**Introduction:**

Until today the assumption in compatibility studies is that rolling stock is an energy consumer. Since several decades rolling stock can also be an energy supplier while braking. Today trains are optimised to regenerate as much braking energy as possible.

This may change the interaction between the different systems.

**Problem definition:**

The EN50163 [1] defines the voltage range from 1800-1950V as allowed for regenerative braking. Until now, experiences at the Dutch 1500V DC network show that the average voltage while braking is still below the no-load voltage of the substations, braking measurements show an average voltage at the current collector of 1750V.

In this situation there is no significant change in the interaction expected and the classic approach for design of energy supply systems in DC networks and the approach for compatibility studies do not need to change.

It is to be expected that with the appearance of more rolling stock equipped with regenerative brakes the average voltage will rise above the no-load voltage of approximately 1800V in a 1500V network. The use of the defined voltage range (1800-1950V) will change the operation of the rectifiers in the substation from normal load to low-load or even no-load modes.

In this situation there is a significant change in the interaction expected and the classic approach for design of energy supply systems in DC networks and the approach for compatibility studies may be insufficient.

This article describes the mechanisms influencing the interference currents in the network and the consequences for studies demonstrating compatibility of line current perturbations from rolling stock with track-side detection systems. We will then discuss what is to be expected and what effect it should have on compatibility studies.

**Method and Results:**

First what we know and see, the mechanisms. The data used are from the Dutch rail network. Then the trends and what we expect.

**Voltage loss:** In the last 30 years we have seen a growth in the number of substations. The number of substations has grown from less then 100 in 1975 till more than 200 in 2000 [7], see figure 1.

![Number of substations and line resistance](image)

**Figure 1** Growth of the number of substations from 1975 until 2010
The growth of the number of substations, the increase of power per substation and the growth of multiple track route sections let to decrease in average impedance “seen” from the train. The average impedance is 40% lower now than it was in 1975 [7], see figure 2, as is the voltage drop lowered and thus the average voltage increased.

The reduced impedance has a positive effect on the losses in the DC-network and the available power for trains, but also on the reduction of harmonics from the substation.

Average Voltage: We have seen the growth of the number of substations and the increase of power per substation. We calculated the number of trains per substation. We see a steady decrease in this number. Now there are less than 3 trains per substation [7].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>number of substations</td>
<td>91</td>
<td>106</td>
<td>120</td>
<td>145</td>
<td>156</td>
<td>212</td>
<td>225</td>
<td>244</td>
</tr>
<tr>
<td>number of trains</td>
<td>667</td>
<td>717</td>
<td>699</td>
<td>664</td>
<td>747</td>
<td>773</td>
<td>768</td>
<td>ca 600</td>
</tr>
<tr>
<td>trains per substation</td>
<td>7,33</td>
<td>6,76</td>
<td>5,83</td>
<td>4,58</td>
<td>4,79</td>
<td>3,65</td>
<td>3,41</td>
<td>2,46</td>
</tr>
</tbody>
</table>

Table 1 Number of trains per substation

The lower voltage los and lower number of trains per substation lead to an increase of the average voltage “seen” from the train. This is without the effects of regenerative braking. In Figure 2 we see that the average voltage is now only 150V lower than the no-load voltage of approximately 1800V.

Regenerative braking: The trend in rolling stock is to increase the efficiency of regenerative braking. The EN50163 defines the voltage range from 1800-1950V as allowed for regenerative braking. Untill now, experiences at the Dutch 1500V DC network show that the average voltage while braking is still below the no-load voltage of the substations, braking measurements show an average voltage at the current collector of 1750V. This is caused by the use of a subset of the allowed voltage range.

Regenerative braking trend: It is to be expected that with the appearance of more rolling stock equipped with regenerative brakes and the complete use of the defined voltage range the voltage will rise above the no-load voltage of approximately 1800V in a 1500V network. This will, in combination with the reduced number of trains per substation, change the operation of the rectifiers in the substation from normal load to low-load or even no-load modes.

In low load mode the rectifiers are no longer continuous conducting and the consequence is a non linear behaviour. This results in the modulation of the various normally present frequencies generated by inverters, choppers in rolling stock.

This phenomenon is known in the Netherlands since the early 90’s, and additional interference current requirements where than introduced in the Guidelines [6], the occurrence was assumed rare. Recent measurements, to prove compatibility with HSL-South, however showed that this assumption is no longer correct.
Discussion
All interference currents, from other rolling stock or other sources, that with or without modulation could possibly result should be considered. As indicated in the standard EN50238 [2] which prescribes that all possible sources of interference should be examined. Although this standard suggests so, a modulating substation is not automatically considered being a source of interference! One example is the excitation of input filters, this generates considerable frequency components able to modulate the substation different from the mains multiples of 300Hz.

Substation in loaded mode:
In a classical energy supplying substation the harmonics are dominated by multiples of 300Hz, and less prone all multiples of 50Hz, caused by the rectifiers. The harmonics of a regenerative braking train are the switching frequencies of the different energy systems. In Figure 3 a FFT of a regenerative braking train is presented. We can see the harmonics at 450, 500Hz and the inverter frequency.

Substation in no-load mode:
When a substation is in no-load mode it is as if it is not there, an open branch. A nearby train will take the substation role and act as impedance and be an energy supplier. Where in the classic approach only the harmonics of the substation had to be taken into account. In de no-load mode the harmonics of a regenerative braking train have to be taken into account.

Substation in low-load mode:
In low-load mode a substation can modulate the different frequencies. This will result in harmonics, higher products of the base frequency, and modulation of different frequencies. Harmonics: In the Dutch law, RKS [5], there is no limit for, for instance, a base frequency of 25Hz, but there is a limit for 75Hz interference currents (0.5A). Under optimal conditions the modulation efficiency is app. 21%, thus a current of 2.4A@25Hz can be modulated in a current of 0.5A@75Hz. The modulation efficiency is different for every frequency.

The base frequencies for modulation can be produced by the power inverters from train.

Modulation: When two different frequencies are modulated, the modulation efficiency depends on the duty-cycle and the phase between the frequencies [8]. The duty-cycle is defined as:

\[ \delta := \frac{1}{\pi} \cos \left( \frac{i_{DC}}{i_{AC.top}} \right) \]
In Figure 4 the modulation efficiency is given as a function of duty-cycle and phase for the frequencies 25Hz and 50Hz and two different duty-cycles. We can see that both the duty-cycle and phase have a strong effect on the modulation efficiency. Further more see on overall average 1/π.

![Figure 4](image)

**Figure 4** Modulation efficiency as a function of duty-cycle and phase.

In the Netherlands interference currents at 75Hz must be lower than 0.5A, as stated in the Dutch Law [5]. Frequencies to take into account are those which can result into an unwanted interference currents at 75Hz, the Law refers to the EN50238 for a compatibility study. The predecessor [6] of the current Regulations was more explicit; the frequencies to take into account in the design and compatibility studies are sum and difference terms of known frequencies eg 300+/−75, 600+/−75Hz, so aside from 75Hz interference currents also current levels at 225, 375, 525 and 675Hz had to be accessed.

The mechanism however does not restrict itself to modulation of these known frequencies. It is to be expected that the mechanism needs to be combined with other present frequencies in the line currents, and the difference terms of not yet commonly known frequencies (eg those of other trains, inrush of input filters and other systems) combined with these interference frequencies.

If not tackled otherwise, future compatibility studies might need the spectral (emissions) and design (filter components for resonances) data of already present trains on the network to be complete.

In recent compatibility studies, performed by Prorail and Lloyd’s Register, for the HSL-South in the Netherlands it was shown that frequency components originating from sources outside the network itself can make situations even more relevant because they were not present before.

**Conclusion**

The result is that the classic approach for design of energy supply systems in DC networks and the approach for compatibility studies needs to be refined if not changed when introducing more rolling stock with regenerative brakes or introducing more efficient regenerative braking in the rolling stock.

The European standard EN50238 which prescribes that all possible sources of interference should be examined offers a good guideline to start. In the new approach for design of energy supply systems in DC networks and the approach for compatibility studies low-load or even no-load operation modes of the rectifiers in the substation need to be considered.

For a substation in low-load operation mode, all interference currents, from other rolling stock or other sources, which via modulation could possibly result, should be considered. As the substation is virtually non existent in no-load operation modes, all interference currents, from other rolling stock or other sources, should be considered.
Challenge A: A more and more energy efficient railway

References
1. Railway applications - Supply voltages of traction systems, EN50163.
2. Railway applications - Compatibility between rolling stock and train detection systems, EN50238.
4. Railway applications - Power supply and rolling stock - Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability, EN50388.
5. Regeling Keuring Spoorvoertuigen, the current Regulations as stated in the Dutch Law.
6. Eisen aan spoorwegvoertuigen t.b.v. infra-compatibiliteit - EMC, Stoorstroom en Impedantie, RLN00024, a previous version of the current Regulations.
7. Verzwaren TEV - veranderende parameters infra, NTC/TE/494/03-230152, Richard Freek en Erwin Meerman
8. Rendement 25Hz-mening ijzeldata, OC/MRdR/1261/03-417489, Mark de Rooij