Railway Transportation Sector

Subjects: Energy & Fuel Technology

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Definition

A wide analysis is presented, detecting which are the main measures adopted for improving the efficiency, related to the power systems for supplying trains and to the train traffic control, with a focus on the storage system integration.

1. Introduction

Railways are an energy efficient mode of transport for both passengers and freight. Passenger railways cover an average value of 4.1 of toe per million passenger-km; the freights rails cover an average value of 3.49 of toe per million passenger-km. It represents 2% of total transport energy demand [1]. The construction of new railway lines, as the growing of the number of trains on the lines increases, imposes that energy savings solutions are increasingly necessary to reduce the energy demand in the future, considering both urban and suburban systems.

Energy efficiency has already improved in the last century thanks to the many technological innovations that have occurred over time in the railway sector: from the first storage systems on board trains (1903) to cover short distances, until today with the development of different types of electrified lines both DC and AC (single and three-phase). The development of high efficiency electric engines and the increasing progress in power electronics allowed reducing the energy demand by trains, also thanks to braking energy recovery utilization. In electrical substation, from the ‘60s to today, the replacement of mercury vapours rectifiers with silicon rectifying diodes in DC electrical substations, and the continuous introduction of high performance electric machines for energy conversion, minimizing the losses, have increased the efficiency of the systems. A continuous evolution concerned also the better integration between train and infrastructure (pantograph/overhead lines and wheels/rails). Evaluations about energy recovery, centred on the control of speed profile, taking into account timetable optimization [2][3][4] and storage design systems [5], offer a best solution to reduce the system’s energy consumption, in order to maximize the effectiveness of regenerative braking. The importance of increasing recovering energy, especially when there is no train that can absorb it, or it is not possible to install a reversible substation, is also discussed [5]. Several solutions have been carried out focusing on trains, power plant design and timetable optimization, in order to decrease the energy dissipated on braking rheostat. Regarding the trains driving performance, many solutions are proposed to optimize driving style management and the design of super-caps on board. Several design solutions have been carried out for the siting and sizing of storage systems in railways power plant and at last, some proposal about optimal scheduling process have been formulated for timetable management. The results of a wide survey on the newest techniques of driving style management with timetable optimization and on the solution of storage systems on board and stationary is summarized in the next paragraph.

2. Efficiency Solutions Based on the Driving Style Management and Timetable Optimization

Energy-efficient driving management coupled with the optimization of timetable allows finding optimal train speed profiles and departures to minimize the energy consumption and get the optimal braking trend due to time delay, so as to maximize the recoverable energy in line. Researches start from 1960, with timetable optimization and energy-efficient driving from the first suggested optimal control model in 1968 made by Ishikawa [4].

Several timetable optimization methods have been proposed in recent years [4]. Albrecht in [6] developed a new method based on dynamic programming, to manage running time of trains using an optimal combination of headway and synchronization time, with the task of reducing power peaks and energy consumption. Chen et al. [7]applied the genetic algorithm to optimize train scheduling; particularly the goal was to reduce power consumptions, preventing the synchronous acceleration of many trains. Ramos et al. [8] presented a method to maximize the braking energy recovery, during off-peak hours maximizing the overlapping time between acceleration and braking of the trains. Kim et al. [9] carried out a multi-criteria mixed integer programming, coordinating the train departure times at the starting stations, so as to minimize the peak energy and maximize regenerative energy utilization. Peña-Alcaraz et al. in [10] tested methods to synchronize the movement of trains in the Madrid Metro Line 3 reaching a 3.52% energy saving. In [11][12] a comparison between to real metro-lines in Italy and Spain is made in terms of energy savings that can be obtained by the recovering of the braking energy of the trains. Yang et al. with several studies suggested a cooperative scheduling model to schedule the accelerating and braking phases of nearby trains. In [13] a simulation performed on real data obtained from the Beijing Metro Yizhuang Line shows a great improvement in the overlapping time of around 22%. In [14] a stochastic cooperative scheduling model taking into consideration the randomness of departure delay, for trains considering busy stations, shows a percentage of save energy around 8%, compared with the cooperative scheduling approach reported in [13]. In [15] the same authors offer a model to optimize the timetable, coordinating trains at the same station to maximize the utilisation of recovery energy and reduce waiting time for the passengers. The model reached an 8.86% energy saving, with a waiting time of 3.22% relevant to the current timetable. In [16] a scheduling approach regarding effective speed profiles, to arrange arrivals and departures of all trains, reaches a 6.97% reduction in energy consumption, in comparison with the current timetable.

In [17] a model, based on a multidimensional state vector subspace for train operation, is presented. A smart scheduling methodology useful for multi-train energy saving operation and an optimization procedure based on a genetic algorithm and regenerative kinetic energy, to lowest total energy consumption, is proposed in [17][18].

In [19] the train trajectory optimization is carried out, in order to define a better train target speed profile, to minimize a cost function, including energy consumption and trains arriving on time for all trains. The minimum energy consumption, under different departure headways, is calculated, by using a heuristic algorithm in [20], reaching a reduction in energy consumption up to 19.2%. Furthermore, several studies on driving style are carried out, to define eco-energy driving profile strategies of the trains to couple with timetable optimisation. The motion stage of a train consists in acceleration, cruising, coasting, and braking management. Generally, the speed profile of trains with short travel distance or close intermediate stops, like in tram and metro systems, could not contain the cruising phase.

In [21] a dual speed-curve optimization for energy-saving operation of high-speed trains is proposed using two optimizations. An offline global and online local optimization, demonstrating the increase in energy saving, compared with other well know existing methods that use one-time optimization processes. The main structures of the dual optimization method proposed include: a global optimization to obtain better driving style; after, the speed trajectory is adjusted in real time by local optimization. Additionally, regarding rolling optimization, a closed loop control is integrated with a consistent optimization process that continuously corrects; at least global optimization is reachable using a genetic algorithm, with characteristics and predictive control, with the local optimization characteristics, to compensate for the limitations of a single optimization process [21].

In [22] the authors propose an integrated approach, consisting of both offline and online techniques. The projected framework generates throttle sequences that lead to energy saving under the constraints of trip time and computation time. This work leverages the fast-growing machine learning techniques, so to extract the optimized driving behaviours of human drivers and encode the learned knowledge into a parameter decision tree for fast online optimization. A case study on a given locomotive proved the effectiveness of the proposed framework and an energy saving of 9.84% on different running conditions can be achieved.

In [23] the authors includes a new method for speed curve definition and tracking control, based on a random reinforcement genetic algorithm (GA) to avoid the local optimum and a sliding mode controller developed for speed curve tracking with bounded disturbance.

An improved chicken swarm optimization algorithm for energy-saving for a train, by taking minimum energy-consumption, accurate stopping and punctuality as optimization objectives is in [24] without changing the existing equipment and infrastructure. Chicken swarm optimization is a global optimization algorithm, which integrates the advantages of genetic, particle swarm and bat algorithms.

In [25], the authors introduce an optimization of train speed curve applied in a real case study of the Taipei Mass Rapid Transit System for journeys from “Dingpu Station” to “Yongning Station”, showing that operational energy consumption could be reduced up to approximately 58%. A real driving method to reduce the traction energy demand is presented in [26]. In this case the authors carry out theoretical optimal driving solutions thanks to a train simulation using an enhanced Brute Force searching algorithm. A driver practical training system (DPTS) is created to help drivers practice energy-efficient driving controls. A train speed trajectory optimization method associated with a driver practical training system (DPTS) is the main goal. Thanks to the DPTS, traction energy consumption is reduced by around 15%.

The authors in [27] propose a methodology that includes an objective function using cardinality and square of the Euclidean norm functions. The optimization model proposed, allows defining properly the utilization of the regenerative energy. To solve the convex relaxation counterpart of the original NP-hard problem, a two-stage alternating direction method of multipliers is designed. The procedure produces an energy-efficient timetable of trains.

Genetic algorithms have been used for a subway line in Milan and it is reported in [28]. The main goal is to fulfil the transition from a traditional system to a driverless one. It shows an energy saving increase equal to 32.89%.

3. Efficiency Solutions Based on Stationary and on Board Energy Storage Systems

Many studies about on board and stationary energy storage systems have been developed, especially for DC railway systems, without a reversible substation, where it is not possible to drive the surplus of regenerated energy back to the main AC power supply. Consolidated energy saving solutions using reversible substation focused on different implementations are reported in [29][30][31][32][33][34][35]. The innovative technologies used to design energy storage systems are super-capacitor, battery, or flywheel and IEC 62924:2017 standard fixed requirements and test methods. The International Union of Railways (UIC) with the sub commission “Energy Efficiency”, creates a database where all relevant railway energy-saving technologies should be analyzed, categorized, and evaluated [36][37].

Regarding on board energy storage systems, they are already in use by some rail transit companies. The main advantages are the reduction of peak power, the stabilization of voltage, the loss reduction and the possibility to operate catenary free [38]. Real applications of on-board storage systems are the Brussels, Madrid metro and Mannheim tramway lines. The percentage of energy saving reported in [39][40][41] are 18.6% ÷ 35.8%, 24% and 19.4% ÷ 25.6%, respectively. To reach high integration with motor drive control, some research studies are focused on the optimal design, sizing and control of on board energy storage systems [42][43][44][45][46]. Focuses on stationary storage systems, the real implementation of wayside Energy Storage System (ESS), show an increase in energy savings of up to 30%. The percentage of energy saving by ESS moreover is influenced by system features and storage technologies. In [47] it is highlighted that auxiliary battery-based substations could represent a feasible solution to store the required energy for partly powering a train, supporting the electric substation during train accelerations and to compensate for voltage drops. Numerous commercially available stationary systems are available. Sitras SES (Static Energy Storage) system, marketed by Siemens, can reach up to 30% of energy saving using a super-capacitor technology that can offer 1 MW peak power for 20 ÷ 30 s, with 1400 A DC discharging current. This system is in Germany (Dresden, Cologne, Koln and Bochum), Spain (Madrid) and China (Beijing). The EnerGstor of Bombardier Company, based on supercaps, is able to reach 20% ÷ 30% of reduction of energy demand [48]. Another system super-caps based in Hong Kong and Warsaw metro systems [49] is developed, by Meiden and marketed by Envitech Energy, with scalability from 2.8 to 45 MJ of storable energy.

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