, shows some drawbacks mainly related to its robustness with respect to traffic perturbations, which are quite common in railway applications. Further troubles arise because railway timetables are also constrained by transport market demand for the employed railway vehicles. As consequence, this further optimization of timetables and signaling could be more efficient only for a few operating scenarios (e.g. intense traffic demand on a line with a quite regular design) than for other ones. In a similar way, additional studies are focused on the improvement of energy efficiency due the driving style, i.e. changing the management of motion phases, to enhance the braking energy recovery [23].
- Reversible feeding substations: power stations used to feed the line could be reversible, to send the regenerative braking energy to the external grid. This solution has been applied to low voltage metro-systems [24,25]. It is also interesting to observe how reversible feeding sub-stations within AC railway lines are already operating (e.g. within the Firenze-Bologna line). Further interesting studies [26] have been performed concerning the multi-level integration of railway grids within systems devoted to the recharge of other electrical transportation systems, trying to solve with a complex coordinated system the troubles due to reverse power flows, arising from different connected systems. Complexity, costs, difficult scalability are the main drawbacks of this solution, which will be probably extensively adopted in the near future, although it actually not yet diffused.

Most of the previously mentioned studies based on the utilisation of energy storage systems are focused on low voltage tramways or light rail DC systems, in which feeding electrical substations (ESSs) are based on diode bridges, thus they are not able to send energy back to the three-phase network. This is mainly due to the parameters that influence regenerative braking. In fact, the peak braking power depends on the vehicle velocity before the braking phase, on the train deceleration and on the vehicle equivalent inertia. On the other hand, the mean recovered energy depends on the vehicle kinetic energy (and then on the squared vehicle velocity) and on the braking frequency (i.e. the number of braking phases scaled with respect to the vehicle travelling time). It is then easy to understand how the analysis and the application of regenerative braking and energy storage devices have been typically carried out considering light railway systems, like tramways or metro systems, instead of high-speed trains. In fact in those situations, the power peaks that must be handled are smaller (i.e. the vehicles are characterised by a reduced weight and are able to reach a lower vehicle speed). However, the recovered energy may significantly rise up, due the high frequency of braking phases within short distances. As shown by several studies [8,27,28], the recovered amount of energy allows a fast payback period for the investment showing the cost-effectiveness of this solution.

Indeed, it can be of interest to evaluate the utilisation of energy storage systems also in case of the high-speed trains, always fed by DC feeding systems. In fact, travelling speed and equivalent inertia are much higher, thus increasing the amount of kinetic energy that can be potentially recovered. On the other hand, reduced number of braking phases and extended railway lines may reduce the cost-effectiveness of the proposed solution, as confirmed by the low achieved interest, although today ever increasing. Therefore, the present research work tried to give some answers regarding these aspects, by analyzing different storage system technologies and configurations, in order to make a cost-benefit analysis for the considered scenario.

First of all the authors have developed two different vehicle-line simulation models: the first model has been developed coupling the Matlab-Simulink™ environment with the innovative object oriented Matlab-Simscape™ language, while the second model has been developed using the open source Modelica environment.

Both the approaches, being object oriented and following the Bond-Graph approach [29] for the modelling of dynamical systems, are characterised by a great flexibility and modularity. They also allow to analyze different scenarios and to perform optimization analysis. These approaches, based on a lumped parameters formulation, handle the physical variables of the