Simulation Study of Power Limitation for City Trams

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Abstract

In this paper, we describe a simulation study aimed at investigating whether a momentary limitation of the tram power output can be effective in reducing current overload, while maintaining the tram performance at an acceptable level. The study was performed on a single-fed tram section in Gothenburg, Sweden.

The simulation results indicate that an adaptive power output limitation, which is only activated when the current and current derivative is above certain limits, is effective in reducing current peaks, while still maintaining required tram performance. Thus, this method could be used to reduce or eliminate power failure on the tram net, without causing unacceptable tram delay.

Keywords:
Tram infrastructure, Simulation, Energy

Introduction

Expanding cities faces great challenges regarding the ability to provide a sustainable mobility for all groups in society. A well-functioning public transport is one important factor for reducing the environmental impact of passenger transport.

Electrically driven vehicles, such as city trams, may be an attractive solution, with regard to local emission, noise and CO\textsubscript{2}. For a city with an existing tram system that has reached its limit regarding frequency of trams, and needs to further increase passenger capacity, a solution may be to increase the length of the trams. However, this results in higher power demand peaks when the trams accelerate, and the tram infrastructure may need to be reinforced.

An alternative, and perhaps more cost-efficient, solution to reinforcement of the infrastructure, could be to limit the tram power-output, and, thereby, the current peaks in the rectifying stations. In this paper, we describe a simulation study aimed at investigating whether a momentary limitation of the tram power-output can be effective in reducing current overload, while maintaining the tram performance at an acceptable level. The study was performed on a single-fed tram section in Gothenburg, Sweden.

Description of Tram System

The tram system in Gothenburg exists since 1902. The voltage is 750 V DC nominally, and the current is transferred to the trams through the overhead line, which is divided into 0.5-2 km long sections. Each section is fed from either one rectifying station, or two parallel stations. The latter is the most common solution. In theory, the stations are perfectly parallel, however, in practice, the voltage from the stations may vary and the load is not perfectly split between the two stations.

A typical rectifying station in the Gothenburg tram system can feed 2500 A instantaneously. If this is exceeded, the current is switched off and remains so for about 12 s. Typically, the reason for power failure is that this “instantaneous” current limit is exceeded. There is also a thermal protection in the rectifying stations, which is set so that a station can feed about 1000 A during a longer period of about 1-10 min. This is, however, normally not a limiting factor, since the overhead line is not overheated during the relatively brief peak power demands.
The tram type that was simulated is the so-called Sirio (in Gothenburg known as M32), delivered from AnsaldoBreda in 2004. This tram has a higher consumption of power than the older trams in Gothenburg. This is mainly due to the larger mass, but also to the more advanced heat- and ventilation-systems and the heavier and stronger electric motor.

**Simulation Model**

To investigate the effect of a power limitation, a tram section in Gothenburg was modeled and simulated by use of Matlab/SimuLink/SimScape. The model can simulate up to 5 trams simultaneously, traveling in either direction, on a parallel- or single-fed tram section. Each tram tries to follow a predefined velocity profile over the section, which includes stopping at the tram stops on the section. A velocity profile was estimated based on realistic acceleration values.

The ability of the trams to follow the desired velocity profile could be hindered by three limitations. Firstly, it could be hindered by a desired power limitation secondly, by the occurrence of a power failure (due to exceeding the maximum current), thirdly, it could be hindered by a lower velocity of a possible tram in front, since the trams are restricted not to run into each other.

The model can be divided into three main parts. The first part models the tram movement. From the velocity and acceleration of the trams, including longitudinal slope over the section, the power demand of each tram is calculated, and, thus, the resulting current in the rectifying station/stations. For each tram, the time for entering the section in either end (0 or L) is defined. The stop time at each tram stop is also defined, as well as the direction (1 or -1) of the trams, see Figure 1.

![Figure 1 - Schematic picture of the tram section in the simulation model. The trams can move in direction 1 or -1, i.e. from point 0 to L, or from point L to 0.](image)

The second part of the model represents the electric circuit with 5 nodes, constituted by the 5 trams, see Figure 2.

![Figure 2 - Maximum 5 trams can be simulated simultaneously in the model. Which tram is in which node will vary with the movement and position of the trams.](image)

The electric circuit is modeled using physical modeling in the Matlab toolbox SimScape. The voltage drop in the nodes depends on the power demand of the tram in each node. Depending on the location of the trams, which tram represents which node varies in time and is identified in the simulation.

More than one tram can be in the same position. For example, before the trams have started, all trams are in position 0 or L. If less than 5 trams are modeled, the trams that are not active stay in position 0 or L during the simulation.

The third part of the model contains the logic for controlling the switch in the rectifying station. The current is disconnected based on given criteria for absolute value on current and/or derivative of the current. Some limits trigger instantaneous opening of the switch when being exceeded, others cause opening of the switch after a time period of exceeding the limit.
Calculation of Power Demand

Between the tram stops, it is desired to accelerate the tram with maximum comfortable acceleration up to about 60 km/h, and then decelerate, with the desired deceleration, in time to stop at the next stop. From the velocity and the position of the tram, the power demand is computed.

The classical formula for computing the total rolling resistance of a railroad vehicle is the Davis formula. [1] AnsaldoBreda has their own version of this formula, developed for the M32 tram. It calculates the total retarding force that acts on the tram due to slope, moving friction and air resistance:

\[ F_{\text{retard}} = \text{mass} \times 0.00981 \times 0.1 \times \text{slope} + \text{mass} \times 0.00981 \times 2.5 + \]
\[ \text{mass} \times 0.00981 \times 3.6^2 \times \text{velocity}^2 / 850 \]

where mass is the tram mass, slope is the section slope in percent (positive for uphill) and velocity is the tram speed. All units are in SI. The accelerating force on the tram is:

\[ F_{\text{accel}} = \text{mass} \times a \]

where a is the acceleration. The power is obtained by multiplying the total force, i.e. retarding + accelerating force, with the velocity. The trams may enter a section with a speed in the simulations (i.e. no power is consumed on the section for accelerating up to the initial speed when entering).

Limitation of Tram Power Output

A desired limitation of the tram power output can be implemented in the model in either of two ways. Firstly, it can be introduced as a pre-set constant limit. Secondly, it can be set as an adaptive limitation that is only activated when there is a risk of exceeding the maximum current in the rectifying station. The activation is dependent on current and current derivative. The continuous power limitation is modeled to occur without any delay, whereas the adaptive limitation is delayed by 1.5 s, to include realistic system dynamics.

The power limitation concerns power for propulsion. Apart from that, each tram is assumed to consume a constant auxiliary power of 42 kW. The auxiliary power is consumed continuously, except for when the tram decelerates.

Simulated Tram Scenario

The simulated section is an end section in Gothenburg at Mölndal Center. The section starts at the rectifying station at Lackarebäck, it contains three tram stops, and ends with the turn of the rail. The slope over the section varies with only about 3-4 m and was therefore neglected. See the Table 1 below for description of the stops over the section.

<table>
<thead>
<tr>
<th>Table 1 – Distance between tram stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifying station 1</td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Tram stop 1</td>
</tr>
<tr>
<td>Tram stop 2</td>
</tr>
<tr>
<td>Tram stop 3</td>
</tr>
<tr>
<td>End of section</td>
</tr>
</tbody>
</table>

The trams are assumed to stop for 20 s at each stop. Between the stops, the trams are assumed to follow the speed profile shown in Figure 3.
Figure 3 - Desired speed profile on the tram section as a function of distance. The trams follow this speed when there are no disturbances such as power failure, a desired power limitation or speed limitation.

Deceleration and acceleration due to possible red lights are neglected. Note that the stop times at the stops are not visible in Figure 3, since it shows distance on the x-axis. The speed profile was constructed assuming the following desired acceleration and deceleration, as a function of tram velocity described in Table 2.

<table>
<thead>
<tr>
<th>Velocity (km/h)</th>
<th>Acceleration (m/s²)</th>
<th>Deceleration (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>1.15</td>
<td>-1.15</td>
</tr>
<tr>
<td>30-50</td>
<td>0.85</td>
<td>-0.85</td>
</tr>
<tr>
<td>50-60</td>
<td>0.35</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

In the simulations, a scenario that represents a realistic frequency of trams for the section in question was used. Trams 1, 2 and 3 were travelling from point 0 to L. The interval between tram 1 and 2 was set to 135 s and between tram 2 and 3 to 145 s. Trams 4 and 5 were modeled as trams ahead of trams 1-3 that had turned and were now travelling in the direction from L to 0. Tram 4 started from L at time 110 s, and tram 5 at 255 s.

A stop time of 180 s was set for stopping at the end of the section (at L). When a tram travelled from L to 0 on the way back, the tram also waited for 180 s before leaving L. This resulted in a total time at L of 360 s, which represents a typical time spent at the end station before travelling back on the section. The start times and directions for the 5 simulated trams are summarized below in Table 3.

<table>
<thead>
<tr>
<th>Tram number</th>
<th>Start time (s)</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0 to L</td>
</tr>
<tr>
<td>2</td>
<td>135</td>
<td>0 to L</td>
</tr>
<tr>
<td>3</td>
<td>280</td>
<td>0 to L</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>L to 0</td>
</tr>
<tr>
<td>5</td>
<td>255</td>
<td>L to 0</td>
</tr>
</tbody>
</table>

Simulation Results

In the simulations, the limit for instantaneous braking of current was varied, to simulate both scenarios including power failure and scenarios not including power failure. Initially, the current limit in the rectifying station was set to 2000 A. Figure 4 shows the result for the current in the rectifying station for this simulation. The maximum allowed power output for propulsion was set to 1200 kW per tram. This is relatively high compared with the power demand of the electric motor. Thus, in practice, this limit does not represent a limitation.
Figure 4 - Current from the rectifying station in the simulation of 5 trams. Green curve shows the switch, which opens at about 330 s, since the maximum current limit of 2000 A is exceeded. Blue curve shows the maximum allowed power output per tram (N.B. in kW), which is 1200 kW. It is included in the picture to show that the limit is constant.

As can be seen in the figure, two power failures occur at about 330-360 s, when the current reaches 2000 A. This happens when two trams accelerate at the same time. At the end of the simulation, the current is about 200-300 A between the accelerations, which is due to that all 5 trams have started, and consumes the auxiliary power of 42 kw (60 A), except for when they are decelerating.

Figure 5 shows the power output for tram 1 to 4 for the simulation with 900 kW power output limit. As can be seen in the figure, at the time 330 s, simultaneous accelerations occur for tram 2 and 3 (green and blue curve), which results in the high current that leads to power failure.

As can be seen in Figure 5, the power output is relatively high when the trams start to accelerate after the power failure. This is due to that the trams have been delayed and then accelerates with the maximum allowed acceleration, which was set to 1.2 m/s². This is larger than the acceleration used during the time before the power failure (i.e. the acceleration in the desired speed profile).

Figure 5 - Power output for tram 1-4. Tram 5 was excluded for clarity. Red curves are power and velocity, respectively, for tram 1. Green curves are power and velocity for tram 2, etc.
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Figure 6 shows the voltage in the 5 nodes in the electrical circuit. The voltage in the rectifying station is set to 700 V, which is the voltage in the overhead line when there is no load. When the trams travel the section, the voltage drops to about 600 V.

![Voltage in node 1-5](image)

**Figure 6 - Voltage in node 1-5.** The power output results in a voltage drop from the initial voltage of 700 V. The max power output for the trams is 900 kW and the max current limit 2000 A. At around 330 s, a power failure occurs and the voltage drops to zero.

**Pre-set Constant Power Limitation**

To simulate how a limitation of the tram power can help avoid power failures, it was first tested what limitation was required for no power failure to occur at a max current limit of 1900 A. At a tram power output limit of 1200 kW, power failure occurs at four occasions, see Figure 7.

![Max Current Limit: 1900 Max Power Limit: 1200 kW](image)

**Figure 7 - Current in the rectifying station for the 5 tram scenario, when the max current limit is 1900 A. The tram power output limitation is 1200 kW (Blue). It is included in the picture to show that the limit is constant.**

When testing stepwise lowering of the max allowed power output (in steps of 10 kW), it turned out that the highest limit of the power output that did not lead to any power failure was 500 kW. In other words, this was the maximum allowed power output that the trams could use without risk causing a power failure. (Apart from 500 kW for propulsion, the trams also consume the auxiliary power of 42 kW.)

The result for the simulation with 500 kW tram power limitation is shown in Figure 8. As can be seen, no power failure occurs, as the current peaks do not reach above around 1800 A.
Simulations were then carried out for a number of max power limitations; below and above the value of 500 kW, since this value, as mentioned above, was sufficient to avoid power failure. This was made to see how various power limitations affected the velocity of the trams, and, thus, their ability to keep the timetable, when their performance was lowered by the power-output limitation. In these simulations, the current limit for power failure was set to 2200 A, so that no simulation would contain a power failure. This was done to be able to see what time delay the power limitation itself caused, without interference of possible power failures.

Figure 9 shows the current from the rectifying station at the strongest power limitation that was simulated; 200 kW. As can be seen, the limitation clearly cuts off the current peaks, which do not reach above around 900 A. The current peaks are also prolonged in time.

The power output for tram 1 at various power limitations, including the 200 kW limitation above, is shown in Figure 10. The behavior is similar for all five trams, however, for clarity, only one tram is shown in the Figure.
It can be seen that for a limitation of 500 kW, only the peak of the power output is cut off. This does not lead to that the power demand is extended in time. A stronger limitation to 200 kW, on the other hand, results in reducing a larger part of the power output, which is thus extended in time. This delay of trams that are limited to 200 kW can also be seen in Figure 11, which shows the velocity for tram 1 at the various power limitations.

The position of tram 1, when it approaches the end of the section (at 1420 m), is shown in Figure 12 for the 200 kW, 500 kW and 1200 kW limitation. As can be seen, the tram is significantly delayed when the power limitation is 200 kW. Tram 1 arrives at the end of the section about 15 s later than when the power is not limited. With the 500 kW limitation, on the other hand, which is sufficient for avoiding a power failure in the simulated scenario, the tram is only insignificantly delayed.
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Adaptive Power Limitation

An adaptive power limitation is applied only when there is a significant risk of exceeding the max current limit. To test this type of limitation, a function that limits the power output to a lower value when certain criteria are fulfilled was implemented.

The high power limit was set to 1200 kW, which in practice is no limitation, and the low limit, used when the criteria were fulfilled, was set to 500 kW. The lower limit was activated when the current in the rectifying station was $\geq 1000$ A, and the derivative of the current was $\geq 50$ A/s. The power limit was then switched back to the high value when the current was $\leq 1000$ A and the current derivative was $\leq -20$ A. A delay of 1.5 s for the activation and deactivation of the low limit was also implemented. The result for a simulation with an adaptive power limitation is shown in Figure 13. As can be seen, the limitation was activated at three occasions (blue curve).

Figure 12 - Position of tram 1 at various power output limitations: 200 kW, 500 kW and 1200 kW. The current limit for power failure is 2200 A.

Figure 13 - Current from the rectifying station in the simulation of 5 trams. Green curve shows the switch, which does not open during the simulation. Max allowed current limit is 1900 A. Blue curve shows the power output limit in kW. The power is limited to the lower value, 500 kW, when the criteria for current and current derivative are fulfilled.

Figure 14 shows three curves. Firstly, the magenta curve shows the position of tram 1 with an adaptive limitation of 500 kW. Secondly, the cyan curve shows the position with the high power limit, i.e. 1200
kW. Thirdly, the black curve shows the position with a continuous limitation of 500 kW. As can be seen in the figure, the delay caused by the adaptive power limitation is almost non-existent, whereas the continuous limitation leads to a small delay. The delay is, however, smaller than 1 s on the total section of 1420 m.

![Figure 14 - Position of tram 1 at various max power limits: 1200 kW (black), continuous limit of 500 kW (cyan), and an adaptive limit of 500 kW (magenta).](image)

**Discussion**

In this study, it was unfortunately not possible to validate the simulation model by comparison with measured values of e.g. current or voltage. Moreover, the current limit for power failure in the model was somewhat lowered from specification values, to ensure that power failure did occur in the simulations, as it is known to do on the real section. On the other hand, the actual power demand in the simulations may have been somewhat lower than in reality, due to the limitation of max five trams on the section.

However, the aim with the simulations was not to investigate absolute values, but qualitative behavior. The simulated results are realistic and in agreement with expected values on the entities that are calculated, such as current, power output and voltage drop. Thus, the model is assumed to constitute a good basis for this qualitative assessment.

In the studied scenario, the maximum allowed power limit for which power failure did not occur was 500 kW. For a scenario that requires stronger acceleration, i.e. a hilly section, this limit may have to be lower, which would result in a larger reduction of tram performance. However, for the adaptive power limitation, the delay of the trams was so small for the 500 kW limitation, that it can be assumed that an even lower power limit could be used without causing unacceptable tram performance.

**Conclusion**

The simulation results indicate that an adaptive power output limitation, which is only activated when the current and current derivative is above certain limits, is effective in reducing current peaks, while still maintaining required tram performance. Thus, this method could be used to reduce or eliminate power failure on the tram net, without causing unacceptable tram delay.

A continuous limitation could also be efficient, but may not work if the tramline is travelled by trams that accelerate heavily and demand high peak power, for example as might be the case for a hilly tramline.

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