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Energetic optimization of regenerative braking for high speed railway systems

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A R T I C L E I N F O

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A B S T R A C T

The current development trend in the railway field has led to an ever increasing interest for the energetic optimization of railway systems (especially considering the braking phases), with a strong attention to the mutual interactions between the loads represented by railway vehicles and the electrical infrastructure, including all the sub-systems related to distribution and smart energy management such as energy storage systems. In this research work, the authors developed an innovative coupled modelling approach suitable for the analysis of the energetic optimization of railway systems and based on the use of the new object oriented language Matlab-Simscape™, which presents several advantages with respect to conventional modelling tools. The proposed model has been validated considering an Italian Direct Current High-speed line and the High-speed train ETR 1000. Furthermore, the model has been used to perform an efficiency analysis, considering the use of energy storage devices. The results obtained with the developed model show that the use of energy recovery systems in high-speed railway can provide great opportunities of energy savings.

1. Introduction

1.1. Energy and railway transportation free markets and their role in a new green revolution

Global Warming and more in general the issues related to pollution are enforcing a growing interest to the increase of efficiency of transportations systems [1], which still represent in Europe and in all industrial countries about 30% of CO_2 pollution sources. This situation has been investigated by both the Europe Environment Office [2] and the Association of American Railroads [3]; furthermore, Fridell et al. [4] performed a number of experimental tests and found out that, in the railway sector, a significant part of emissions is due to mechanical braking. Railway transportation represents the most efficient technology in terms of pollution and energetic efficiency, but the continuous technological improvements accomplished by its competitors (i.e. ground and air vehicles) are reducing this gap. Furthermore, the current market growth for high-speed and freight sectors in industrialized countries with high population densities would be strongly enhanced by the improvement of the efficiency of the system.

Another important aspect, which is pushing towards a strong energy optimization of the railway system, is the liberalization process of both energy and transportation markets: this process is stimulating all the stakeholders in the railway sector (i.e. energy infrastructures and suppliers, railway infrastructures and vectors) to accurately measure and quantify energy consumptions and their costs. In particular, the combined liberalization of both energy and railway sectors should give to the infrastructure managers the opportunity to apply different costs to traveling trains according to the real measured energy efficiency. Furthermore, the possibility of acquiring energy from different suppliers would allow to optimize costs with respect to the line geographic location, to seasonal factors involving the availability of different resources and, finally, to specific requirements of railway vectors/transport manager. In this scenario, the competition between the different subjects involved in the entire railway field and the need to respect interoperability issues established by the European Railway Agency in the Technical Specifications for interoperability (TSI) [5], will further stimulate the optimization of train energy consumptions, as reported in the analysis of different methods to improve railway energy efficiency performed by Douglas et al. [6].

1.2. Regenerative braking and energy storage systems: state of the art and literature review

In modern railways, aside from the classic considerations that should be made concerning the traction systems and the electrical line, one of the greatest source of energy savings is the use of

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regenerative braking (see Bartłomiejczyk and Połom [7], who investigated the perspectives of braking energy recovery within urban electrified transports like tramways); in particular, the growing diffusion of trains with distributed traction systems has drastically increased the percentage of energy that can be recovered during the train braking phase. Using regenerative braking instead of the classical dissipative braking allows to convert a relevant part of the train kinetic energy in electric power, without dissipating it over the pneumatic brakes friction surfaces, with another important advantage in terms of brake maintenance costs. Furthermore, the reduced wear and prolonged life of pneumatic brake pads and discs can produce significant benefits in terms of pollution, since the brakes wear produce solid particles and contaminants whose impact on the environment is still a matter of monitoring and research: Abbasi et al. [8] analysed the particles due to brake wear and proposed a comparison index to identify their impact, Gehrig et al. [9] performed experimental tests in a Switzerland railway node and Salma et al. [10] performed their experimental analyses on polluting particles near Budapest.

The application of regenerative braking involve the availability of a load or a storage device (whose performances in electric vehicles have been investigated by Marr et al. [11]) able to manage the energy recovered from the braking phase of the train: Hillmansen and Roberts [12] found that a significant percentage of the railway energy consumption could be saved using proper storage devices.

The peak power W_{rmax} that has to be managed during regenerative braking is roughly proportional to the maximum speed reached by the train before braking $\dot{x}_{\max}$, to the deceleration of the train during the braking phase $\ddot{x}_{brk}$ and to the train equivalent inertia m_i, which takes into account also the contributions to kinetic energy due to motors, gearboxes, axles, wheels and brake discs.

On the other hand, the mean power W_{rmean} that can be regenerated depends on the kinetic energy of the train $m_i\dot{x}^2_{\max}$ and on the braking occurrence f_b (i.e. defined as the number of braking events with respect to traveling time). On tramways and light urban railways, the vehicles traveling speed and equivalent inertia are much smaller with respect to high-speed trains, but the braking frequency f_b is much higher: therefore, the mean regenerated power W_{rmean} is relatively high with respect to the peak power W_{max}. For this reason, the power management of regenerative braking is typically easier on tramways, metro and light urban railways with respect to high-speed lines. Furthermore, the length of metro and tramway lines is typically lower than conventional lines: hence it is easier to implement customized innovative solutions (e.g. the synchronization of trains accelerations and decelerations, investigated by Peña-Alcaraz et al. [13]). Consequently, the application of energy storage systems on metro, tramways and more in general on light railway systems has been widely recognized as an important opportunity for energy optimization and has been extensively investigated by different authors, while the application of energy recovery systems in high-speed trains is still an open research field: Falvo et al. analysed the energy efficiency of a metro system, comparing a Spanish and an Italian line [14] and González-Gil et al. [15] investigated the most important energy savings possibilities in urban railway.

Research works available in literature can be typically classified as follows:

- Energy storage systems location: energy storage systems can be stationary or installed on board the vehicle. Barrero et al. [16] investigated the advantages and disadvantages of on-board and stationary energy storage devices, using a simulation tool to analyse the metro line of Brussels, while Teymourfar et al. [17] investigated the use of stationary supercapacitors within the Tehran metro network. The on-board configuration allows to reduce electrical line losses and assures system autonomy even with bad or discontinued current collection. On the other hand, stationary systems connected to the infrastructure are easier to install and maintain, avoiding additional weights and encumbrances on vehicle, which can penalize performances and available payload for goods and passengers.
- Energy storage systems application and usage: the most typically analysed applications are tramways or metro, where energy storage systems allow to save energy, reduce line voltage fluctuations and optimize both energy and infrastructure costs. In particular, Teymourfar et al. [18] analysed the possibility to perform energy recovery within a metro network, Ceraolo and Lutzemberger [19], using the Modelica™ environment, analysed and compared different configurations useful to increase the efficiency of tramways, Barrero et al. [20] analysed the energetic efficiency of light railways, investigated the sizing of UltraCapacitors for the Brussels tramway [21] and performed an analysis on a set of on-board supercapacitors for a tram, evaluating also the effect of power converter (Barrero et al. [22] and Van Mierlo et al. [23]), while González-Gil et al. [24,25] analysed different strategies to enhance the energetic efficiency of urban railway systems, including regenerative braking. Furthermore, Iannuzzi et al. [26] proposed a technique to optimize the sizing of ultracapacitors for light railways and Mir et al. [27] designed a supercapacitor storage system for tramways. The shortage of research works concerning energy recovery in high-speed railway applications represents an important lack, which should be filled in order to enhance the efficiency of the entire railway system.
- Energy storage technology: Vasebi et al. [28] developed an innovative method for the calculation of batteries State Of Charge, which is fundamental for the correct analysis of batteries behaviour; Tsang et al. [29] proposed and validated a model for the analysis of Li-ion batteries (which are the most suitable for the use in the railway field), as well as Castano et al. [30]; on the contrary Zhu et al. [31] analysed the use of Pb-acid batteries for energy storage purposes. Other researchers have studied batteries behaviour considering their use together with other storage devices, like Trovão and Antunes [32], who investigated the possibilities to use a hybrid storage systems coupling batteries and supercapacitors, or with fuel cell-powered systems, like Guo et al. [33], who analysed the use of batteries in a fuel cell-powered locomotive (the batteries are able to store braking energy and to cover transient energy requests), Paladini et al. [34], who investigated the use of both on-board batteries and supercapacitors in a fuel cell-powered vehicle, developing a Matlab-Simulink™ model (the use of Matlab-Simulink™ is typical in the analysis of this kind of systems), and Thiounn-Guermeur [35], who developed a hybrid locomotive which uses two different storage systems. Supercapacitors are relatively new with respect to batteries, but it is possible to find in literature many studies concerning their behaviour, like that by Sharma and Bhatti [36], where they proposed a detailed analysis of the characteristics of supercapacitors and of their applications, or that by Steiner et al. [37], where they analysed the use of on-board ultracapacitors. Among the many possibilities to implement energy storage, researchers have analysed the different performances that a device could provide in different systems; an important work is that by Kondoh et al. [38], who performed a comparison of different energy storage systems, highlighting which technology could better suit specific applications. Finally, for a correct use of energy storage devices it is fundamental to be aware of the subsystems needed for their operation (see Fernão Pires et al. [39], who analysed the power