Electrical Power and Energy Systems 102 (2018) 201–210

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Evaluation of the impact that the traffic model used in railway electrical simulation has on the assessment of the installation of a Reversible Substation

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ARTICLE INFO

Keywords:
Railway power systems
Railway electrical simulation
Traffic model
Traffic regulator
Reversible Substations

ABSTRACT

Nowadays, one of the strategies that are being applied in DC railway networks to improve energy efficiency is the installation of Reversible Substations or Energy Storage Systems. The assessment of their impact on the network consumption is typically based on simulation. The accuracy of the results provided by the simulations relies on the accuracy of the models used. This paper focuses on the traffic model used in electric railway simulators. A preliminary literature review has shown that, in most cases, the traffic models of electric railway simulators involve too many simplifications that can lead to non-accurate results. This lack of accuracy can have a great impact in the assessment of the infrastructure improvements, reason why a more accurate traffic model is proposed. The proposed traffic model includes different headways, different time shifts at terminal stations, non-constant dwell times, different train speed profiles and a specific module of the traffic regulation system in real time. The energy saving resulting from the installation of a Reversible Substation obtained with both models –the one used in the literature and the one proposed in this paper– has been compared to illustrate the risk of using a too simplified traffic model. The comparison shows that the simplified model used in the literature produces non-accurate enough estimations of the energy saving.

1. Introduction

The improvement of the energy efficiency is one of the main objectives in DC-electrified railway systems. One of the possible strategies is to increase the utilization of the regenerated energy produced by trains during the braking phases [1,2]. In DC railway lines, if there are not Reversible Substations (RSSs) neither Energy Storage Systems (ESSs) installed, the regenerated energy can only be consumed by other trains which are motoring at the same instants that the regenerated energy is being produced. This coordination of braking and motoring events can be maximized with the timetable optimization [3–5]. If the regenerated energy cannot be re-used, it must be dissipated in the rheostats (on-board resistors), which supposes a considerable loss of energy efficiency. For this reason, the installation of RSSs [6–9] and ESSs [10–18] is typically considered as the best infrastructure improvement in order to increase the receptivity of the system (its capability to accept regenerated energy). Nevertheless, a rigorous study about the impact that this possible installation has on the use of regenerated energy and on the global energy saving must be performed before taking the final investment decision.

The decision process to assess these electrical infrastructure improvements is usually based on railway network electrical simulations and calculates the energy saving obtained with each possible type of investment: RSS or ESS, size, location, etc.

Initially, to perform the railway network electrical simulations, the train traffic mesh is created. It contains the power consumption and regeneration profiles of each train at each time instant and at each location of the railway line. Then, the load flow of the electrical circuits, which results from integrating the traffic mesh within the electrical infrastructure, is solved. Finally, the consumption (or regeneration if a RSS is installed) at each Substation (SS) is computed.

The traffic model has a great impact when analyzing the receptivity of a line and, in general terms, the efficiency [8,19]. Thus, an oversimplified traffic model consisting of a single traffic timetable with constant dwell times can lead to significant errors in the computation of the energy saving associated with the installation of RSSs or ESSs, and therefore, to an incorrect decision making.

The vast majority of studies uses oversimplified traffic models: a single traffic timetable, with just one headway value (the time interval

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https://doi.org/10.1016/j.ijepes.2018.04.030
Received 31 October 2017; Received in revised form 8 March 2018; Accepted 24 April 2018

between two consecutive trains) and with constant dwell times [20–26]. Few papers consider different headway values (operation at peak and off-peak hours), which slightly enhances the variety of the traffic scenarios simulated [11,27,28].

For a better traffic model, more parameters must be included. Three of the main parameters that define a traffic scenario are: a) the headway (already defined), b) the dwell time at stations and c) the time shift at terminal stations (the gap between the departure instants of the trains which are at each terminal station) [19,29].

A first step in this direction is given by [29], where it is stated that traffic variables such as dwell time must be modelled stochastically and that they have an important impact on the energy interactions between trains in the line. In this line [30,31], consider “stochastic operation characteristics” to find the optimal placement of RSSs. Nevertheless, in all these studies the only improvement of the traffic model which is explicitly described is the use of different headway values to represent peak and off peak operation hours, without giving any more details about any other traffic variable.

In [8], in order to obtain accurate results in the simulation of a DC railway line with RSSs, different headway values are used as well as a range of values for a parameter called “synchronization delay”. The “synchronization delay” measures the shift between two trains on adjacent roads (up and down roads) along all their trajectory (not only at the departure instants, as happens with the time shift used in this paper). Using a range of values for the “synchronization delay” involves a variable probability of coincidence between braking and motoring events of different trains, which has a direct impact on the receptivity of the line. This way, it models the traffic variability to some extent, but with less accuracy than the time shift and the non-constant dwell time used in this paper.

In [32] there is a step forward by explicitly using different headways and non-constant dwell times in order to determine the impact that the installation of ESSs can have on the demand charge of a railway line, but different time shifts are not included in this study. Finally, in [29], apart from different headways and non-constant dwell-times, the use of variable time shifts is included in order to carry out an energy saving study with RSSs.

In addition to the traffic variables previously presented, another element which plays a pivotal role in the traffic model is the speed profile [33]. In railway systems, different speed profiles are used: the flat-out profile (minimum travel time and maximum energy consumption) and other speed profiles which require higher travel times and typically have lower energy consumption. These speed profiles can be designed with “eco-driving” techniques, which make it possible to increase the energy efficiency through the computation of the speed profile with the lowest consumption for a given travel time [34–40]. Usually, the eco-driving design includes coast commands (null traction). Currently, the speed profile to be selected among the available ones is determined by the traffic regulation needs.

The impact that the use of different speed profiles has on the energy consumption of the network, as well as on the assessment of infrastructure investments, has not been studied in detail. There are very few studies about this topic and the existing ones are very simplified. In [8], two cases regarding the use of different speed profiles are considered: flat-out and coasting allowance of 7.4%. In [27] it is stated that different driving patterns are used in the study of the optimal installation of RSSs without giving more details. In the rest of the literature the most common practice is to use the flat-out profile to perform the analysis.

In railway lines equipped with ATO (Automatic Train Operation), speed profiles are selected in real time by the traffic regulation system at the control center. This system computes and sends the driving commands to every train in order to accomplish with the target schedule. The speed profiles are automatically executed by the on-board ATO equipment. The traffic regulation system has a big influence on the real-time traffic behavior. Nevertheless, there exist no examples where a traffic regulator model is integrated within the electrical railway simulator in order to study the impact that the traffic regulation has on the consumption, as well as on the installation of RSSs or ESSs.

Consequently, this paper proposes a new simulation-based model for assessing electrical infrastructure improvements in DC railway lines. It includes an accurate traffic model with different headway values, different time shifts, stochastic modelling of dwell times based on statistical distributions, and a specific module of the traffic regulation system with different speed profiles. In addition, this paper analyzes the results from applying the proposed model to a case study, which is particularized to the installation of a RSS.

In Section 2, an overall view of the model proposed in this paper to assess the possible railway infrastructure improvements is given. Then, the details about the traffic model proposed are provided in Section 3. In Section 4, the case study is presented. In Section 5, the energy saving obtained with a RSS is computed with both traffic models (the one used in the literature and the one prosed in this paper) and the results are compared. Finally, the main conclusions are presented in Section 6.

2. Model for assessment of railway electrical infrastructure improvements

The model proposed in this paper has the goal of helping in the decision-making process about the investments required for the infrastructure improvements, by analyzing in detail the energy saving that can be obtained when improving the electrical infrastructure (see Fig. 1).

The model must be realistic enough from the point of view of the energy saving obtained with each type of investment. With this aim, the model, based on simulation, contains a traffic model that improves in different ways the models presented in the literature as it introduces more complete information about the traffic of the railway line.

This traffic model uses different headway values (taking into account the different operation periods during the day), introduces variations in the time shift, applies traffic noise (stochastic behavior of the dwell time) and observes the possibility of using different speed profiles at each interstation. Besides, as can be seen in Fig. 1, a simplified model of a traffic regulator for small disturbances has been included. The disturbance is the deviation of train departures with respect to the commercial timetable due to the “traffic noise” or delays.

This allows generating not only one traffic scenario, but a high number of traffic scenarios that represent better the possible situations that can take place in the railway line. The traffic scenarios contain the information about train positions and consumptions for every time instant. These scenarios are introduced into the electrical scenario generator, which integrates the traffic scenarios within the electrical infrastructure (including the possible improvements that can be installed on it, such as RSSs and ESSs) giving as a result the electrical scenarios (also called “snapshots”) at each time instant. The electrical scenarios represent the consecutive electrical circuits to be solved by the application of load flow techniques [41–44]. They are solved in the load flow module that, after some data processing, provide the final results (consumption in SSs, rheostats losses, receptivity, efficiency, energy losses, etc.).

The steps to assess the impact of an infrastructure improvement are the following:

1. Generate a big enough number of traffic scenarios so as to take into account the traffic variability.
2. Generate, for each traffic scenario, the consecutive electrical scenarios.
3. Simulate these electrical scenarios with the current infrastructure characteristics in order to compute the current consumption in SSs and the rest of the electrical variables required.
4. Introduce the infrastructure improvements (for example the installation of a RSS) and simulate, for each traffic scenario, the