An open source software for railway electrical supply system simulation

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***Abstract*—In this paper it is shown a new way to proceed in what concerns to the simulation of high speed railway systems, based on the 1x25 and 2x25 configurations. This approach, relies on highly efficient open source software such as OpenDSS to solve the electrical circuits resulting from the model of the above configurations. Moreover, Python is the open source programming language used as interface with OpenDSS, the processing of the input data and the presentation of results. The effectiveness of the tool is demonstrated with several test cases and a practical system using real traffic data.**

***Index Terms*—electrical simulator, electrical supply system, high-speed railways, OpenDSS.**

I. Introduction

The proposed tool is aimed to the simulation of the electric system feeding the rolling stock of high speed railways. Concretely on the so called 2×25 and 1×25 electrical configurations, which employ electricity at industrial frequency to feed the overhead line. These systems are widely spread in Europe and many other countries, being one of the most frequently used configurations for high speed applications [1].

These systems are connected to the industrial grid through a traction substation (TS) that adapts the voltage level to 25 kV. In order to reduce the induced unbalance caused by the monophasic transformers, each TS is connected to a different couple of phases, making a whole rotation every six TS. Hence, the whole railway line is divided in sections of the same structure, each one supplied by a single TS, which implies a change on the currents phase from one section to the other.

The wire system is usually composed by the following conductors: messenger and catenary at 25 kV (the first keeps the second horizontal), the rails which work as the return path for the current, communication and protection conductors, and optionally a return wire connected to the rails to improve the return path of the current.

The difference between the 1×25 and the 2×25 configuration is reflected on the employment of autotransformers connected between the messenger and catenary bunch and the feeder. In the resulting configuration the power is distributed at 50 kV even though the trains remain connected to a 25 kV wire. The periodical installation of those autotransformers along the line reduces considerably the voltage drop from the TS to the train, the system losses and the electromagnetic inference between the conductors. Furthermore it increases the power transmission capacity and permit to increase the distance at which TSs are located.

Due to the many advantages offered by the 2×25 configuration, respect to the 1×25 performance, a relevant number of modern railway projects are based entirely, if not mainly, on this system. For example, in Spain only the first high-speed railway connection, the Madrid - Sevilla AVE, was developed using the 1×25 system. All the following high speed lines were built using partially or totally the 2×25 scope. Nowadays this configuration is used to fed around 80% of the national high-speed system [2].

The complexity of the resulting electric circuit of either 1×25 or 2×25 impede the use of commercial software to solve the power flow equations, as those are formulated to deal with the normal configurations used in power distribution or transmission circuits. Therefore, specific software or some simplification is needed to deal with the resulting circuit [3], [4]. The advantage of using the open source software OpenDSS [5] is that it is flexible enough to represent any kind of distribution circuit configuration, permitting thus to simulate the exact circuit of the configurations mentioned above.

II. Problem Approach

The aim of the present tool is to show with a high degree of fidelity the phenomena in terms of power flow related to any railway circulation through a given track. To do so, it has been considered the employment of a succession of models, representing each one a single instant of the catenary system. When placed one after the other, from the very first instant in which the earliest train enters the section until the exit of the last convoy, it will be possible to recreate the temporal evolution of the different electrical variables (as frames composing a film).

The model to build for every single considered instant will be composed by the relevant elements in terms of power flow, which will be discussed later on. The combination of those pieces will make possible to build the entire track, that when simulated and solved using the suitable method, will provide the value of the electrical parameters which define the current state of the system.

The approach should be flexible enough to adapt to the different possible conditions, in terms of way of exploitation, considered equivalent wires, employed configuration, number of tracks, etc. but not as complex as to lose usefulness due to

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a longer simulation or onerous implementation. The adopted approach is useful for systems operating at 1×25 or 2×25, with the possible consideration of the return wire. Multiplex configurations can be considered for any conductor, but they would be reduced to an unique equivalent conductor.

The way in which the double track is modeled should be considered. Some applications decide to reflect the impact of this fact just in the electrical parameters calculation, including the presence of some additional conductors in order to find a single and equivalent track for the whole system. Instead, the chosen scope keeps the individuality of each track to keep a high degree of information and fidelity.

Finally, the position in the track and power consumption of the train at each instant along its circulation are input data of the algorithm.

III. Electric System Model

In order to carry out the simulation, looking for obtaining the electrical variables related to the circulation of a convoy through the track, it is needed firstly to build a model of the railway electrification system. This circuit will have as goal to represent in an accurate way the involved and relevant elements for the power flow calculation. A reliable and simple model should be obtained to optimize the simulation process.

Before entering on the details and different aspects of the circuit and how the modelling has been carried out, it is suitable to make a brief review of the elements involved in the general structure of the two systems into study.

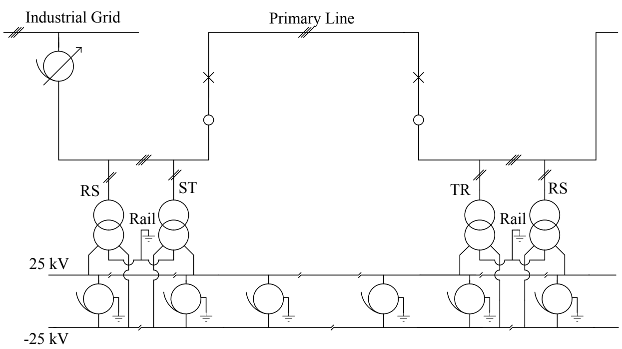

Fig. 1. General structure of a 2×25 electrical supply system.

A. Electrical supply system general structure

The electrical supply system is connected to the industrial grid through the TS. The main element in this installation is the power transformer, which reduces the voltage from the grids level (usually 132 kV) to 25 kV, or 50 kV if the 2×25 system is employed.

Downstream the secondary side of the transformer begins the catenary system, which is composed by a succession of the so-called cells. This are the minimum structural units of the catenary, with a length of 400 to 1500 m delimited by the earth-conductors grounding the tracks on both sides through impedance bounds (IB). Those connections impose periodically the ground voltage reference. Inside each cell the wires just remain invariant, hanging from the mast with no connection between them. Any possible connection will take place at the border between two adjacent cells. Usually, when grounding, a filter is placed to reduce the harmonic content. Fig. 1 displays the typical configuration of the 2×25 system.

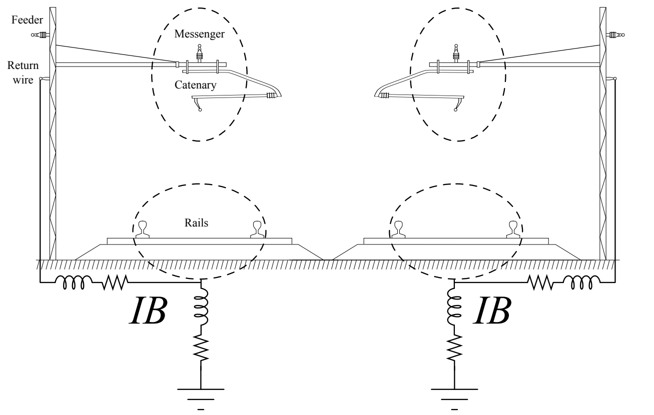

Fig. 2. Model of a double track 2×25 system showing the grounding connections.

Further elements are installed in order to ensure a flexible, versatile and reliable supply system, that ensure a prompt response to any failure. Those elements are called auxiliary points, and usually are protection devices, sectioning points, parallel points of supply (PPS), etc. A special one is the parallel autotransformation point (PATP), which connects the autotransformers between the messenger and feeder wires in the 2×25 configuration. These auxiliary points are usually installed every 10 to 15 km, depending on the particular conditions of the railway line.

B. System modeling

As usual, not all the existing elements are considered to build a model. The main reason is that most of them do not have a clear influence in the system performance when working in normal service. Despite of their importance may be appreciable for other purposes, they have a relative impact in the power flow calculations. Examples of those elements are the protection and measurement devices. This simplification is a compromise between reliability and complexity.

In the TS, only the power transformer is taken into account. The conductors along the cells are represented using the pi model. This is computed previously considering all the tracks, conductors and earth wires, in order to obtain the RLC parameters. At the end of each cell, the earth conductors are connected in parallel through the Impedance Bound (IB) connection, and grounded through a grounding resistance of 2 Ω (a typical value in this kind of studies). Fig. 2 show the conductor layout of a double-track 2×25 system.

Concerning the auxiliary points, only the PPSs and PATPs are taken into account, as they are the only ones affecting the power flow in a appreciable way during usual working conditions. Meanwhile the PPS is just a parallel connection between the homonym conductors of each track, the PATP

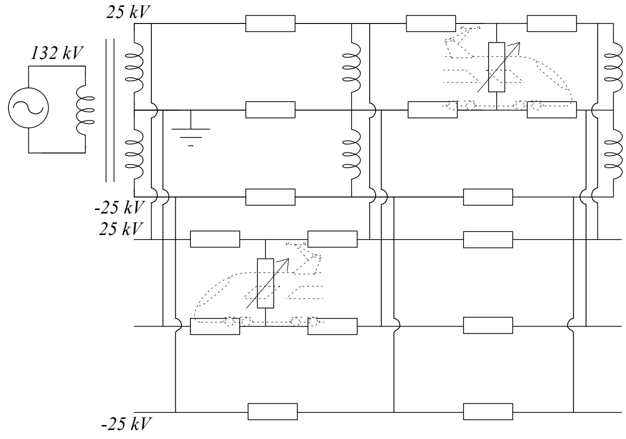

Fig. 3. Simplified circuit of a 2×25 double-track supply system.

features a set of autotransformers which strongly influence the power flow in the 2×25 configuration. Fig. 3 depicts a section of a double track 2×25 circuit.

The last element to be modeled is the train itself. The position and consumption of the train are part of the algorithm input data. At each instant of the simulation the locomotive is modeled as a constant power load at the proper distance of the TS. Only when the voltage falls below a minimum level, the locomotive is modeled as a constant impedance (Fig. 4).

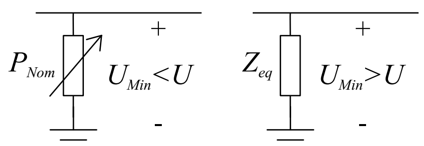

Fig. 4. Train electric model depending on the voltage level.

With this set of elements and their model it is possible to build an appropriate circuit to obtain through its simulation the sought information regarding the voltages and currents along the track.

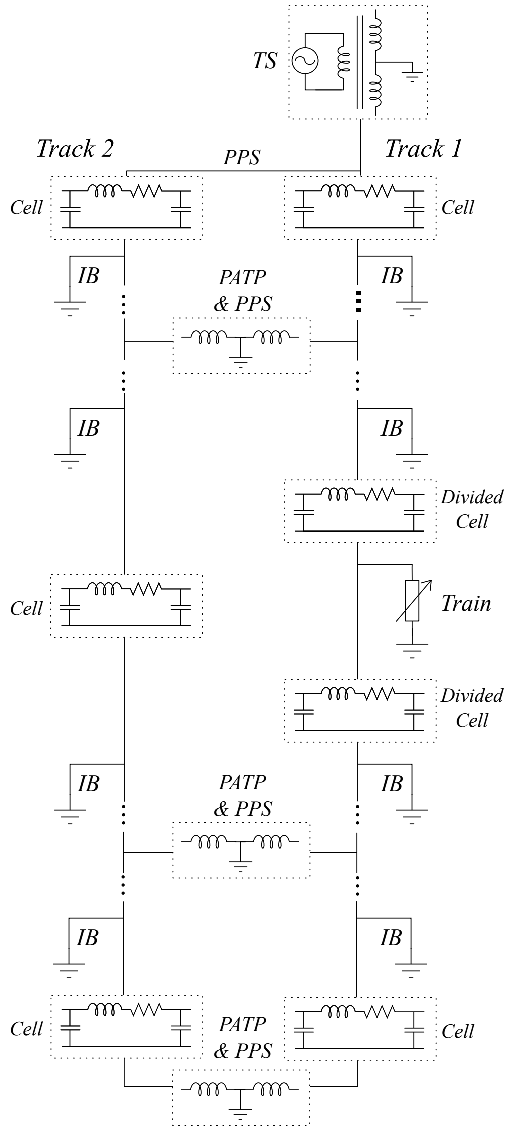

Fig. 5. Resulting model for a 2×25 double-track supply system.

IV. Algorithm

This section describes the proposed methodology to effectively simulate the system performance. There are two main procedures involved: one relative to building the circuit for each considered instant, and another one regarding the acquisition of the information, data management, simulation arrangement, etc.

A. System building loop

This first algorithm seeks to complete the construction of the model for each instant of the simulation. The main challenge related to this process is to ensure its flexibility in order to adapt to the various situations that happen during the normal operation. The only factor that distinguish one iteration from the other are the train positions in the track, as the electrical supply system do not change during the simulation. Fig. 6 details the proposed process. The loop repeats as many times as cells are in the system. It is remarkable that those cells can be employed to perform an analysis at any range of frequencies, given that they are characterized through the typical RLC parameters, which are obtained internally depending on the information facilitated by the user. Despite of that, along the shown results always a frequency of 50 Hz has been settled.

This part is almost entirely developed using OpenDSS. The general framework and user interface is managed using the Python programming language. The model is built declaring each element using OpenDSS particular coding language, and connecting them properly through the bars and their bus (important for the specific connection between the different phases of the same line).

B. Implementation

Once it is defined the employed algorithm to carry out the construction of the circuit, and the information it needs,

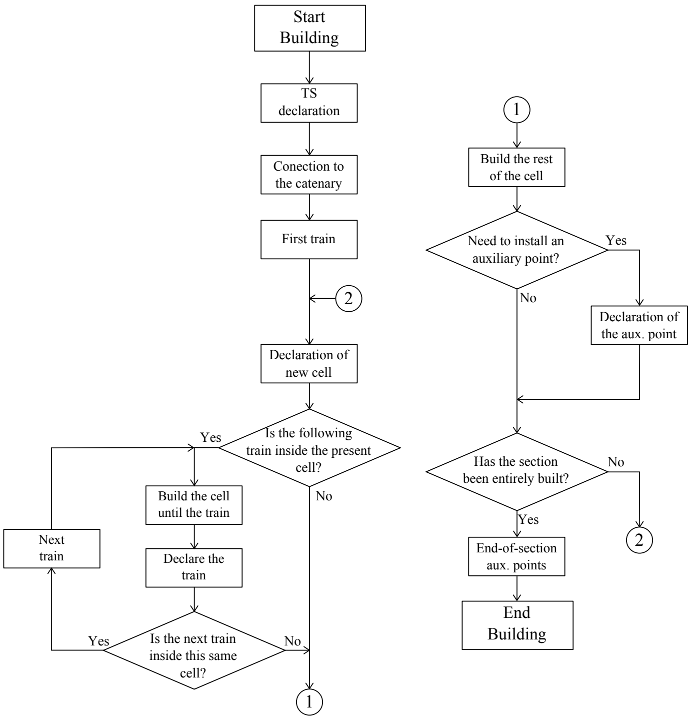

Fig. 6. System building flowchart.

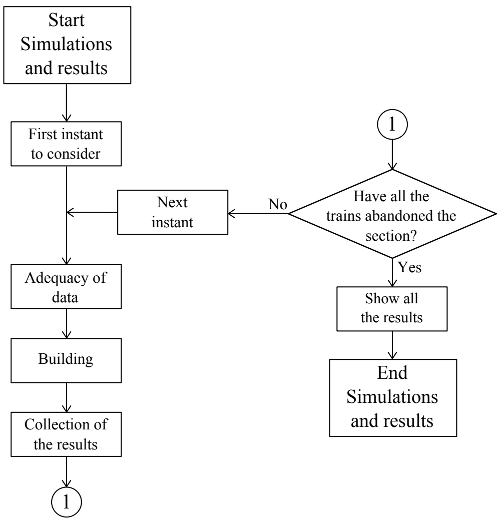

Fig. 7. Simulation flowchart.

the following step is to adapt the input data to the building loop requisites. According to this, the following stages can be defined. First, gather all the input information relative to the railway line operation (trains schedule, system configuration, etc.). Next, the adaptation of the input data to be processed by OpenDSS. The last module is in charge of carrying out the simulations and process the results to generate suitable information. The implemented algorithm also allows the user to repeat the simulation changing some parameters. Fig. 8 depicts graphically this procedure.

Once the algorithm is completed, the user get useful information related to the system behavior, as the voltage profile along the different circuits, the power consumption evolution, the currents distribution, power losses, etc. for any instant of time.

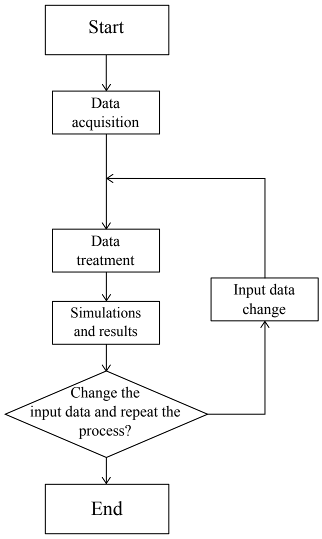

Fig. 8. General algorithm's flowchart.

V. SIMULATIONS

This section is devoted to show the results of different types of simulations. Current and voltage profiles are related to static solutions, whereas the evolution of the power is referred to an over time one. The following specific cases are presented:

A. Single train circulation in 1×25 and 2×25 configurations

The aim of this case is to assess the impact of the electrical configuration. This is a theoretical scenario in which the same train, with a constant power consumption of 8 MW, circulates along a railway of 30 km composed of two parallel tracks, connected every 12 km.

Fig. 9 compares the power withdrawn from the TS for each configuration. It can be noticed that the 2×25 configuration has a lower consumption for the full journey. This is due to the lower power losses of this configuration, as the voltage profile is improved with respect to the 1×25 configuration. Fig. 10 shows a snapshot of the voltage profile along the catenary when the train is close to the middle of the journey.

B. Double train circulation in a 2×25 configuration

A circulation of two convoys through parallel tracks is considered. In the previous case, the better performance of the 2×25 configuration was demonstrated. Now the simulation is focused on the operation. Specifically, the scenarios to consider are the following ones: a first case of simultaneous circulation of two trains in opposite direction, and a second one where one of the locomotives is injecting power using its regenerative brake.

As expected, a symmetrical evolution of the power demanded to the TS is obtained, as shown in Fig. 11. The peak

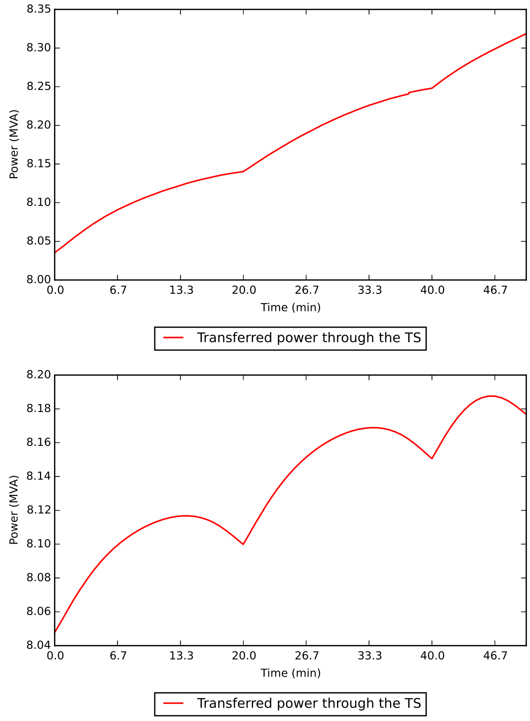

Fig. 9. Power consumption evolution for a single train circulation. Top: Using the 1×25 configuration. Bottom: Using the 2×25 configuration.

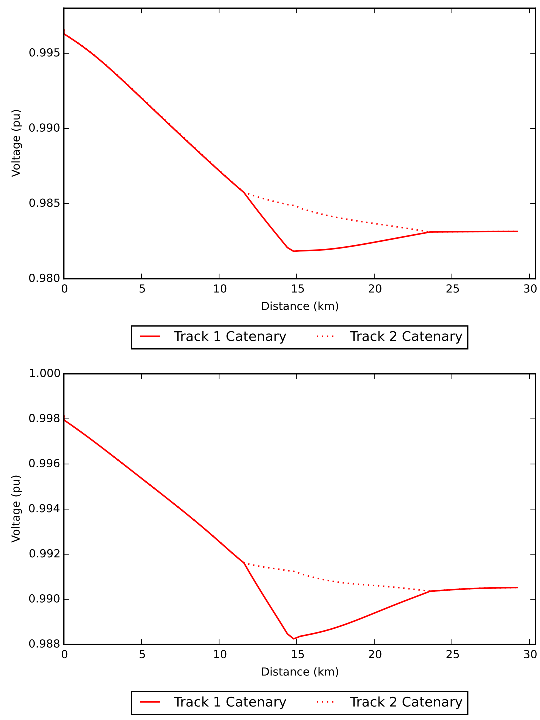

Fig. 10. Voltage profile for a single train circulation. Top: Using the 1×25 configuration. Bottom: Using the 2×25 configuration.

power consumption is happens in the middle of the simulation, when the losses related to the power transmission are at their highest value. Fig. 12 shows a snapshot of the voltage along the catenary in this case.

In the second situation, the whole scope changes radically, given that now one train is injecting 6 MW during its circulation, which is used to feed the second train. The expected behavior is similar to the typical double-fed supply configuration of DC railways, working the braking train as a TS. Obviously this is a theoretical scenario, due to the fact that it is not real for a train to be breaking along such a big distance injecting a constant power into the supply system.

As it can be seen in Fig. 13, the evolution of the power consumption is totally different to the previous situations, presenting now an irregular shape due to the dependence of the power losses to the distance to both the TS and the braking train.

A positive peak of voltage is located at the position of the pantograph of the second train (Fig. 14). This injects power to the catenary and PPSs. As the current distribution depicted in Fig. 15 shows, a power transmission from the TS to the train absorbing power is still needed, given that its power demand is higher than the braking train's generation. In case there is only a braking train, the injected power would be transferred entirely to the industrial grid through the TS.

C. Real Situation

As a final scenario to consider, the simulation regarding a real situation of a high speed railway line in Spain. It takes into account the information related to the consumption of a train when circulating through this line inboth directions (tracks 1 and 2). The train schedules were obtained from the Spanish railway operator (Renfe) webpage. The simulation could be set up to reproduce the circulations of a whole day.

It is not expected to find a similar results with respect to the ones seen before. In this case there are many sudden power variations due to the train stops and velocity constraints. Fig. 16 shows the evolution of the power injected from the TS to the supply system, along the whole day some similar power impulses are repeated, which are the result of several combination of train circulations along both tracks.

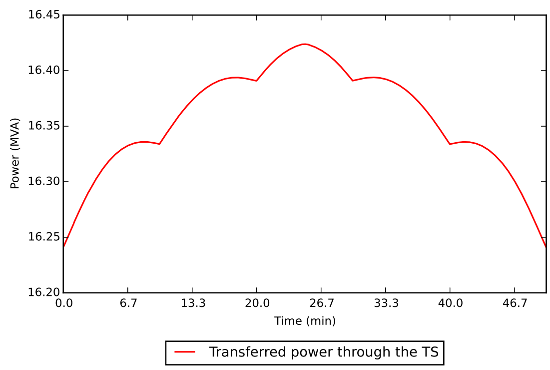

Fig. 11. Two trains in simultaneous circulation. Evolution of the power withdrawn from the TS.

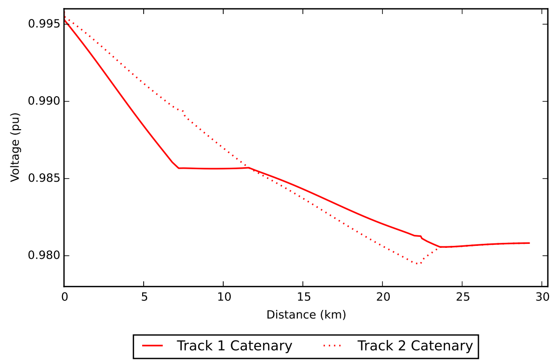

Fig. 12. Two trains in simultaneous circulation. Snapshot of the voltage profile along the two catenaries.

Fig. 13. One train braking. Evolution of the power withdrawn form the TS.

VI. Conclusion

In this paper it is described a methodology to simulate the electric circuit of the most usual configurations for high speed railways. The algorithm starts by gathering the information from the infrastructure and traffic data. The latter is needed to obtain the admittance matrix of the circuit. Adding the traffic information the circuit is solved for each time instant using the open source software OpenDSS. The train dynamics is not included in this work. However, this feature will be included in future versions of the software.

The results demonstrate that by using this methodology a good representation of the electric system behavior can be obtained. This is useful for the planning stage of a new line or for the operation optimization of existing infrastructure.

Acknowledgment

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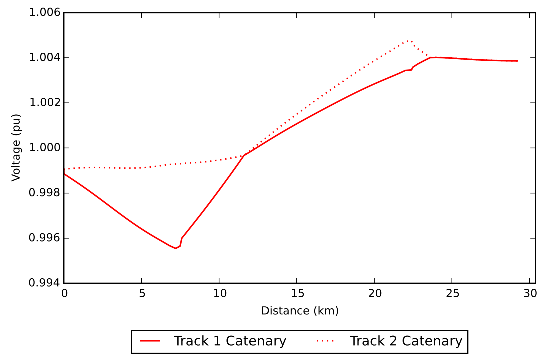

Fig. 14. One train braking. Snapshot of voltage profile.

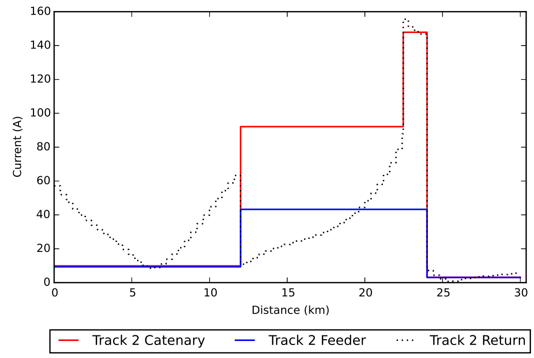

Fig. 15. One train braking. Current distribution in the track where the braking train circulates.

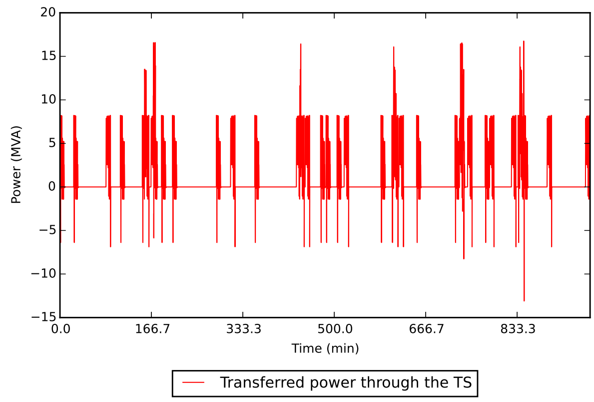

Fig. 16. Evolution of the power injected from the TS for a real scenario.

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