Analysis of energy-saving strategies in railway power supply systems

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Abstract

This paper presents some results obtained with an electric railway simulator. This tool has been mainly developed for studying energy consumption in both AC and DC electrified railway systems. Two case studies have been carried out. The first one analyzes a DC electrified underground system, assessing the energy saving related with the introduction of trains equipped with regenerative braking, reversible substations, etc. The second case study consists in an AC electrified high speed line where improvements due to the introduction of regenerative braking, capacitor banks and enhanced +25kV /-75kV electrification are analyzed.

Key words

Railway electrification, energy efficient, load flow, railway power supply

1. Introduction

Railway operators are always looking for a reduction in their operative costs. One of the cost items where it is up to be evaluated how much money may be saved is the energetic bill, which sometimes represents a significant fraction of the total costs (especially in underground and commuter systems).

Analytically dealing with an electric railway problem is rather hard: first, these problems are highly non-linear (especially in the DC railway case); then, they are in addition complex time-variant systems where loads are constantly changing their values and positions. For these reasons, in most cases a simulator is the most suitable tool for handling such a complex system. It may be stated that an electrical simulator is a key point for the study and management of energy consumption in railway lines where electric traction is used.

The aim of this work is to compare different possibilities of saving energy regarding the electrification of railway systems: usage of train braking regeneration, off-board energy storage, capacitor banks, rectifier and inverting substations for DC railways, impact of voltage supply level, etc. These technologies are already available, but there is a need of analyzing their impact both as single or combined improvements.

The energy consumption will be analysed for each possibility in the same line and circumstances, thus improving investment decisions. The final purpose is to achieve a more energy efficient railway and/or an increment in the capacity.

2. Simulator Features

The simulator makes it possible to analyze DC, AC and mixed AC-DC electrified railway lines.

In the DC side, the simulator features the electrical models of the main components from an energy consumption point of view:

- Regenerative Braking: Both the possibilities of dissipating braking energy in dedicated resistors or returning it into the network (when possible) are considered.
- Reversible Substations: Most of today electrical substations in DC-electrified railway lines are unidirectional, i.e. they only allow power to flow from the AC to the DC side. However, there are reversible substations which work in two electrical quadrants hence allowing current to flow from the AC to the DC side and vice-versa. The simulator permits using both kinds of substations.
- Energy Storage Devices: Provided in a railway system the consumption is fairly time-variant, energy storage is sometimes a key factor for energy saving. In addition, these devices may
also be used with the aim of reducing voltage variance in the feeder line, hence reducing the probability of having voltage dips in the line. Energy storage devices may be placed in fixed posts or on-board.

In an analogue way, the simulator offers the possibility of using the most important devices in the AC side in order to be able to carry out energy consumption studies:

- Regenerative Braking.
- Several Supply Systems: The so called 1x25kV and 2x25kV are available. Moreover, enhanced supply systems such as the asymmetric +25kV/-75kV one may be evaluated.
- Capacitors Banks: They are habitually used in electrical systems to control the reactive power and, as a consequence, losses and voltage levels.

3. Simulator Results

The simulator solves the successive electrical problems that arise at each time instant while trains are moving. A constant three-second time step has been used. At each time instant, the simulator solves the corresponding electric circuit and stores all the relevant results. Then, the energy saving analysis is conducted by aggregating these results.

The following are the main simulator outputs:

- Consumption in substations and trains.
- Braking power, which is divided into effectively regenerated power (returned into the feeder line) and power dissipated in rheostats.
- Losses in transmission lines, feeder lines, substations, transformers and autotransformers, etc.
- Minimum and maximum voltages in the feeder line.
- Line reactivity factors.

4. Simulator Structure

Figure 1: Electrical simulator structure

Figure 1 shows the simulator structure. It consists of three fundamental modules:

- Electrical Scenarios Generator: It generates the consecutive electrical circuits to be solved from the infrastructure and the operative information (time schedule, position and power consumption/generation of every train, etc.).
- Load Flow: This block deals with solving the load flow problem at each time instant considered. AC, DC or mixed AC-DC systems may be solved.
- Results Aggregation: This module is in charge of aggregating the results of the load flow module in order to obtain significant magnitudes (for instance, it calculates energy results from the instantaneous power data).
In the following, each module is described in detail.

4.1. **Electrical Scenarios Generator Module**

The objective of the Electrical Scenarios Generator module is to create the electrical problems to be solved. Since trains are changing their position and consumption in time, these circuits are not the same at each instant. It is hence necessary to generate a sequence of circuits at regular time intervals representing these different situations. A time step of three seconds has been selected. This allows a precise enough simulation and it is affordable from a computational load point of view. The block creates these circuits from the following information:

- **Infrastructure.** This represents the time-invariant part of the circuits, i.e. the electrification elements. It includes the electrical features of the feeder line (overhead conductor or third rail), track and substations, track lengths, line topologies, supply voltage, substation positions, etc.
- **Time Schedule:** Description of the train timetables needed to derive their position and consumption evolution in the considered system. It may be defined, for instance, in terms of departure times and headways.
- **Speed Profile:** This represents the information about the behavior of an individual train. That is, its consumption, speed, etc. at each point of the track. A speed profile simulator which simulates the train main variables profiles from the track and its own characteristics is required.

4.2. **Load Flow Module**

Each circuit generated by the Electrical Scenarios Generator module represents a load flow problem which is solved using the Newton-Raphson method [1]. The Load Flow module creates a result file for each instantaneous circuit which contains all those electrical magnitudes which are necessary for energy studies (voltages, currents, powers, etc.).

When a DC-electrified railway is studied, the electrical infrastructure is composed of an AC and a DC part, which are linked by means of transformers and rectifiers in substations. There are different options to solve this mixed load flow problem, which may be grouped into two categories: sequential and unified methods [2]. The first class solves the AC and DC sides separately. The solution process is based on an iterative method where the solution of one of the sides is taken as an input for the solution of the other one. Convergence is reached when AC and DC magnitudes in the linkages (substations) are congruent. The unified methods solve the problem as a whole, and hence a rectifier model is required. The simulator implements mixed AC-DC Newton-Raphson method to solve the load flow problem. Several rectifier models have been utilized, being the one in [2] the most complex.

If reversible substations (rectifier plus inverter) are considered, energy may flow both from the AC to the DC side and vice-versa. An inverter model such as that utilized in [3] is required.

Since the DC problem has plenty of nonlinearities, the simulator has to check that the solution at each iteration is feasible. For instance, if a non-reversible substation is considered and its current in the provisional results is negative, that means that the substation is likely to cut off. The solution must be discarded and new calculations must be carried out taking this into account. In the same line, if a train reaches the maximum accepted voltage at its pantograph or collector shoe, which is common in strong braking combined with low line receptivity, a change in its behavior must be considered. In this situation, a fraction of the regenerated power must be dissipated in the rheostats for the voltage not to go on rising. Also energy storage devices have several operating modes (inactive, loading, unloading, etc.).

4.3. **Results Aggregation Module**

The result files generated by the previous module are processed in the Results Aggregation module in order to make global studies. For instance, the integration of powers at each instant is carried out in this block in order to calculate energies. Net energy in substations, losses in substations and feeder line, energy dissipated in rheostats, regenerated energy, etc. are calculated in this block.
5. **Case Study: Line 3 of Metro de Madrid.**

The first case where the simulator has been applied is Metro de Madrid Line 3. The following figure shows a simplified schematic of this line.

![Metro de Madrid’s Line 3 simplified schematic](image)

The main electrical characteristics of Line 3 in Metro de Madrid are the following:

- Six electrical substations equipped with 12-pulse rectifiers.
- The feeder line nominal voltage (DC) is 1.5kV, but it is operated with a 1.75kV no-load voltage.
- Double track.
- No isolators are used to electrically divide the line.

The following are the main operative constraints taken into account:

- Peak hour: A train every 2 minutes.
- Off-peak hour: A train every 15 minutes.
- Metro de Madrid S3000 train considered.
- Maximum traction power: 1.5MW.
- Maximum braking power: 1.5MW.
- Consumption of auxiliary equipment: 200kWh/h.

### 5.1. **Peak hour analysis**

In the following, the results of the analysis of the peak hour in Line 3 of Metro de Madrid are shown. Several possible scenarios are considered: trains without regenerative braking, with regenerative braking and reversible substations.

![Villaverde Alto substation power and voltage results in the peak hour.](image)

The figure shows AC and DC voltages and power consumption in Villaverde Alto substation in the peak hour for the three different scenarios considered. This line is very well dimensioned and the no-load voltage is set to a high level, which yields high voltages even in this peak hour scenario. Moreover, efficiency (defined as the ratio between the net power in trains and the net power consumption in substations) is quite high, greater than 98%.

When trains are equipped with regenerative braking, they try to return their kinetic energy into the feeder line after supplying the auxiliary consumption in the train. This is not always possible, and it...
depends on line receptivity. When power is returned into the line, the pantograph (or collector shoe) voltage tends to rise, and the way it does depends on the state of the network in that moment (voltages, consumptions, etc.). If pantograph (or collector shoe) voltage reaches a certain threshold, the energy surplus is dissipated in rheostats.

Voltages with regenerative braking are even higher than those without it, especially in moments where significant braking is taking place. Losses in rheostats are quite low. The most remarkable fact is that consumption in substations falls around 30%.

When reversible substations are simulated, the differences with the case where non-reversible substations are considered are rather small in the peak hour. Around the time instant 100, Villaverde Alto substation is working in inverter mode, so delivering power to the AC side. It should be noticed that the vertical scale in this third graph (eastside) is slightly different than the one in the rest of figures.

While the improvement obtained with regenerative braking is noticeable, reversible substations do not seem to contribute significantly to the efficiency of the system in these circumstances. The amount of energy returned into the AC side does not affect so much the energetic budget. However, it must be noticed that this is a partial conclusion for this well dimensioned line and in a peak time scenario (which increases line receptivity).

Losses in rheostats, which were quite low with regenerative braking, become nearly zero with reversible substations.

5.2. Off-peak hour analysis

The results of the analysis of the off-peak hour operation in this underground line are now shown. The same scenarios as those in the previous analysis are considered: trains without regenerative braking, with regenerative braking and reversible substations.

![Figure 4: Villaverde Alto substation power and voltage results in the peak hour.](image)

The figure shows AC and DC voltages and power consumption in Villaverde Alto substation. This line is very well dimensioned and the no-load voltage is set to a high level, which yields even higher voltages than those in the peak hour scenario. Moreover, efficiency (defined as the ratio between the net power in trains and the net power consumption in substations) is quite high, greater than 99%.

When trains are equipped with regenerative braking, voltages are even higher than those without it, especially in moments where significant braking is taking place. Consumption in substations falls around 25%.

An analysis of the braking energy after supplying auxiliary consumptions in trains (i.e. the energy that the set of braking trains try to return into the feeder line) yields a 70% of energy successfully regenerated vs. a 30% of energy dissipated in rheostats. Please note that at each time instant, the addition of the successfully regenerated power and the dissipated in rheostats power is the total braking power minus the power required to feed the auxiliary equipment.

When reversible substations are simulated, the net consumption in substations falls nearly the 30% with regard to the consumption without regenerative braking. The additional energy saving comes from the fact that now the 96% of the braking energy after supplying auxiliary consumptions is successfully returned into the line, and only the 4% of this reusable energy is dissipated (and so wasted) in rheostats. That is, reversible substations nearly eliminate energy in rheostats.
The following table gathers the main results obtained in the analysis of this case study both for peak and off-peak hours.

### Table 1: Metro de Madrid Line 3 results summary (one hour)

<table>
<thead>
<tr>
<th></th>
<th>Peak hour (one hour)</th>
<th>Off-peak hour (one hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MWh) SS* consumption</td>
<td>18.16</td>
<td>12.11</td>
</tr>
<tr>
<td>Energy saving</td>
<td>N/A</td>
<td>33.30</td>
</tr>
<tr>
<td>Trains consumption</td>
<td>17.87</td>
<td>16.11</td>
</tr>
<tr>
<td>Returned (feeder line)</td>
<td>0.00</td>
<td>4.22</td>
</tr>
<tr>
<td>Trains net**</td>
<td>17.87</td>
<td>11.90</td>
</tr>
<tr>
<td>Energy Losses (MWh) Rheostat</td>
<td>0.16</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>Overhead conductor</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>0.12</td>
</tr>
<tr>
<td>Energy Losses (% of substation) Rheostat</td>
<td>0.12</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Overhead conductor</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>SS</td>
<td>0.06</td>
</tr>
<tr>
<td>Efficiency***</td>
<td>0.984</td>
<td>0.982</td>
</tr>
<tr>
<td>Voltage (V) Maximum</td>
<td>1704</td>
<td>1790.1</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>1587</td>
</tr>
</tbody>
</table>

* 'Trains net' is the energy delivered by substations which is effectively used by trains.

** SS stands for "Substation".

*** Efficiency is defined as the ratio between trains net energy and the consumption in substations.

The main conclusions for this DC-electrified railway line are the following:

- There is an important energy save when regenerative braking is used in both peak and off-peak hour scenarios.
- Reversible substations help to minimize the energy dissipated in rheostats. Since this is nearly zero in the peak time scenario, the effect of this technology is not noticeable. However, in the off-peak hour scenario, this kind of substation help to get additional energy saving. It must be remarked that, although important in relative terms, the absolute energy saving is not that important due to the fact that the amount of energy in the off-peak scenario is rather lower than that in the peak one.
- Regarding feeder line voltages, it can be observed that regenerative braking leads to higher maximum and minimum pantograph voltages. It should be noticed that in this case study, with such a good infrastructure, no voltage drop problems arise, and so the importance of regenerative braking in avoiding voltage dips may be hidden.

The second case where the simulator has been applied is the Madrid-Zaragoza stretch in the Madrid-Barcelona high speed line.

The figure shows a simplified schematic of this line in the stretch between Madrid and the electrical substation of Brihuega, where all the elements present in this mixed AC line may be observed. There is a short $1\times25kV$-electrified stretch in Madrid surroundings. Then, the electrification becomes $2\times25kV$ until Zaragoza (actually until Barcelona). See [4] for further details on this kind of electrification.

The following are the main operative constraints taken into account:

- Peak hour: A train every three minutes (in each direction). It must be remarked that this frequency is much higher than the current maximum frequency in this line.
- Talgo-Bombardier S102 train.
- Maximum traction power 8MW with an efficiency of 0.91 in the traction chain.
- Maximum braking power 8.33MW with an efficiency of 0.9.
- Consumption of auxiliary equipment: 325kWh/h.
- Train power factor ($\cos \phi$): 0.95 (this represents a worst case condition regarding losses).

Six different scenarios which can be divided into two groups have been simulated. In the first group, trains without regenerative braking have been used. Then, taking infrastructure into account, three scenarios have been simulated: the current electrification itself, an alternative with capacitor banks, and asymmetric +25kV/-75kV electrification. In the second group, the same three scenarios with trains equipped with regenerative braking have been simulated.

The following table gathers the most significant results obtained in these six simulations:
When trains without regenerative braking running in the current infrastructure are simulated, the main results are the following:

- Efficiency over 98%, hence losses in the feeder lines and autotransformers lower than 2%.
- The equivalent power factor in substations is lower than that of the trains due to reactive power consumption in the lines, autotransformers and the substations themselves.
- 23.5kV minimum pantograph voltage.

Connecting capacitor banks is a common practice in power systems to effectively reduce the reactive power consumption and hence the apparent power. These devices have been connected in diverse points of the line (in the substations, close to autotransformers near neutral zones, in intermediate points, etc.) and no significant differences have been found.

The main consequences of connecting these devices are the following

- The reactive power consumed in the system is now generated both in substations and in the capacitor banks. Actually, the simulated capacitor banks generate around 50% of the reactive power in this scenario.
- Noticeable improvement of the equivalent power factor in substations.
- Since currents are lower, a 10% reduction in the feeder line losses is observed.
- The minimum pantograph voltage rises to 24.6kV, which means that traffic capacity in the line is increased.

The last kind of infrastructure simulated, the asymmetric +25/-75kV electrification is an alternative to reduce currents in conductors, hence reducing losses and increasing line capacity. The introduction of this electrification leads to the following results:
Challenge A: A more and more energy efficient railway

- 48% reduction in losses. This is related to the effective double supply voltage. This reduction is rather important in relative terms, but it must be noticed that this particular line is very well dimensioned, and hence losses are quite low.
- Minimum pantograph voltage rises to 25kV, with the consequent increase in line capacity.

A second batch of simulations has been carried out with the same infrastructure characteristics as before, but now with trains equipped with regenerative braking. This feature yields the following differences in the first infrastructure scenario (current infrastructure):

- Trains net consumption is decreased around 12% (both active and reactive power). As a consequence, consumption in substations is also decreased.
- Conductor losses are also reduced as a result of the load decrease (approximately 10%).
- 23.56kV minimum pantograph voltage.

In the simulation including capacitor banks, the following results are observed:

- There is a 20% reduction in conductor losses with regard to the case without regenerative braking and a 10% reduction in comparison with the case with regenerative braking but without capacitor banks.
- Minimum voltage rises to 24.7kV, with the consequent increase in theoretical line capacity.

To conclude this second batch of simulations, the asymmetric +25/-75kV combined with regenerative braking trains has been simulated:

- Conductor losses decrease 54% with respect to trains without regenerative braking, and 48% if compared with the first case in this second simulation batch. Once again, this reduction is rather important in relative terms, but it must be noticed that this line is very well dimensioned, and hence losses are quite low.
- Minimum pantograph voltage rises to 25.05kV, which yields the maximum line capacity in all the simulated scenarios.

Just to finish this case study simulations, a couple of scenarios with the current infrastructure and trains every 60 minutes (with and without regenerative braking) have been analyzed with the following results:

- Efficiency over 99%.
- Hence, conductor losses below 1%.
- Regenerative braking reduces substation consumption in the same proportion as with the heavy traffic conditions (12%)
- Capacitor banks should be disconnected (at least partially) for voltages not to have an excessive rising.

The main conclusions of this AC-electrified line analysis are the following:

- Regenerative braking yields around 12% energy saving.
- Line is overdimensioned, which leads to quite few losses.
- The different infrastructure cases considered in both simulation batches only affect losses, so representing a small overall energy consumption reduction.
- The use of capacitor banks yields a significant reduction of reactive power (equivalent power factor) in substations, as expected.
- 10% conductor losses reduction may be observed when connecting capacitor banks.
- This reduction in conductor losses reaches 50% in the +25/-75kV electrification cases.
- Regenerative braking, capacitor banks and asymmetric electrification increase the minimum pantograph voltage in the line, being the case with regenerative braking and the latter electrification the one with the highest theoretical line capacity.
7. Conclusions
This simulator has shown to be able to deal with both AC and DC railway lines. In addition, its implementation allows any kind of complex track topology to be introduced.

With the simple set of simulations presented in this paper, the simulator has made it possible to assess the actual energy saving related to regenerative braking and other technologies.

Since both the AC and DC railway lines analyzed are clearly overdimensioned for their current traffic level, no voltage dip problems have arisen. But for other cases, as relatively old railway infrastructure where a traffic increase is desired, the simulator arises as a powerful tool to advise whether the line is likely to withstand the new load or not.

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9. References


