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Smart traffic-scenario compressor for the efficient electrical simulation of mass transit systems

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ABSTRACT

The electrical infrastructure of DC-electrified mass transit systems (MTSs) is currently under review. The improvement of MTS infrastructure is commonly tackled by means of optimisation studies. These optimisers usually take large times to obtain their solutions, mainly due to the traffic scenarios that must be taken into account.

The optimisation time may be reduced by increasing the sampling time used to obtain the traffic scenarios. However, due to the fast acceleration and braking cycles in MTSs, it is not clear to which extent the sampling time may be increased. In the majority of cases, this parameter is simply set to 1 s.

To tackle this concern, this paper presents a compression algorithm which makes it possible to thoroughly reduce the number of snapshots to be included in a given traffic scenario with good energy-saving accuracy figures. The traffic-scenario compressor presented is performed in two stages: a first step finds clusters of similar snapshots in the uncompressed traffic scenario; then a second stage searches for a specific set of trains' positions and powers that may be directly included in the traffic model used in the optimisation study.

The results obtained have shown that the compressor makes it possible to obtain an 80% optimisation-time reduction for a given traffic scenario with a total energy-saving error lower than 5%.

1. Introduction

Improving the electrical infrastructure in order to increase the system receptivity to regenerative energy is becoming a Mass Transit System (MTS) operator common concern. Although there are some studies which propose innovative ways of improving the MTS infrastructure based on low-impedance supply systems [1,25], the main technologies used nowadays in this field are Energy Storage Systems (ESSs) and Reversible Substations (RSs).

In the first group, there are a number of references that analyse the benefits for MTSs from the inclusion of fixed or on-board ESSs, not only from the energy-efficiency standpoint, but also from the train-voltage-variability one [27,26,6,9,8,3]. Although the results with this technology are technically good, these system still present high prices per MW and maintenance costs [13].

In the RS side, it has been proven that it is possible to reduce the system energy consumption by more than 10% by installing reversible converters at certain electrical substations (SSs) [15]. This may make economically attractive to invest in this kind of infrastructure upgrades, even taking into account that reversible converters are also expensive devices [13].

However, it is not simple to justify the profitability of investing in electrical infrastructure improvements. The interactions of trains rolling on the MTS tracks with other trains and with the electrical SSs are fairly complex to study. Relatively small changes in some variables may lead to large changes in other ones, and vice versa. Consequently, the studies aimed at improving the electrical infrastructure of an MTS are usually optimisation studies which obtain the best SSs to upgrade, bearing in mind that the required investment must be economically feasible. There are two main approaches in this type of study: (1) using formal closed optimisation models, and (2) using electrical multi-train simulators. The traffic model resulting from the developments in this study suits both approaches. However, this study focuses on the simulation approach to illustrate the computation time and accuracy figures obtained.

Taking this into account, it must be noted that the obtainment of the MTS energy consumption under certain traffic circumstances requires the simulation of a set of snapshots representing the trains' positions and consumed or regenerated powers. For the result to be reliable, the traffic model must represent the general

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interactions between trains in the MTS. This usually leads to heavy computational burdens. Furthermore, a simulation-based optimiser might require hundreds or thousands of simulations of the system under different infrastructure configurations to converge to a good improvement solution. Thus, it arises as a critical concern to reduce the simulation time to improve the computation-time performance of the optimisation method.

For this purpose, there are two main options: (a) reducing the computation time required to solve each snapshot; (b) simulating (or using, in general) a lower number of snapshots. The work in this paper focuses on the latter approach.

Some MTS electrical optimisers found in the literature clearly express the impacts of using a large number of snapshots in the traffic model [2,9,5]. However, sometimes the range of sampling times they analyse is too high for MTSs, as is the case of [2], which studies a single train running in a long track. In addition, the technique used for reducing the number of snapshots is simply sub sampling. Other times the techniques used to reduce the number of snapshots is not applicable when the number of trains in the line rises up, which is the case of usual MTSs in peak and off-peak operation [9].

However, the sampling time in MTS infrastructure optimisation is quite usually omitted, even after acknowledging the impact of this parameter in the computation efficiency of the methods [4,6,7,14,26,27,19]. The inspection of the graphs in these papers suggests that they use one-second sampling time to obtain the electrical snapshots to be solved.

As already mentioned, there is a straightforward approach to reduce the number of snapshots to be solved: sub sampling. However, the accuracy of the energy-saving results may be affected by the necessary loss of information derived from sub sampling. It is not clear to what extent the number of snapshots may be reduced. Indeed, this has not been tackled in the literature. However, in rapid transit systems as MTSs, acceleration and braking phases usually last from 10 to 20 s. The overlapping of these phases, which determines the energy efficiency of the system, may follow any complex pattern. Thus, it does not seem easy to increase the sampling time without a significant decrease in the energy-saving accuracy.

To tackle this concern, this paper proposes a novel algorithm to compress the snapshots in a given traffic scenario. This algorithm aims to improve the computation-time efficiency increase with respect to simple approaches like sub sampling. The compressor focuses on the most relevant electrical variables in the system and groups similar snapshots in an initial clustering stage. Then, it searches for an optimised equivalent load and regeneration profile for each cluster. The result is a compressed traffic scenario containing a low number of snapshots which is equivalent to the uncompressed one.

This paper is organised as follows: Section 2 introduces the fundamentals of the compression algorithm, and then it presents its details. Section 3 starts by presenting the case study used in this paper and some methodological definitions. Then, it shows the maximum achievable compression and energy-saving accuracy results obtained with the compressor. Finally, the main conclusions and contributions of the paper are presented in Section 4.

2. The traffic-scenario compressor

2.1. MTS power-system particularities

MTS power systems feature several characteristics that increase the complexity to study them. The main reason is that most MTSs are direct-current (DC) electrified systems [24,23]. For historical reasons (DC motors were easier to control), this kind of electrification spread in urban systems like tramway or underground. Currently, some other advantages of DC power transmission still make railway infrastructure designers to use DC electrifications in new MTSs. Examples of these advantages are: the reduced electro-magnetic emissions (avoiding interferences with the signalling system), the lower number of conductors required for the supply systems, the fact that from the utility grid perspective DC railways are balanced loads, etc.

Fig. 1 shows the electrical structure of a general DC-electrified MTS. It may be observed that there are both AC and DC nodes in the system. The interfaces between both parts are, in the majority of cases, diode rectifiers which exhibit a highly non-linear behaviour (they cannot drive currents from the DC side to the AC one, etc.). The typical elements devoted to improve the infrastructure, i.e., reversible converters and energy storage systems (ESSs) are also non-linear devices, with several operational modes.

Regarding the loads, it must be noted that trains also feature several characteristics which increase the complexity of the system analysis. First, they are moving loads, and thus the impedances between the elements in the electrical circuit vary with time. Second, trains' powers are highly variable, and they may be positive (in motoring phases) or negative (in braking phases), but in both cases they are independent from the pantograph voltage (and thus non-linear). Finally, during braking, if the train pantograph voltage hits the maximum voltage allowed in the system, the train must clamp this voltage and send the excessive regenerative-braking power to rheostats, which leads to an additional non-linearity from the load flow solution perspective.

2.2. Compression fundamentals

In the derivations in this paper, a traffic scenario which contains snapshots obtained at one-second sampling time will be referred to as 'uncompressed scenario'. E.g.: a traffic scenario used to represent the 7-min-headway traffic operation of the system will contain 420 snapshots, whereas the 4-min headway traffic scenario will contain 240 snapshots.

Obviously, the same traffic scenario, after being processed by the compressor will be named 'compressed scenario'.

The traffic scenario compression algorithm presented in this paper is based on the equivalency between a single snapshot in the compressed scenario and a set of snapshots in the uncompressed one. The equivalent snapshots in the compressed scenario will be referred to as Equivalent Load Profiles (ELPs). The accuracy of this equivalency will be high if the set of snapshots are similar, but it could be poor if the represented snapshots are heterogeneous. In any case there will be a loss of information as the number of snapshots represented by a single ELP is increased.

Consequently, it has to be properly assessed which variables must be represented as accurately as possible in the equivalent model. This will in turn depend on which kind of results a particular study focuses on, and will allow having a higher or lower compression of the traffic scenarios. E.g.: The traffic in a study which aims to obtain energy-saving results, where average values play a key role, will be easier to compress without leading to wrong conclusions than the traffic in a study where the maximum power delivered by the SS converters is to be determined.

The target for the compressed scenario in this paper is to be accurate in energy savings. The reason is that in the studies devoted to improve the MTS electrical infrastructure, this is the key variable for evaluating the benefits in terms of emission reduction and the payback time of the required investment.

Specifically, the compression approach presented in this paper aims at obtaining an accurate compressed model for studies that deal with the inclusion of RSs in a given MTS line. This technology (RSs) is currently the most usual choice when an MTS line is to be