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System energy optimisation strategies for metros with regeneration ☆

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A B S T R A C T

Energy and environmental sustainability in transportation are becoming ever more important. In Europe, the transportation sector is responsible for about 30% of the final end use of energy. Electrified railway systems play an important role in contributing to the reduction of energy usage and CO_2 emissions compared with other transport modes. For metro-transit systems with frequently motoring and braking trains, the effective use of regenerated braking energy is a significant way to reduce the net energy consumption. Although eco-driving strategies have been studied for some time, a comprehensive understanding of how regeneration affects the overall system energy consumption has not been developed. This paper proposes a multi-train traction power network modelling method to determine the system energy flow of the railway system with regenerating braking trains. The initial results show that minimising traction energy use is not the same as minimising the system energy usage in a metro system. An integrated optimisation method is proposed to solve the system energy-saving problem, which takes train movement and electrical power flow into consideration. The results of a study of the Beijing Yizhuang metro line indicate that optimised operation could reduce the energy consumption at the substations by nearly 38.6% compared to that used with the existing ATO operation.

1. Introduction

The railway system is one of the most efficient forms of land based transportation (Hillmansen and Roberts, 2007). With the rapid increase in industry and populations in cities, metros are becoming an increasingly popular choice to satisfy transportation demand and reduce air pollution caused by car exhausts. However, despite the inherent efficiency, the energy used by the rail industry is high, making the study of railway energy efficiency of global importance.

There is a large and growing volume of literature concerning traction energy optimisation, as the traction energy usage accounts for around 60–80% of the total energy consumption for railway operation (Douglas et al., 2015). Chang proposed a genetic algorithm (GA) to optimise train speed profiles (running trajectories) using appropriate coasting control (Chang and Sim, 1997). Both classical and heuristic approaches are utilised in Wong and Ho (2004) to identify the necessary coasting points for a metro system. A heuristic method offers a faster and better solution for multiple coasting points compared with classical searching methods; and multi-coasting points control performs a better energy saving in a long interstation section

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than a single coasting point. In Bocharnikov et al. (2007), the balance of energy consumption and journey time penalty are considered in the optimisation. Different searching algorithms, such as Ant Colony Optimisation, GA, and Dynamical Programming are compared in optimising single-train and multi-train trajectories in Chang et al. (2001) and Lu et al. (2013). It was found that Dynamical Programming performed better than both GA and ant colony optimisation in searching for energy-efficient driving styles. An analytical method was utilised to prove optimal driving strategies for routes with variable gradients in Howlett (2000), Howlett et al. (2009), and Liu and Golovitcher (2003). A numerical algorithm was proposed to calculate the optimal speed profiles by distributing the journey time into different sections, which achieved fast optimisation (Su et al., 2013, 2014).

With the development of regenerating trains, the use of regenerative braking energy has been studied widely. Optimisation of the train braking speed trajectory was studied to increase the total regenerative braking energy in a blended braking mode using the Bellman-Ford algorithm (Lu et al., 2014). By optimising the braking speed trajectory, the regenerative braking energy can be increased by 17.23% compared with constant braking rate mode. Different scenarios were analysed to optimise Automatic Train Operation (ATO) speed profiles taking into account the energy recovered from regenerative trains (Domínguez et al., 2014, 2012). An integer programming model was formulated to improve overlapping time between the accelerating and braking trains by headway and dwell time control (Yang et al., 2013). In Li and Lo (2014), joint optimisation of the timetable and speed profile was illustrated using an integrated energy-efficient operation model by a GA. Energy-efficient dwell times were identified using a GA and an allocation algorithm, based on a metro system after traction energy optimisation (Yang et al., 2015).

However, the railway traction power network has largely been ignored in most previous studies of timetable scheduling, although the modelling of electrical power flow has been studied over many decades (Chymera et al., 2010; Goodman, 2007; Goodman and Siu, 1994; Mellitt et al., 1978, 1984). From the point of view of energy transfer, not all regenerated braking energy can be used by accelerating trains – some of it is lost in the power distribution resistance. The utilisation of regenerative braking energy depends on the distance between braking and motoring trains as well as on the tractive power demand. The effectiveness of regeneration must be solved using power flow analysis. Various iterative methods were proposed to solve the non-linear power flows in the traction power network with regenerating trains, such as Newton-Raphson iterative method, Point-Jacobi method, Zollenkopf's bifactorisation and incomplete Cholesky conjugate gradient (ICCG) methods (Cai et al., 1995a, 1995b; Pires et al., 2007). Through the energy evaluation of a DC railway system with regenerating trains, the relationship between substation energy and headway for system with and without regenerating trains was illustrated (Tian et al., 2016a, 2016b). The results indicated that the substation energy consumption can be reduced by 22–44% when the regeneration is turned on. It was found that the available energy and substation energy demand vary with different headways and there is a 27% difference between the best and worst headways.

In this paper, an approach to optimise substation energy consumption by modifying interstation speed profiles and dwell times is proposed. A simulation method combining the vehicle motion and power network modelling is introduced and used as a tool to evaluate energy flow of DC railway system with regeneration. The system energy consumption statistic characteristics are studied and an 'energy factor' is defined to simplify the optimisation. Finally, a case study based on Beijing Yizhuang Metro Line is used to illustrate the performance of the system energy optimisation algorithms.

2. Model formulation

2.1. Nomenclature

M	mass of the train [kg]
λ	rotary allowance
v	train speed [m/s]
t	time [s]
F	tractive effort applied at the wheels [N]
g	acceleration due to gravity [m/s^2]
α	gradient angle [rad]
F_R	resistance of motion [N]
K	curvature resistance coefficient [Nm]
r	radius of curvature of the track [m]
A	Davis equation constant coefficient [N]
B	Davis equation linear term coefficient [N/(m/s)]
C	Davis equation quadratic term coefficient [N/(m/s)^2]
N_T	total number of trains (each train runs one cycle)
n	train index
P_{mech_n}	mechanical power at wheels for each train [W]

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