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Energy saving in metro systems: Simultaneous optimization of stationary energy storage systems and speed profiles

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ABSTRACT

High electric energy consumption is one of the main challenges of metro systems, which the operators deal with. Among several energy saving methods, this paper focuses on the simultaneous application of speed profile optimization and energy storage systems, to efficiently utilize regenerative braking energy. With this approach, a substantial reduction in energy was achieved for the case study of Mashhad LRT Line 1. In addition, because of the simultaneous utilization of the schemes, the required capacity of stationary energy storage systems was decreased in comparison with the case of normal (not optimized) speed profile. To demonstrate the validity of the proposed method, two procedures were done. First, the optimization of stationary supercapacitor energy storage systems was performed by using experimental results (real world, not optimized speed profiles) so that the total input energy would be minimized. In the second procedure, the optimal speed profiles were determined and optimum energy storage was recomputed. The results show a significant reduction of energy in the latter procedure, as well as lower energy storage system costs.

1. Introduction

Urban electric rail transportation is developing in big cities because of features such as safety, high energy efficiency, high capacity, accuracy, punctuality and low environmental pollution. High energy consumption of this system is one of the challenges that has attracted many researchers. Two best measures to raise energy efficiency in these systems, especially the traction energy are first, energy saving, which in most of the previous researches has been equivalent with economic driving. The second solution is recovery of the regenerative braking energy of trains, which can be provided by trains' timetable adjustment, use of reversible substations to return the energy to upstream network and energy storage systems (ESSs) (Martinisa and Gallob, 2013), (Gonzalez Gil et al., 2014).

In recent years, many studies have been performed on energy saving by optimal train driving. Most of these studies were conducted in single train systems. The optimal control theory and Pontryagin's maximum principle were used in (Scheepmaker and Goverde, 2015). Genetic algorithm (GA), simulated annealing (SA), ant colony optimization (ACO), decision theory and expert systems methods were also utilized for this purpose (Kim and Chien, 2011; Lu et al., 2013; Domínguez et al., 2011; Yin et al., 2014). In all of the above studies, travel time was assumed constant and it was attempted to optimize the movement of trains and minimize energy consumption by greater use of coasting mode. A single train system with multi-objective functions was considered and

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optimization was done by using multi-objective optimization methods such as particle swarm optimization (PSO) and evolutionary algorithm (Chevrier et al., 2013; Domínguez et al., 2014; ShangGuan et al., 2015; Fernández-Rodríguez et al., 2015; Liu et al., 2015). The general goal was that in addition to minimizing the energy consumption, traveling time was also lowered. In other words, the energy-time Pareto front was determined. In all of the above researches, regenerative energy was not considered. In (Su et al., 2014), (Goodwin et al., 2015), which have studied multi-train systems, regenerative braking energy issue was not taken into account. An algorithm was presented for train trajectory optimization problem as a multi-phase optimal control model, which considered signaling, time and speed constraints (Wang and Goverde, 2016). Afterwards, a multi-train trajectory optimization method was proposed to minimize energy consumption and reduce delays (Wang and Goverde, 2017). Although operational constraints have been met, but the regenerative braking energy has not been considered.

In (Su et al., 2015; Li and Lo, 2014; Zhao et al., 2017) while train speed profiles were optimized, recovery of regenerative braking energy was also maximized by timetables adjustment. An optimization method for multi-train network with regenerative braking system was proposed to solve the energy saving problem, and showed that by only minimizing traction energy of the trains, one cannot minimize the energy usage in whole system (Tian et al., 2017). A comprehensive review was done in (Yang et al., 2016), (Scheepmaker et al., 2017) on energy-efficient train operation methods, which could be used in driver advisory systems (DAS) or automatic train operation (ATO) systems. A complete comparison was made between direct and heuristic methods. Finally, it was concluded that the methods must be used with a trade-off between energy efficiency and traveling time in future researches. In the last studies, which are often known as energy-efficient train operation, although the issue of regenerative energy has been paid attention to, only acceleration and braking synchronization capability of trains were used.

In relation to the use of ESSs, numerous studies were conducted, some of which such as (Devaux and Tackoen, 2014) compared different methods of reusing regenerative energy and a variety of ESSs. Stationary and onboard ESSs were compared in (Barrero et al., 2010). Control methods for charge and discharging of ESSs and their effect on raising energy efficiency were investigated, moreover, improving power quality parameters such as voltage fluctuations and the peak of substations power, were considered (Iannuzzi and Tricoli, 2012; Ciccarelli et al., 2012, 2014, 2016, 2017; Gao et al., 2014). Determination of the optimal size and location of the stationary ESSs was also studied. An analytical optimization method was proposed to determine an optimal design for stationary Lithium-ion Capacitor (LiC) ESSs in light electrical transportation systems (Ciccarelli et al., 2013). A method was introduced to predict the maximum instantaneous regenerative energy in each substation. Based on these values of regenerative energy, the appropriate stationary supercapacitor (SC) ESSs was determined for energy saving (Teymourfar et al., 2012). A method based on both power and capacity constraints of SC ESSs was introduced and showed that this approach could realize effective recovery of whole absorbed braking energy and have high energy-saving/weight ratio (Shen et al., 2012). A DC railway power flow algorithm was developed, considering stationary ESSs to calculate the optimal power and capacity of ESSs (Lee et al., 2011). Mixed integer linear programming was used to optimize the size of hybrid ESSs consist of batteries and SCs (de la Torre et al., 2015). The objective function was the minimization of total investment operating costs. SA GA optimization method was proposed for SC ESSs locating and sizing (Wang et al., 2014). The objective functions were energy saving rate, regenerative braking cancelling rate and installation costs. A cost-benefit analysis was done to determine the recovery rate of costs. An optimization method based on GA was proposed to optimize energy management, location and size of stationary SC ESSs simultaneously in order to obtain the best economic efficiency and voltage profile (Xia et al., 2015). In researches related to ESSs, the energy efficiency was increased, only by using recovery regenerative braking energy.

In this study, for the first time, ESSs and optimal speed profiles were used simultaneously for energy efficiency increasing. In other words, by combining energy savings with regenerative braking energy recovery, while the energy consumption of the entire network was reduced, the capacity of ESSs decreased as well. For this purpose, first for the network with normal train speed profiles, the optimum capacity of stationary ESSs was calculated, then the same calculation was performed for optimum speed profiles and it was shown that in the latter case, both total input energy and ESS capacity were reduced. It is worth recalling that in all of the previous studies done in the field of computing or optimization of energy storage capacity, normal speed profiles or speed profiles corresponding to the minimum travel time (flat out) were considered. This has led to calculating a large capacity of energy storage that may not be used completely.

2. Rail transit system simulation

Urban electric railway network includes traction substations, power lines, and rails as feeders of network and the trains as electric loads. ESSs are integrated as additional equipment to the network for increasing energy efficiency. Modeling of each part is expressed in the following briefly.

2.1. Train modeling

The operation of train is expressed according to mechanical equation (Vuchic, 2007):

$$M.\quad a = F_T(v) - R_T(v) \tag{1}$$

Where M is the total mass of the train and passengers, a is the acceleration of the train, and v is the velocity of the train. F_T is the traction effort of the train and R_T is the total train resistance. The train resistance is determined according to the physical characteristics of the track and for the specified acceleration, the amount of required tractive effort could be determined from the characteristic of train. The amount of electric power consumed by the train P_{cons} in motor mode and regenerative braking power P_{regen}