Optimisation of rolling stock, timetable and traction power supply for an urban railway system

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Abstract

Quite often urban transport systems are legacy systems. The main part of the infrastructure was created a long time ago, while other parts have been upgraded to meet new demands. The introduction of new elements in such a transport system is an issue which should be studied with care. In general, compatibility between all major system elements cannot be guaranteed by compliance with standards or guidelines. While the major part of the traction power supply system (TPS) of the Cascais Line is relatively old, the introduction of new rolling stock, with a considerably higher power demand (higher traction effort, powerful airco units) and a more exacting timetable was contemplated by the train operating company CP. REFER, the infrastructure provider wanted to study the effects of these changes towards catenary and substations carefully. Using the Holland Railconsult simulation tool DITEM®, the Cascais Line has been modelled with a high level of detail, considering track, signalling, catenary, substations, rolling stock and timetable. The existing situation was modelled, the simulation results matched well with the known behaviour. As a next step new types of rolling stock and new timetables were studied. A number of future problems with respect to catenary temperature and loading of substations, and behaviour during disturbances within the TPS System could be predicted. This enabled pre-emptive measures to be taken. Due to the high level of detail a minimum number of measures could be deduced, which leads to an economical solution. The use of a sophisticated simulation tool proved very useful in the modification and modernisation process of this suburban railway system.

Keywords: simulations, optimisation, traction power supply, rolling stock, timetables, environment.
1 Introduction

The Cascais Line with a length of ca. 26 km connects Lisbon (Cais do Sodré Station) with the coastal area of Cascais and Estoril, see Figure 1. The first part of the line from Cascais to Pedrouços was opened on Sept. 30th, 1889, on Sept. 4th, 1895 the line was completed to Cais do Sodré. In 1926 the line was electrified using 1500 V d.c., in those days one of the most modern systems. It was the first railway line to be electrified in Portugal and the Iberian Peninsula. The rolling stock used before the present upgrading originated mostly from the fifties, sixties and seventies. In 1950 rolling stock was purchased in the United Kingdom (Craven), a variant thereof was produced in Portugal in 1959 (Sorefame), seven car units were introduced in 1971. In 1976 the line was incorporated in the CP (Caminhos de Ferro Portugueses) network (presently REFER), previously the line was leased to Sociedade Estoril. In order to cope with the ever increasing demand for transport between the suburban areas of Lisbon and the inner city the total seating capacity of the three rail axis Sintra, Azambuja and Cascais, which was 34144000 in 1995 has now been increased significantly. As the Cascais Line links not only Cascais but also the complete Estoril coast to Lisbon, the importance of this line for daily commuters to Lisbon can hardly be overstressed. On a daily basis approximately 100,000 persons are transported. Apart from relieving traffic jams on the three main routes (CRIL, CREL and Marginal), this also account for a reduction in the emission of 4200 tonnes per year of pollutants. This is in line with the adaptation of "Letter of European Cities for Sustainable Environment - Aalborg Letter" by the Lisbon authorities in 1994.

Figure 1: Overview of Lisbon – Cascais area.

At the turn of the millennium CP and REFER contemplated a refurbishment of the rolling stock and a renewal of the infrastructure. Among other works REFER planned a full track renewal, refurbishment of buildings and a new parking yard at Carcavelos. REFER also wanted to suppress all level crossings by building new over and underpasses and to update the line for the future rolling stock. The Train Operating Company (CP) on their part contemplated the use of new rolling stock, a refurbishment of the old rolling stock and the introduction before the year 2001 of up to 12 quintuple units. The old units were
equipped with rheostat controlled engines and pull approximately 700 A. The new quintuple units (see Figure 2) will be equipped with powerful air-conditioning units and with power electronically controlled engines including regeneration of braking energy and will pull up to 2300 A. Secondly CP wanted to upgrade the timetable, introducing more trains per hour per direction, thereby again improving services for the customer. In a co-operation between REFER and Holland Railconsult the project “Simulations Cascais Line” was started. The goal of this project was to determine the impact of both the new rolling stock and the new timetables on the fixed installations, in particular the catenary and the substations. A large number of simulation tools are available, ranging from a high level of detail to a very abstract level of modelling, for both a.c. and d.c. systems [1]. As it was the wish of REFER that both a technical and an economical optimum should be reached for a complex legacy system, it was decided that a simulation tool with a very high level of detail should be used for the studies, therefore DITEM® was chosen.

2 DITEM simulation tool

2.1 Overview

DITEM® is a powerful train simulation tool which enables a visualisation of the relations between energy consumption, timetable, rolling stock, infrastructure and behaviour of engine drivers. The tool can be used for the design of the electrical infrastructure of a railway line, but also for determining the capacity of a railway station. All output is presented in a graphical way, in order to enable the user an easy assessment of the relations between for instance a time delay of a train, power installed along the line and timetable.
2.2 Functional decomposition

The simulation tool DITEM® is based on discrete time steps. For each time step the entire set of trains, infrastructure, and energy transport is subject of the calculation. All events of the time step are logged and can be shown to the user at the end of the simulation process. During each time step five components are taken into consideration:

- Rolling Stock Model;
- Traction power supply system;
- Timetable;
- Engine driver;
- Infrastructure.

2.3 Rolling stock model

Each type of train is modelled in DITEM® using the following relations:

- Maximum torque of the engine at a given speed;
- Power available for train acceleration at a given catenary voltage;
- Driving resistance as a function of speed;
- Auxiliary power consumption for lighting, air-conditioning, control systems (independent of train acceleration);
- Maximum total power consumption (sum of traction and auxiliary power).

When a train is braking similar relations exist, to determine the amount of energy which is fed back into the catenary. This module determines the current used per train and the acceleration of the train given the voltage at the pantograph.

2.4 Traction power supply system

The electrical network in DITEM® is a precise copy of the as build situation. Along the line substations are installed from which the catenary is fed, as well as switching stations where the different feeding sections of the catenary are coupled using circuit breakers. The parameters of each substation are determined by the type of rectifier, transformer, and feeding cables on the High-Voltage side. Basically the voltage on the catenary can vary from 700 V to 3000 V d.c., depending on the type of system modelled. All tracks of a section of the line are fed independently, all trains take their energy at their exact time dependent location. This module determines amongst others the voltage at the pantograph, given the current required by the rolling stock, but also the currents and voltages at the substations, etc.

2.5 Timetable

Within the timetable used in the model, the route of the train, the stops at stations, the connections (for passengers) to be realised and the minimum delay per station are taken into account.
2.6 Engine driver

All factors which may influence the use of the infrastructure and the energy sources are taken into account in the model, including the behaviour of the driver. The following elements can be incorporated in the model, using a statistical distribution:

- Duration of a stop at a station;
- Reaction time of the driver for an instruction given by a signal or sign along the line;
- Variations in driving style of the driver when approaching a station.

2.7 Infrastructure

Within DITEM® the exact infrastructure as given by the real life situation can be simulated. The safety of trains is based on signals along the line which can give speed instructions to the driver. The lay-out of the line is taken into account using curve radii and inclinations. The infrastructure also includes the locations of substations, switching stations, and the electrical resistance of the catenary and the running rails (the return circuit).

2.8 Temperature

As the temperature of the catenary is an important issue, the module TEMPEL is present. This module calculates the temperature of the catenary taking into account all relevant factors such as:

- Current transported;
- Electrical resistance of catenary;
- Wind speed and ambient temperature;
- Solar radiation;
- Amount of clouds present;
- Radiation from catenary (Stefan-Boltzman equation);
- Reflection of catenary (shining when new, dark when old);
- Wear of catenary.

2.9 Output

The simulation tool gives the user information in a simple graphical way, giving insight in:

- The energy consumption during the day with a normal timetable, with an adjustable level of disturbance created by human behaviour;
- The behaviour of the traction power supply system during a disturbance in the electrical network;
- The actual and average voltage on and current in the catenary;
- The temperature of the catenary based on all relevant parameters;
- The delay in time of trains based on a given level of quality of the traction power supply system;
- The stability of a timetable in relation to a given infrastructure.
3 Modelling of the Cascais Line

3.1 General

A general overview of the Cascais Line can be found in Figure 1. The input data were provided by REFER and describes the various layers present in the model:
- Network Layer;
- Civil Structure Layer;
- Signalling Layer;
- Electrical Layer;
- User Layers:
  - Timetable;
  - Rolling Stock;

3.2 Network layer

The network layer (see 2.7) is mainly determined by the track layout [2]. As shunting and parking could be excluded, extra tracks at stations and yards could be omitted. This leads to a double track layout with one track for each direction. The exact length is 25.7 km, with stations at the following locations, see table 1. The design velocity is 90 km/h.

<table>
<thead>
<tr>
<th>Station</th>
<th>Location [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cais do Sodré</td>
<td>0</td>
</tr>
<tr>
<td>Santos</td>
<td>0.947</td>
</tr>
<tr>
<td>Alcântara-Mar</td>
<td>2.668</td>
</tr>
<tr>
<td>Belém</td>
<td>4.862</td>
</tr>
<tr>
<td>Algés</td>
<td>7.8</td>
</tr>
<tr>
<td>Cruz Quebrada</td>
<td>9.793</td>
</tr>
<tr>
<td>Caxias</td>
<td>11.763</td>
</tr>
<tr>
<td>Paço de Arcos</td>
<td>13.205</td>
</tr>
<tr>
<td>Santo Amaro de Oeiras</td>
<td>15.57</td>
</tr>
<tr>
<td>Oeiras</td>
<td>16.207</td>
</tr>
<tr>
<td>Carcavelos</td>
<td>17.8</td>
</tr>
<tr>
<td>Parede</td>
<td>19.513</td>
</tr>
<tr>
<td>São Pedro</td>
<td>21.062</td>
</tr>
<tr>
<td>São João</td>
<td>22.519</td>
</tr>
<tr>
<td>Estoril</td>
<td>23.669</td>
</tr>
<tr>
<td>Monte Estoril</td>
<td>24.358</td>
</tr>
<tr>
<td>Cascais</td>
<td>25.7</td>
</tr>
</tbody>
</table>

3.3 Civil structural layer

The main goal of this layer (see 2.7) is to take into account effects of vertical and horizontal curves in the alignment [2] of the track on the power consumption of the rolling stock. Therefore only those elements which have an influence of more
than 5% on the energy consumption are taken into account. As the Cascais Line is mainly situated along the coastline, vertical curves have a small influence.

### 3.4 Signalling layer

All main signals (see 2.7) have been included in the model on the positions given by [3]. A signal can have three aspects in the model:

- Safe (Green);
- Stop (Red);
- Next signal shows stop (Yellow).

Especially in disturbed situations signals can have an influence on power consumption. After a disturbance a large number of trains are stopped in front of a red signal, once the disturbance is removed, a large number of signals show green, leading to the simultaneous acceleration of a large number of trains, hence a more than average demand on the traction power supply system. A description of this phenomena also known as “grouping of trains” can be found in [4].

### 3.5 Electrical layer

Each substation has two rectifiers, a no load voltage of 1700 V (minimum 900 V), feeds both directions of the line, and has four circuit breakers. Resistances are the following: catenary 89.9 mOhm/km, return circuit is 22 mOhm/km (open line) or 44 mOhm/km (stations). An overview of the substations can be found in table 2. Also see 2.4.

<table>
<thead>
<tr>
<th>Substation</th>
<th>Cais do Sodré</th>
<th>Belém</th>
<th>Cruz Quebrada</th>
<th>Paço de Arcos</th>
<th>Carcavelos</th>
<th>São Pedro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location [km]</td>
<td>0.158</td>
<td>4.834</td>
<td>9.605</td>
<td>13.245</td>
<td>17.5</td>
<td>21.23</td>
</tr>
<tr>
<td>Nominal transformer load [MVA]</td>
<td>1.348</td>
<td>2</td>
<td>2</td>
<td>1.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Maximum rectifier load [kW]</td>
<td>1200</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td>Maximum cont. Rectifier[A]</td>
<td>750</td>
<td>1173</td>
<td>1173</td>
<td>750</td>
<td>1173</td>
<td>1173</td>
</tr>
<tr>
<td>Internal Resistance [Ohm]</td>
<td>0.22</td>
<td>0.14</td>
<td>0.14</td>
<td>0.18</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Resist. Feeder – catenary [Ohm]</td>
<td>0.024825</td>
<td>0.0075</td>
<td>0.0015</td>
<td>0.01875</td>
<td>0.00375</td>
<td>0.01875</td>
</tr>
<tr>
<td>Maximum cont. current feeder [A]</td>
<td>854</td>
<td>854</td>
<td>854</td>
<td>854</td>
<td>854</td>
<td>854</td>
</tr>
<tr>
<td>Peak (1 sec.) current feeder [A]</td>
<td>1900</td>
<td>1900</td>
<td>1900</td>
<td>1000</td>
<td>1800</td>
<td>1600</td>
</tr>
<tr>
<td>Peak cur. Feeder [A]/dura. [sec]</td>
<td>1600/10</td>
<td>1600/10</td>
<td>1600/10</td>
<td>1600/2</td>
<td>1400/2</td>
<td></td>
</tr>
<tr>
<td>Resistance return circuit [mOhm]</td>
<td>2.25</td>
<td>0.375</td>
<td>0.375</td>
<td>1.125</td>
<td>0.375</td>
<td>0.375</td>
</tr>
</tbody>
</table>

### 3.6 User layers

The timetable used [5] gives between 4 and 8 trains/hour and direction (upgraded timetable up to 12 trains). Rush-hour 7 AM to 9 AM is modelled, rolling stock is
one set UTE-UQE for existing types, and two coupled UME’s for refurbished types. Maximum speed is 90 km/h, halting time is 30 sec. Also see 2.3 and 2.5.

4 Simulations

4.1 Results

For the loading of a substation, the instantaneous value of the power delivered, the 1, 5 and 15 minute average values, see Fig. 3. For the quality of the supply voltage [6] see Fig. 4. The loading of the rectifier groups is also calculated [7], an example can be found in Fig. 5. Note that the “old” rolling stock can be supported, but the refurbished version leads to an overloading (short duration & permanent) of the rectifier groups. An important result is the temperature of the catenary, see Fig. 6 (T_{env} 50 °C, wind velocity 5 m/s, 1 kW/m² solar radiation, absorption of conductor 60 %). Note that the maximum of 80 °C is surpassed.

![Figure 3: Power delivered by substation Sao Pedro.](image)

![Figure 4: Voltage characteristics.](image)
4.2 Analysis

The simulations proved that the infrastructure could support the situation present, although a number of circuit breakers were experiencing temporary overloads, which was confirmed by REFER maintenance staff. The refurbished rolling stock, in combination with the new timetable and the existing infrastructure leads to a number of problems. For instance with respect to the quality of supply voltage at the pantograph [8], the loading of rectifiers in substations, circuit breakers and temperature of catenary at a number of locations.
4.3 Recommendations

Based on the simulation results it was recommended:
- To increase the power of all substations;
- To examine the circuit breakers carefully with respect to their loadings and characteristics;
- To increase the cross-section of the catenary;
- To proceed with the realisation of the planned substation Cascais.

5 Conclusions

Suburban railways systems like the Cascais Line play a major role in the modal shift from cars to public transport, thereby making substantial reductions in emissions of pollutants possible. Upgrading these railway systems, at minimal investment cost using powerful modern analysis is needed. It can be concluded that the simulations were very useful in determining the operational envelope of the infrastructure system. A number of detailed recommendations could be made for improvements needed in order to enable infrastructure to support the new refurbished rolling stock in combination with a more demanding timetable.

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References