Ice on the Overhead Line, AC Railway Systems

Analysis of OHL Ice Recordings

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1 Summary

This report presents an analysis of the recordings from several different tests with electric (AC) rail vehicles at conditions with ice on the overhead line, or from tests where such conditions were simulated. A vehicle operating at these conditions is known to generate high levels of DC and other interference components in the line current.

The analysis comprise 4 different types of vehicles:

- The DB locomotive BR185 (AC-AC) in single and double traction and in combination with the CFL Z2000 EMU (AC-DC) (50 Hz)
- The DSB/SJ EMU ET/X31, a. k. a. OTU (50 Hz and 16 2/3 Hz)
- The UK EMU class 357, a. k. a. Electrostar (50 Hz)

The following conclusions can be made from the analysis:

- The DC generated due to OHL ice is unidirectional, and always flowing into the generating vehicle
- The total DC emitting from two or more vehicles in a multiple formation is not higher than the DC emitting from a single vehicle, and normally somewhat lower. This is due to the fact that the first pantograph-OHL interface is a stronger DC generator than the following interfaces, meaning that the following vehicles in the multiple formation serve as return current paths for the DC being generated by the first vehicle
- The levels of the line current harmonics are more or less proportional to the level of the DC. This applies to both the Total Harmonic Distortion (Root-Sum-Square of all even and odd harmonics) and to individual harmonics such as 100 Hz (6th harmonic in a 16 2/3 Hz system)
- No clear relationship is seen between the level of interharmonics such as 77 Hz and the level of the DC
- It seems to be beneficial to run AC-AC powered vehicles (4-quadrant converters plus AC motors) at a slightly lagging phase angle. On the other hand, an AC-DC vehicle (phase-angle controlled thyristor rectifiers plus DC motors), which by nature runs with a lagging phase angle, is seen to generate equally high direct currents as an AC-AC locomotive
- The DC level seems to be independent of the RMS value of the fundamental current, i. e., of the electric power, and of the vehicle speed

- Scraping the OHL with a passive (i. e., that carries no current) pantograph in front of the active one has only a limited effect. There are indications, however, that a more efficient scraping can be obtained by means of two vehicles (both activated) in a multiple formation.

- This leads to the theory that it might be even more efficient to scrape the OHL by means of two electrically parallel pantographs on the same vehicle. Unfortunately, this has not been tested in any of the available recordings

- Only the analysis method with a running average filter provide the necessary information about the direct currents that are generated due to the OHL ice

- The analysis support the theory that the DC is caused by a voltage source at the OHL-pantograph interface, and that this source exists whenever an arc is present

2 Contents

Appendices:
1. Signal Processing for Comparative Analysis
2. Test results, BR185 (single vehicle)
3. Test results, OTU EMU (50 Hz)
4. Test results, OTU EMU (16 2/3 Hz)
5. Test results, BR185 (double traction)
6. Test results, BR185 plus Z2000
7. Test results, Electrostar EMU (simulated ice tests)

3 Introduction

3.1 Background

This report has been prepared within the framework of the OHL Ice Working Group that was set up at the ESC UserGroup workshop in Paris, Feburary 5th 2002.

The report presents the results from a uniform analysis of the recordings from several different tests with electric (AC) rail vehicles at conditions with ice on the overhead line, or from tests where such conditions were simulated. A vehicle operating at these conditions is known to generate high levels of DC and other interference components in the line current.

It is the aim of the report to provide answers to the following questions:

- How does the level of the DC relate to other variables, such as train speed or power?
- How do the direct currents distribute themselves in a complete railway system with several trains (some maybe in a multiple formation), substation supply transformers, etc?
- How well do the observations on a macroscopic level correlate to the theories that describe the mechanisms of the DC generation?

An additional goal has been the comparison of different signal processing methods for calculating the DC component in the line current.

3.2 Input Data

Data recordings from the following test events have been available for the analysis.

Revision 0:

- Test of the DB locomotive class BR185 in Luxembourg, December 2001. The recordings include operation with a single locomotive, 2 locomotives in double traction, and real-life-like operation with 2 locomotives and a CFL Z2000 EMU
- Tests of the DSB/SJ EMU class ET/X31, but commonly referred to as OTU. The tests were performed at the Bombardier test track in Västerås in March 2002.
- Tests of the UK "Electrostar" EMU (Class 357 and others) on the test track in Cerhenice in the Czech Republic July 2001. During these tests, OHL ice conditions were simulated by reducing the pantograph upward pressure to the

lowest value that still allowed the train to run. Due to the low contact force, a considerable arc was developed at the OHL-pantograph interface

Future revisions of the document are expected to include recordings from more tests.

4 Data Recordings, Analysis, and Presentation

4.1 Data Recordings

All data have been recorded by means of Sony DAT recorders. The raw data has been transferred to CD-ROM's, where it is available as .bin and .log files.

The following signals have been used in the analysis:

Line voltage:	Voltage transformer (built-in transformer of the vehicle)
Line current:	Hall-effect current transducer
Vehicle speed:	Dobbler radar (BR185), built-in speed sensors (others)

4.2 Analysis

The analysis of the recorded signals has been performed in accordance with the document *Signal Processing for Comparative Analysis*, Rev. 1, Lars Buhrkall 2002-07-31. This document is found as Appendix 1.

4.2.1 DC

In order to compare different analysis methods, the DC contents of the line current has been found in 3 different ways. In addition to the following, all 3 methods use an initial notch filter for the 16 2/3 Hz or 50 Hz fundamental:

- A 2.5 Hz low-pass filter followed by a 1 s running average filter. This method preserves full information (both magnitude and direction) about any "true DC", but it is highly unlinear. As an example, this method will completely reject a 1 Hz component.

- A 2.5 Hz low-pass filter followed by a 1 s moving RMS filter. This method is much more linear than the running average filter, but all information about the direction of the DC is lost.

- A 2.5 Hz low-pass filter followed by a 0.01 Hz high-pass filter and a 1 s moving RMS filter. The addition of a high-pass filter removes the DC offset that is normally seen with Hall-effect current transducers, but it is clear that any "true DC" is also removed.

The responses of each of these analysis methods to an artificial input signal (a negative ramp followed by a 0 - 4 Hz, 1 V cosine) are shown in figure 4.2.1.1 below.

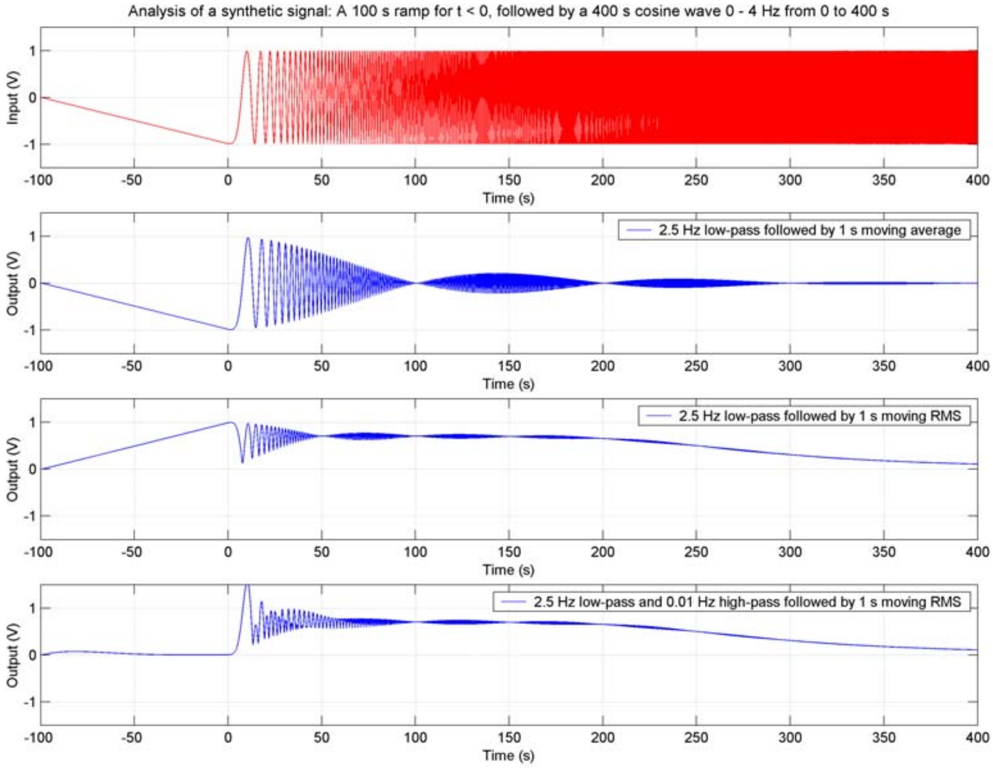


Figure 4.2.1.1. Response of DC analysis methods

The low-pass + moving average method is correct at DC and the lowest frequencies. Above this frequency band, the low-pass + high-pass + moving RMS method is correct.
The low-pass + moving RMS method gives a correct amplitude, but the information about the direction of the DC is lost.

4.2.2 Interference Currents

The following interference currents are calculated:

Track circuits:

16 2/3 Hz supply:	100 Hz
50 Hz supply:	77 Hz. This frequency is considered to be representative for 75 Hz and 83 1/3 Hz track circuits as well

Telecom:
Psophometric currents

General line interference:
Total Harmonic Distortion, i. e., Root-Sum-Square of all even and odd line current harmonics

4.3 Presentation of Results

The analysis results are presented by a set of plots for each single test, and by a set of 3D histograms that summarise the results from a complete test series.

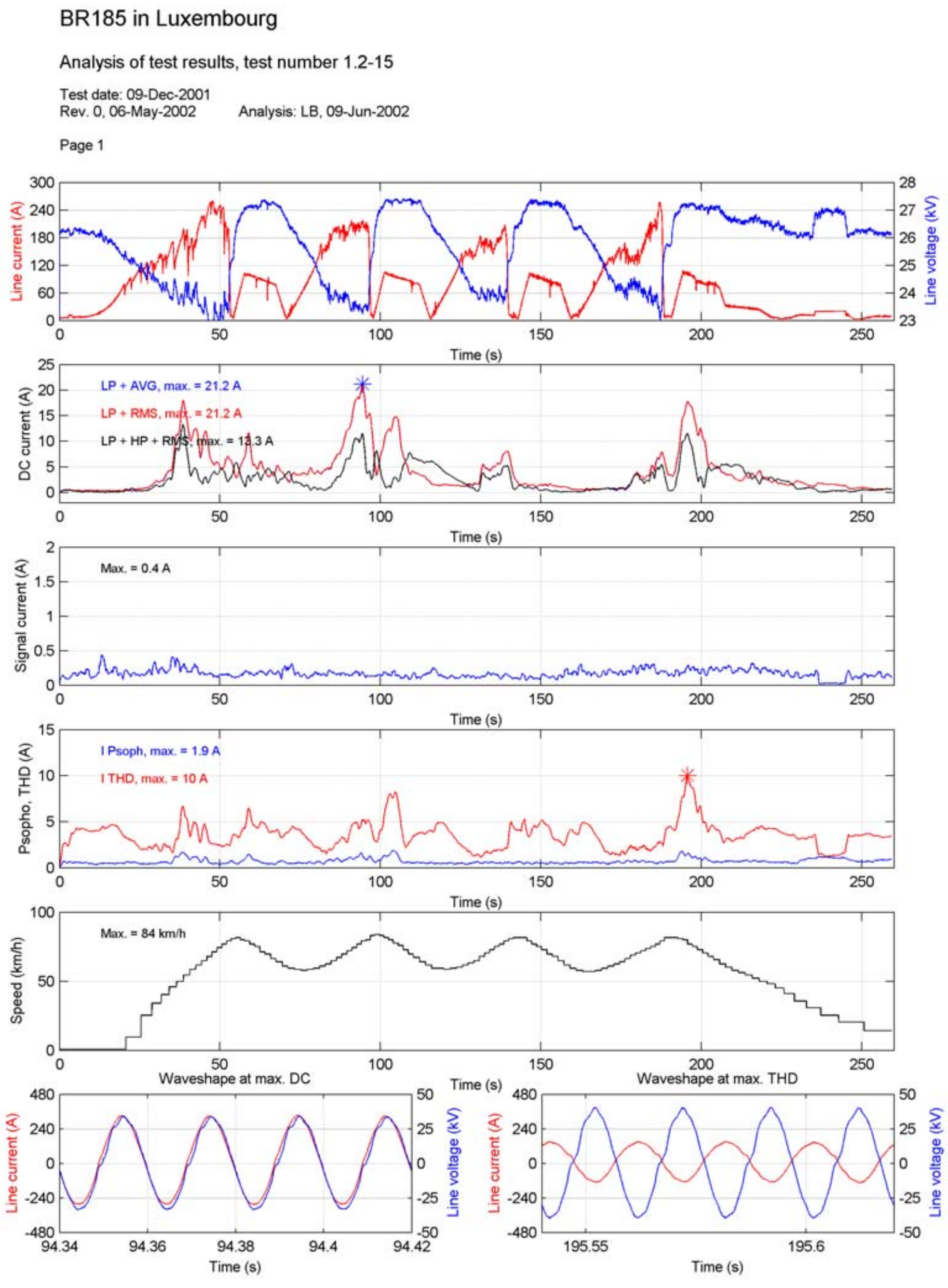
4.3.1 Individual Test Results

Figure 4.3.1.1 (next page) shows an example of the plots that present the results from an individual test. This figure is also found in Appendix 2 and as the file BR185 Solo\1 BR185 Test 12-15.png. From the top, the curves show:

- RMS line current (red) and RMS line voltage (blue)
- DC component of the line current, analysed in the 3 different ways described above
- Current level at the signal frequency, i. e., 100 Hz at 16 2/2 Hz sypply and 77 Hz at 50 Hz supply
- Psophometric current and current THD
- Vehicle speed
- Waveforms at the point with maximum DC level (left) and maximum THD (right)

The tests with more vehicles in dual traction or in a more complex operation pattern are presented by slightly different sets of plots.

The printouts from the individual tests are generally not explained in detail, but found as appendices for self study only.



BR185 in Luxembourg

Analysis of test results, test number 1.2-15

Test date: 09-Dec-2001
Rev. 0, 06-May-2002 Analysis: LB, 09-Jun-2002

Page 1

Figure 4.3.1.1. Results printout, individual tests

4.3.2 Summary of Test results

Each series of similar tests are summarised by means of the set of 3D histogram plots as shown below in figure 4.3.2.1, which is also found in Appendix 4 and as the file OTU 16 Hz\OTU 16 Hz All Tests.png.

These plots aim for providing qualitative information about the relationship or the dependency between the direct currents and other quantities. Take the lower left plot as an example. This plot shows how often a certain combination of RMS line current and direct current have occurred throughout all tests with a single BR185. Deep red colour indicates that a specific combination occured often, while the deep blue background colour indicates that these combinations never occurred during the tests.

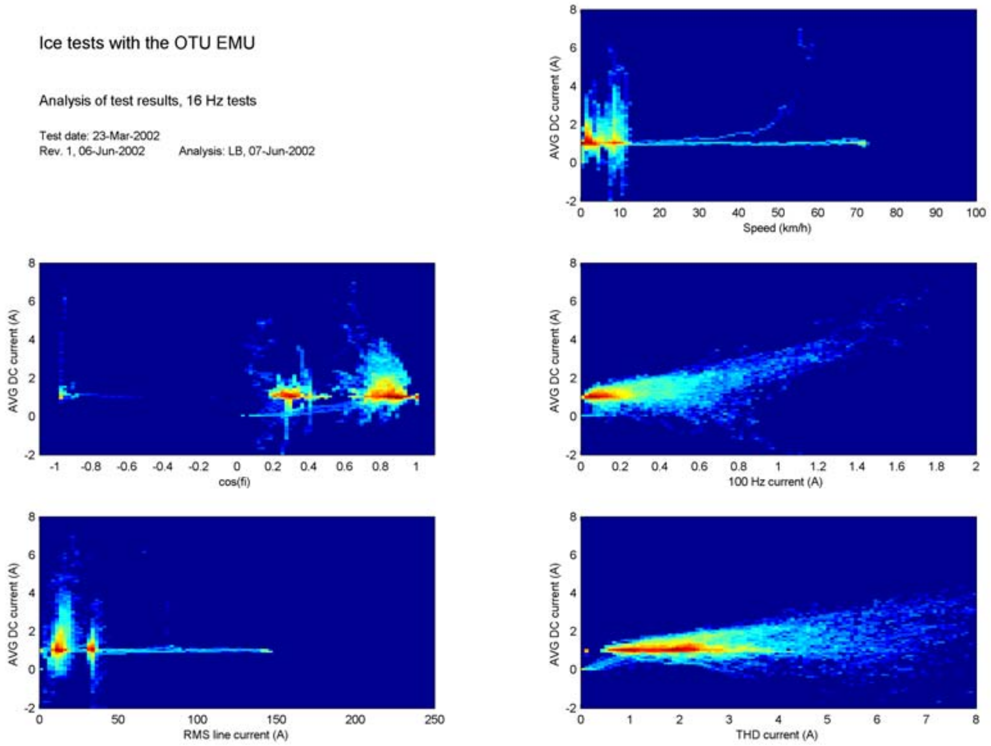


Figure 4.3.2.1. Summary of test results

Please note that the colour scale is logarithmic. It is also important to notice that the plots do not represent a statistical analyse in a strict scientifical meaning. If any given combination have occurred particularly often, this is more likely to be due to the specific test condition than to the behaviour of the vehicle as such. This is seen in the lower left plot in the figure; the vehicle operated in a no-load condition with a RMS current of 10 A or 30 A during almost all the total testing time.

5 Analysis Results

5.1 *Single Vehicle Operation*

5.1.1 BR185 Locomotive, 50 Hz

2 DB locomotives class BR185 were tested in Luxembourg during December 2001. At the tests on the Luxembourg-Troisvierges line (North from Luxembourg City through the Ardennes) during the night December 8th to 9th, ice was found on the OHL on some of the non-tunnel sections of the line.

The recordings from the heading locomotive have been analysed in the following. At some tests, the 2nd locomotive was completely deactivated (open main circuit breaker), while at other tests, it was activated in different configurations. It is clear that is not really exactly single vehicle operation, but based on the argument that the heading loco cannot see whether the 2nd loco is connected in dual traction or it is running on another track or some km away, the conditions for the heading loco have been considered to be the equivalent of single unit operation.

Summary of the test results

The test results are summarised in figure 5.1.1.1 below, and in full size in Appendix 2, first page (file BR185 Solo\1 BR185 All Tests.png).

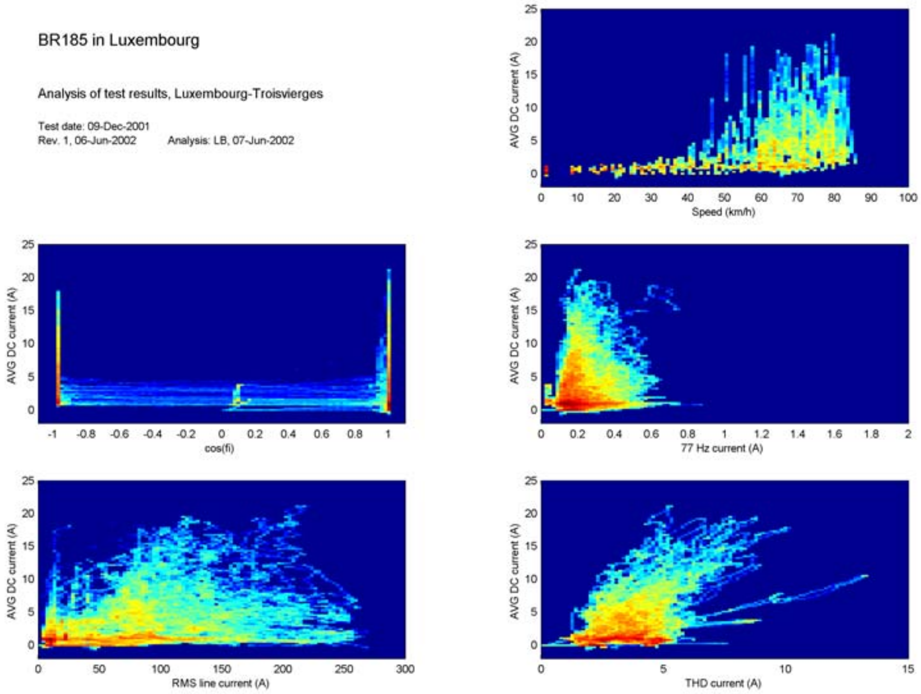


Figure 5.1.1.1. Summary of test results, single BR185

The following conclusions can be made:

- The DC is unidirectional (always positive into the locomotive)
- There is no correlation between the DC level and the fundamental current
- The high DC levels are seen at speeds above 40 km/h, and at cos(φ) = 1 or -1. This is probably due to the fact that maybe 99 % of the total distances were run at these conditions, and maybe because most stops were made within station areas where the heat from surrounding buildings could have reduced the build-up of rime
- If anything, the DC is inversely proportional to the 77 Hz current
- The DC and the THD are more or less proportional

Detailed test results

The detailed printouts from each test are found in the following pages of Appendix 2. The test numbers from the original test report for CFL have been maintained.

Test no.	Maximum DC level	Configuration 2nd BR185	Link to picture file
1.2-10	10.6 A	1 bogie	BR185 Solo\1 BR185 Test 12-10.png
1.2-11	17 A	2 bogies	BR185 Solo\1 BR185 Test 12-11.png
1.2-12	19.6 A	1 bogie	BR185 Solo\1 BR185 Test 12-12.png
1.2-13	12.3 A	Circuit breaker open	BR185 Solo\1 BR185 Test 12-13.png
1.2-14	6.8 A	1 bogie	BR185 Solo\1 BR185 Test 12-14.png
1.2-15	21.2 A	2 bogies	BR185 Solo\1 BR185 Test 12-15.png
1.2-20	15.2 A	Circuit breaker open	BR185 Solo\1 BR185 Test 12-20.png
1.2-21	16.9 A	1 bogie	BR185 Solo\1 BR185 Test 12-21.png
1.2-28	11.1 A	Circuit breaker open	BR185 Solo\1 BR185 Test 12-28.png

5.1.2 OTU EMU

The OTU EMU was tested by Bombardier during the night 23rd to 24th of March 2002, on the test track in Västerås. Ice was artificially applied to the OHL by means of a water spray. The tests were performed in order to evaluate different settings f the control and protection systems of the train set. Tests were made at both 50 Hz and 16 2/3 Hz.

5.1.2.1 OTU 50 Hz tests

3 different categories of 50 Hz tests were made:

1. Acceleration-braking at normal power
2. Acceleration-braking at low power
3. Acceleration-braking at low power, with the reference value of the reactive current controller set to 13 A (ind.) rather than 0 A

Summary of the test results, 50 Hz

The test results are summarised figure 5.1.2.1.1 below, and in full size in Appendix 3, first page (file OTU 50 Hz\OTU 50 Hz All Tests.png).

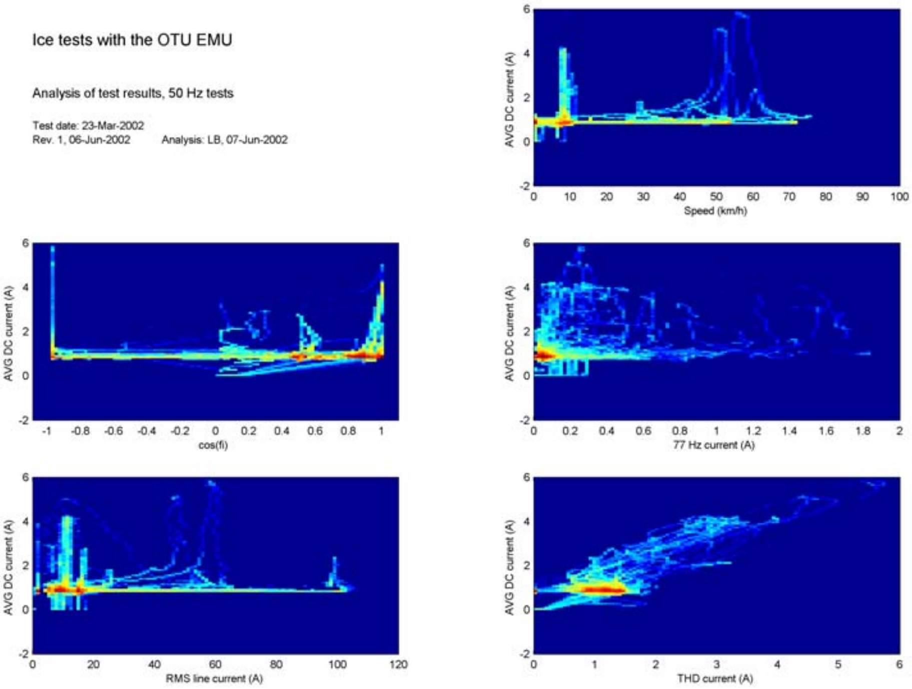


Figure 5.1.2.1.1. Summary of test results, OTU EMU at 50 Hz

The following conclusions can be made:

- The DC is unidirectional (always positive into the train set)

- The maximum DC seems to be lower with the 13 A reactive current reference (cos(φ) ≈ 0.5 - 0.6) compared to cos(φ) = 1
- The DC is more or less proportional to the THD
- If anything, the 77 Hz current and the DC are more or less inverse proportional
- No other correlations are clear

Detailed test results, 50 Hz

Test no.	Maximum DC level	Power	React. current ref.	Link to picture file
44	4.1 A	Low	0 A	OTU 50 Hz\OTU 50 Hz Test 44.png
45	3.1 A	Low	0 A	OTU 50 Hz\OTU 50 Hz Test 45.png
46	4.2 A	Low	0 A	OTU 50 Hz\OTU 50 Hz Test 46.png
47	≈ 4 A	Low	0 A	OTU 50 Hz\OTU 50 Hz Test 47.png
48	1.4 A	Low	13 A	OTU 50 Hz\OTU 50 Hz Test 48.png
49	1.0 A	Low	13 A	OTU 50 Hz\OTU 50 Hz Test 49.png
50	0.9 A	Low	13 A	OTU 50 Hz\OTU 50 Hz Test 50.png
51	0.9 A	Low	13 A	OTU 50 Hz\OTU 50 Hz Test 51.png
52	2.7 A	Low	13 A	OTU 50 Hz\OTU 50 Hz Test 52.png
53	1.0 A	Low	13 A	OTU 50 Hz\OTU 50 Hz Test 53.png
54	4.2 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 54.png
55	1.5 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 55.png
56	1.1 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 56.png
57	5.1 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 57.png
58	5.0 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 58.png
59	0.8 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 59.png
60	2.4 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 60.png
61	1.1 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 61.png
62	1.8 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 62.png
63	1.0 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 63.png
64	1.8 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 64.png
65	5.8 A	Normal	0 A	OTU 50 Hz\OTU 50 Hz Test 65.png

Effects of the reactive current

Comparing the tests with low power and 0 A reactive current reference (no. 44 - 47) to those with 13 A reactive current reference (no. 48 - 53) confirms that small amounts of reactive current reduce the DC levels.

The maximum level of DC in each test is analysed in the table below.

	Reactive current reference		Relative level
	0 A	13 A	$\frac{I_{DC,13\,A}}{I_{DC,0\,A}}$
Mean value of max. DC level	3.9 A	1.3 A	0.33
Standard deviation of max. DC level	0.5 A	0.7 A	-
Mean + 2 * standard deviations	4.9 A	2.7 A	0.55

This means that the 13 A reactive current reduces the DC level at low power to approximately 55 % of the value seen without reactive current.

5.1.2.2 OTU 16 2/3 Hz tests

3 different categories of 16 2/3 Hz tests were made:

1. Acceleration-braking at normal power (only 2 tests)
2. Acceleration-braking at low power
3. Acceleration-braking at low power, with the reference value of the reactive current controller set to 30 A (ind.) rather than 0 A

In addition, tests were made with alternative settings of some parameters of the control system. These tests are not included in the present analysis.

Summary of the test results, 16 2/3 Hz

The tests are summarised in figure 5.1.2.2.1 below and in full size in Appendix 4, first page (file OTU 16 Hz\OTU 16 Hz All Tests.png).

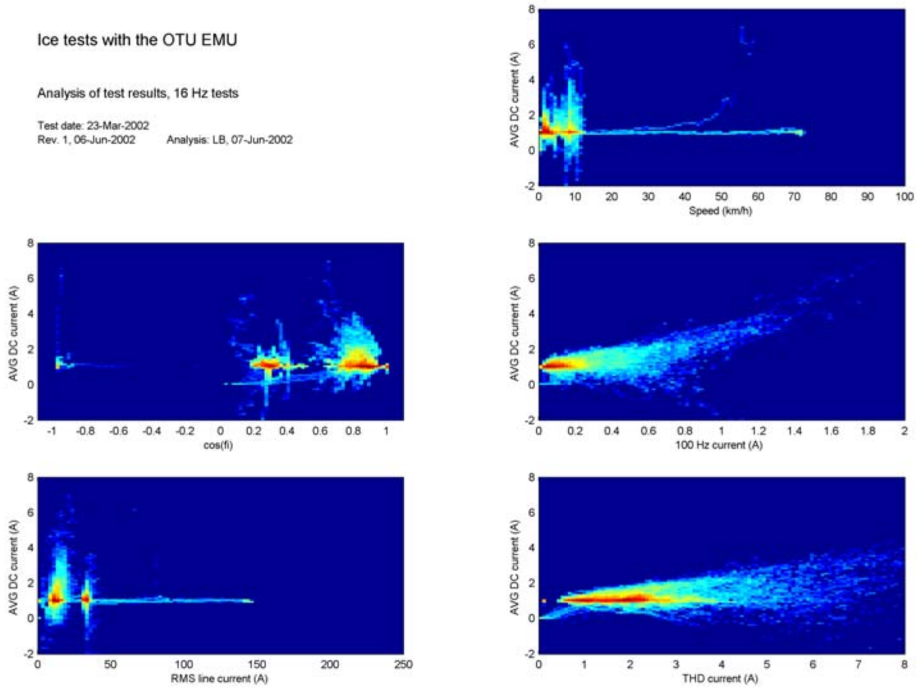


Figure 5.1.2.2.1. Summary of test results, OTU EMU at 16 2/3 Hz

The following conclusions can be made:

- The DC is generally unidirectional (positive into the vehicle). Only relatively short transients with the opposite direction are seen in a few tests. A closer look at the actual wave shapes indicate that this is due to transformer inrush following a complete interruption of the current

- The maximum DC seems to be lower with the 30 A reactive current reference (cos(φ) ≈ 0.2 - 0.4) compared to cos(φ) = 1

- The DC is more or less proportional to the 100 Hz current and the THD
- No other correlations are clear

Detailed test results, 16 2/3 Hz

Test no.	Maximum DC level	Power	React. current ref.	Link to picture file
4	4.2 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 4.png
5	3.0 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 5.png
8	1.9 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 8.png
9	3.2 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 9.png
12	2.0 A	Low	30 A	OTU 16 Hz\OTU 16 Hz Test 12.png
13	2.1 A	Low	30 A	OTU 16 Hz\OTU 16 Hz Test 13.png
14	3.3 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 14.png
15	2.3 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 15.png
16	1.5 A	Low	30 A	OTU 16 Hz\OTU 16 Hz Test 16.png
17	1.6 A	Low	30 A	OTU 16 Hz\OTU 16 Hz Test 17.png
20	2.3 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 20.png
21	1.4 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 21.png
22	4.0 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 22.png
23	5.0 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 23.png
24	3.6 A	Low	30 A	OTU 16 Hz\OTU 16 Hz Test 24.png
25	2.3 A	Low	30 A	OTU 16 Hz\OTU 16 Hz Test 25.png
28	5.8 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 28.png
29	3.2 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 29.png
38	3.6 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 38.png
39	6.0 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 39.png
40	4.7 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 40.png
41	2.5 A	Low	0 A	OTU 16 Hz\OTU 16 Hz Test 41.png
42	(17.6 A)	Normal	0 A	OTU 16 Hz\OTU 16 Hz Test 42.png
43	6.9 A	Normal	0 A	OTU 16 Hz\OTU 16 Hz Test 43.png

The DC level in test 42 is affected by the transient due to a protective shutdown of the control system.

Effects of the reactive current

Comparing the tests with low power and 0 A reactive current reference to those with 30 A reactive current reference confirms that small amounts of reactive current reduce the DC levels.

The maximum level of DC in each test is analysed in the table below.

	Reactive current reference		Relative level
	0 A	30 A	$\frac{I_{DC,30\,A}}{I_{DC,0\,A}}$
Mean value of max. DC level	3.5 A	2.2 A	0.63
Standard deviation of max. DC level	1.3 A	0.8 A	-
Mean + 2 * standard deviations	6.2 A	3.7 A	0.60

This means that the 30 A reactive current reduces the DC level at low power to approximately 60 % of the value seen without reactive current.

5.1.3 Class 357 "Electrostar"

The UK EMU class 357 "Electrostar" was tested at the test facilities in Cerhenice in the Czech Republic during July 2002. One series of tests was performed with the upward pressure on the pantograph being reduced in order to create arcing, thereby aiming for conditions similar to ice on the OHL.

Only the first 4 min of each test have been analysed, due to PC memory limitations.

Summary of the test results

The tests are summarised in figure 5.1.3.1 below and in full size in Appendix 7, first page (file Electrostar\E-star All Tests.png).

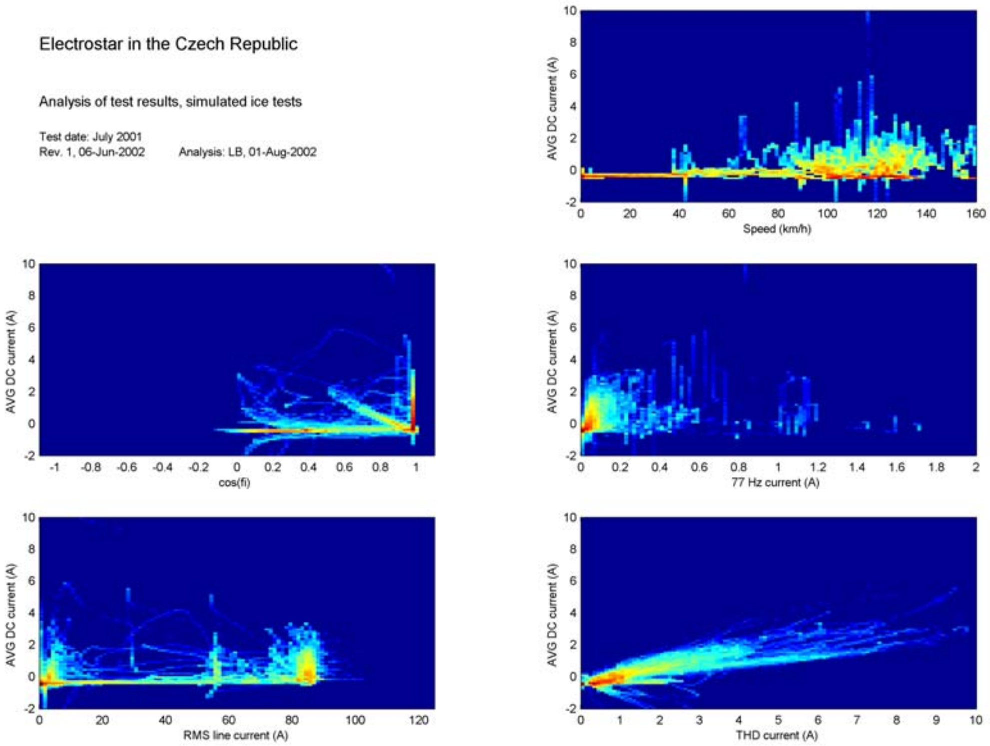


Figure 5.1.3.1. Summary of simulated ice tests with Electrostar

It should be noted that regenerative braking is inhibited on the Electrostar due to the special UK rules.
The negative DC values seen in the graphs are all due to transformer inrush. The polarity of the inrush current is random.

The strange relation between cos(φ) and the direct current (upper left plot) with the DC sometimes increasing with a decreasing cos(φ), is believed to be related to the action taken by the control system of the 4-quadrant converter during certain protection sequences.

Apart from these comments, the plots look pretty much like the corresponding plots of the BR185 and the OTU at ice conditions, meaning that the method of simulating ice conditions by means of a reduced pantograph contact force is relevant and provides useful information.

Detailed analysis

The printouts from the detailed analysis are found in Appendix 7

Test no.	**Link to picture file**	**Comment**
LNF3AK006	Electrostar\E-star LNF3AK006.png	
LNF3BK007	Electrostar\E-star LNF3BK007.png	
LNF3AL029	Electrostar\E-star LNF3AL029.png	Transformer inrush with negative DC
LNF3CL032	Electrostar\E-star LNF3CL032.png	Transformer inrush with negative DC
LNF3AD007	Electrostar\E-star LNF3AD007.png	
LNF3BD008	Electrostar\E-star LNF3BD008.png	Transformer inrushes with negative DC
LNF3CD009	Electrostar\E-star LNF3CD009.png	

5.2 *Double Traction*

5.2.1 2 BR185 Locomotives

2 DB locomotives class BR185 were tested in Luxembourg during December 2001. At the tests on the Luxembourg-Troisvierges line (North from Luxembourg City through the Ardennes) during the night December 8th to 9th, ice was found on the OHL on some of the non-tunnel sections of the line.

The recordings from this dual traction formation have been analysed with the prime focus on the following questions: How do the direct currents split between the two locomotives? Is the total DC from a double formation approximately equal to twice the value of a single locomotive, or is it lower than that?

During these tests, the DC supervision system of the BR185s had been disabled (compare to section 5.3.1).

Results print-out

An example of the results of the double traction test is shown in figure 5.2.1.1 below (full results print-out of this example in the file BR185 Dual\2 BR185 Test 12-15.png).

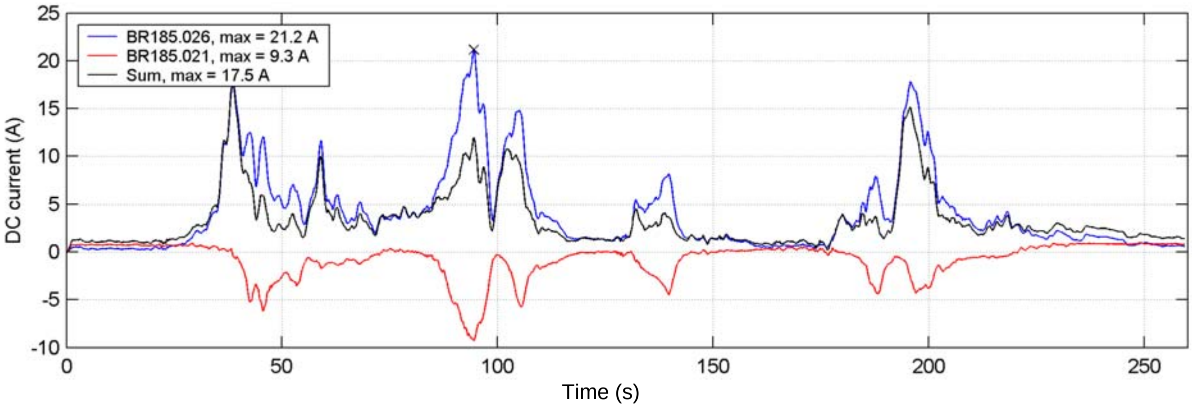


Figure 5.2.1.1. Distribution of DC, double traction with the BR185

The example of figure 5.2.1.1 is typical for the test results. The DC in the heading locomotive (BR185.026, blue line) is highest, with positive direction into the vehicle. The DC of the 2nd loco (BR185.021, red line) is smaller and has the opposite direction, i.e., out of the vehicle. This means that the total DC from the multiple formation is no higher than the level from one vehicle alone, and normally somewhat lower than this value.

Summary of the test results

Figure 5.2.1.2 below summarises the double traction tests, and illustrates the current distribution between the two locomotives (file BR185 Dual\2 BR185 All Tests.png).

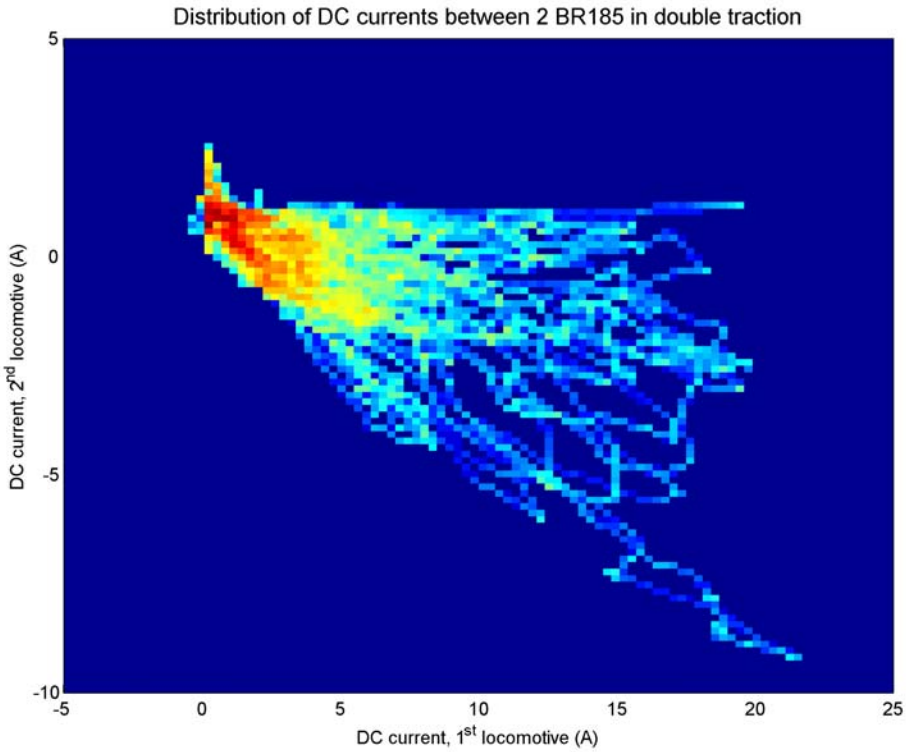


Figure 5.2.1.2. Current split between 2 BR185s in double traction

Figure 5.2.1.2 shows that while the DC in the first loco $I_{DC,FIRST}$ varies between 0 and approximately 22 A, the DC in the second loco $I_{DC,SECOND}$ varies between 0 and a value of approximately $-½ \cdot I_{DC,FIRST}$ (all offsets being neglected)

Detailed test results

The table below refers to the detailed printouts.

Test no.	**Max. DC, 1st loco**	**Max. DC, 2nd loco**	**Link to picture file**
1.2-10	10.6 A	-2.8 A	BR185 Dual\2 BR185 Test 12-10.png
1.2-11	17.0 A	-5.7 A	BR185 Dual\2 BR185 Test 12-11.png
1.2-12	19.6 A	-5.0 A	BR185 Dual\2 BR185 Test 12-12.png
1.2-14	6.8 A	-1.6 A	BR185 Dual\2 BR185 Test 12-13.png
1.2-15	21.2 A	-9.3 A	BR185 Dual\2 BR185 Test 12-15.png

5.3 *Multiple Vehicle Operation*

5.3.1 2 BR185s And 1 Z2000 EMU

As a part of the acceptance testing with the BR185 in Luxembourg, a combined system test was arranged on the Luxembourg-Wasserbillig line December 7th, 2001. This test involved simultaneous measurements in 2 trains and in the Hollerich substation in Luxembourg City. One measurement train was made up with 2 BR185s in double traction, and the other was a single CFL Z2000 EMU with phase-angle controlled rectifiers and DC traction motors. The two trains ran on the approx. 36.8 km long double-track line in a predetermined pattern.

The actual weather conditions with high air humidity and temperatures well below zero caused a considerable build-up of rime, and rather high levels of DC were seen.

Due to the fact that the currents were measured simultaneously in both locomotives, in the Z2000 and in the substation, these tests provide rather unique information about the current distribution in a complete railway system. It should be pointed out, though, that the levels of background noise are rather high on the Wasserbillig line, also at low frequencies. This is believed to be due to the steel plants in Southern Luxembourg, which are supplied from the same power utility as the substation in Hollerich. This background noise means that the OHL ice is not the only source of the direct currents seen in the analysis, a fact which becomes evident when looking at the first 25 s of test 2.1-11 (file BR185 and Z2000\Test 21-11.png). On the other hand, when OHL ice is present and the trains are running, the ice is clearly the stronger generator.

During these tests, the protection systems of the BR185s were still set to open the main circuit breaker if the DC contents of the primary current exceeded a certain level (compare to section 5.2.1).

Printout example

Figure 5.3.1.1 below shows an example of the printout of analysis results (also in file BR185 and Z2000\Test 21-27cs.png).

From the top, the curves show:

- The speed of the two trains, with the 2 BR185s in red and the Z2000 in blue
- The total RMS line currents of the two trains, with BR185.026 in magenta, BR185.021 in red, and the Z2000 in blue. In the tests 9 to 11, BR185.026 was running in front, while the BR185.021 was in front in the remaining tests
- The DC currents in the two trains and in Hollerich substation. The train DCs have the same colours as the corresponding RMS currents, while the current in Hollerich is green. The directions are positive into the line (Hollerich) and into the trains.

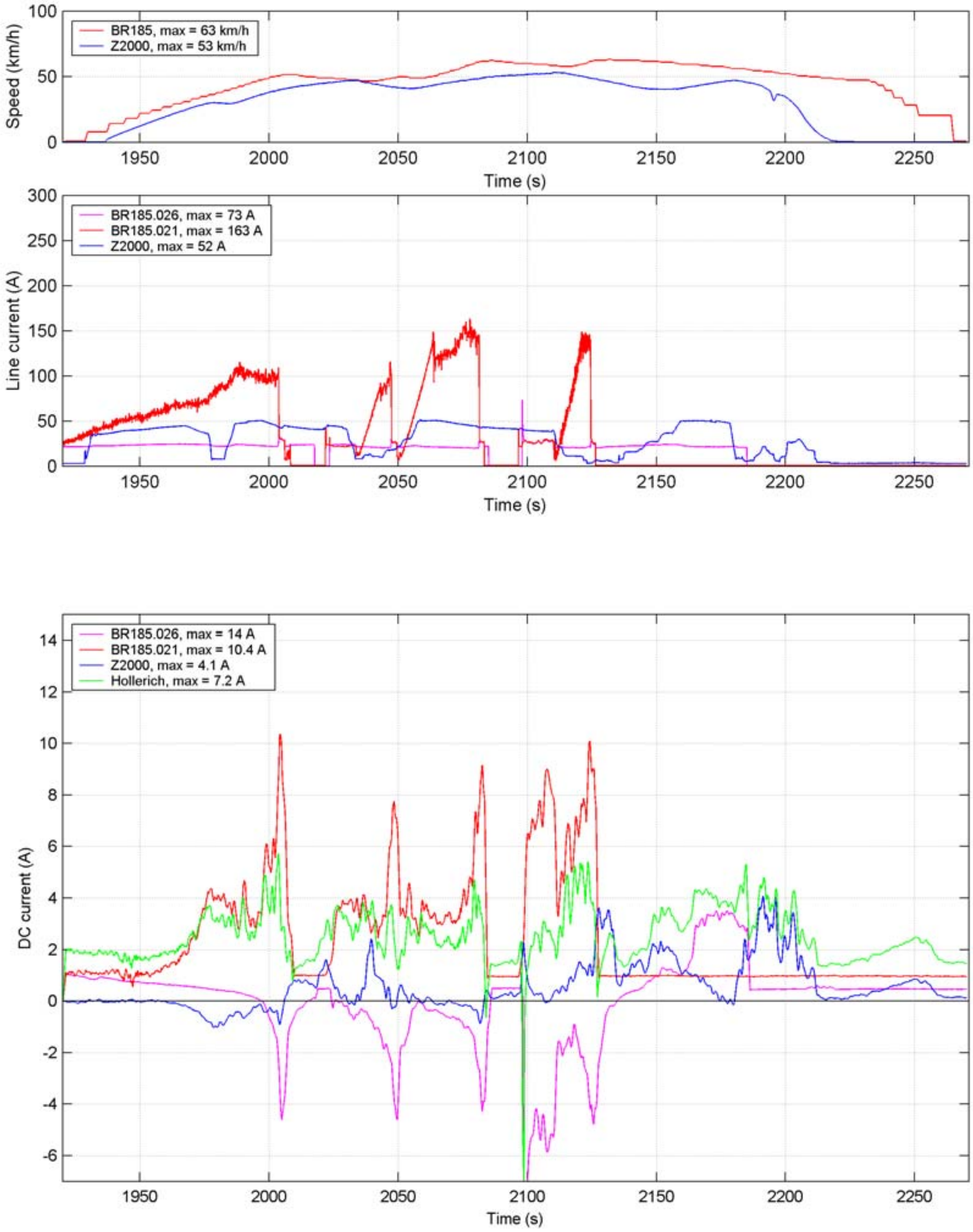


Figure 5.3.1.1. Printout of analysis results, tests with 2 BR185 and Z2000

Taking into account that the current transducers may have DC offsets of up to 1 A, the curves in the lower plot show that $I_{HOLLERICH} = I_{BR185.026} + I_{B185.021} + I_{Z2000}$, just as expected.

It should also be noted that the figures are based on recordings from 3 DAT recorders located in different places, and that the synchronisation has a tolerance of ± 1 s.

The figure in this example might need some further explanation:

- The BR185.021 runs first in the train, with full traction. The BR185.026 runs as 2nd loco, with only the auxiliary converters in operation (no traction). This train runs from km-point 24.6 to 19.5 on the 36.8 km long line.
  The Z2000 runs with full traction from km-point 33.5 to 30.6.

- At t ≈ 1970 s, the DC generated by the BR185.021 due to OHL ice starts to exceed the background noise. The Z2000 and later also the BR185.026 form part of the return current loop, i. e., the DC level in the BR185.021 is higher than in Hollerich.

- At t ≈ 2005 s, 2045 s, 2080 s, and 2125 s, the DC becomes so high that the protection systems of the BR185.021 inhibit the 4-quadrant converters. The inhibits at t ≈ 2005 s, 2080 s, and 2125 s are further followed by an opening of the main circuit breaker a few seconds later. It remains open after the last event, with the offset current of the transducer being approximately 1 A.
  At t ≈ 2020 s and 2085 s, and from 2180 s and onwards, also the main circuit breaker of the BR185.026 is open.

- In the interval from t ≈ 2165 s to 2180 s, the BR185.026 is the dominating DC generator, despite the fact that the pantograph of the BR185.021 in front of it is still up and has just scraped the ice off the OHL. Considering that the DC that was generated by the BR185.021 just before this varied a lot makes it difficult to give any definite statements about the effect of scraping, but at least it can be concluded that scraping does not remove all ice.
  It should further be noted that also the Z2000 generates DC from t ≈ 2180 s and onwards, even though the two pantographs of the BR185s had scraped the OHL only approximately ½ hour earlier.

Detailed analysis printouts

The printouts from the detailed analysis are found in Appendix 6.

Test 2.1-9

1st BR185	2nd BR185	Z2000	Link to figure file
Full traction	Aux. only	Full traction	BR185 and Z2000\Test 21-9.png
Run km 19.5 to km 24.6		Km 24.6 to km 19.5	

The major part of the DC up to t ≈ 1950 s is believed to be background noise, except for a burst being generated by the Z2000 at t ≈ 1900 - 1915 s.

From t ≈ 1960 s and onward, the Z2000 generates considerable levels of DC, up to 12 A. The two BR185s serve as return paths for this DC.

Test 2.1-10

1st BR185	2nd BR185	Z2000	Link to figure file
Full traction	MCB open	Full traction	BR185 and Z2000\Test 21-10.png
Run km 24.6 to km 27.7		Km 19.5 to km 15.3	

Again a considerable background noise is seen. The Z2000 generates high levels of DC from t ≈ 2300 s to ≈ 2520 s.

Test 2.1-11

1st BR185	2nd BR185	Z2000	Link to figure file
Half traction	MCB open	Full traction	BR185 and Z2000\Test 21-11.png
Run km 27.7 to km 30.6		Km 15.3 to km 12.0	

Very high background noise up to t ≈ 2850 s. The Z2000 generates DC with levels up to 11 A.

Test 2.1-23

1st BR185	2nd BR185	Z2000	Link to figure file
Full traction	Full traction	Aux. only	BR185 and Z2000\Test 21-23.png
Run km 36.8 to km 33.5		Parked at km 36.8	

The 1st BR185 (no. 021) generates DC. The Z2000 and (at t ≈ 330 - 350 s) the BR185.026 are return paths.

Test 2.1-24

1st BR185	2nd BR185	Z2000	Link to figure file
Half traction	Half traction	Aux. only	BR185 and Z2000\Test 21-24.png
Run km 33.5 to km 30.6		Parked at km 36.8	

The BR185.021 generates DC throughout most of the test, with the Z2000 being part of the return path.

The protection systems of the BR185.021 open the main circuit breaker at two occasions, at t ≈ 755 - 775 s and again from t ≈ 865 s and onwards. During these events, the BR185.026 becomes the prime source of DC, until its circuit breaker is also opened. The scraping of the OHL by the pantograph of the heading BR185.021 has a limited effect only.

Test 2.1-25

1st BR185	2nd BR185	Z2000	Link to figure file
Half traction	MCB open	Aux. only	BR185 and Z2000\Test 21-25.png
Run km 30.6 to km 27.7		Parked at km 36.8	

The BR185.021 generates DC throughout most of the test, with the Z2000 being part of the return path. The protection systems of the BR185 open the main circuit breaker at two occasions.

Test 2.1-26

1st BR185	2nd BR185	Z2000	Link to figure file
Full traction	MCB open	Aux. only	BR185 and Z2000\Test 21-26.png
Run km 27.7 to km 24.6		Parked at km 36.8	

The BR185.021 generates DC throughout most of the test, with the Z2000 being part of the return path. The protection systems of the BR185 open the main circuit breaker at two occasions.

Test 2.1-27

1st BR185	2nd BR185	Z2000	Link to figure file
Full traction	Aux. only	Full traction	BR185 and Z2000\Test 21-27.png (and -27cs.png with a better scale of the lower plot)
Run km 24.6 to km 19.5		Km 36.8 to km 33.5	

Please refer to the explanation given in the previous section.

6 Discussion of the Results

6.1 Equivalent Circuit Model

The analysis support the theory that a DC voltage source of up to 20 V can exist at the OHL-pantograph interface, due to the differences in the anode and cathode voltage drops of copper and carbon. The voltage source has its positive polarity at the pantograph.

If only one vehicle is present on a line, the magnitude of the direct current is determined by the said voltage and by the total resistance in the return path that is made up of:

- The resistance of the primary winding of the main transformer, which may vary from 0.5 Ω in a locomotive to more than 10 Ω in an EMU
- The line resistance, i. e., the OHL and catenary and the rails and return conductors
- The resistance of the supply transformer and of any autotransformers or transformers for point heaters, etc.

With more vehicles on the line, multiple voltage sources exist. These sources are basically connected in parallel. Figure 6.1.1.

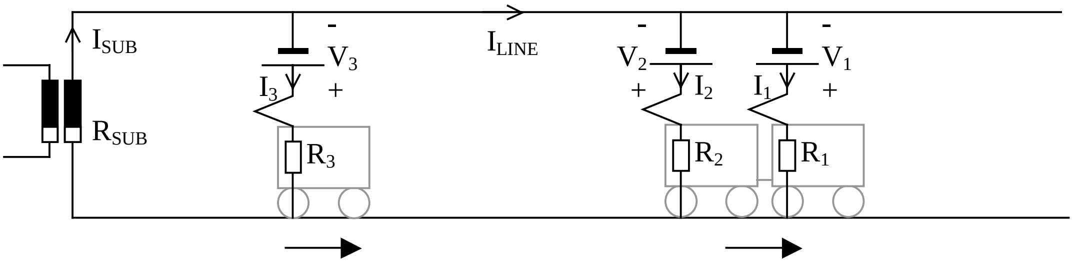


Figure 6.1.1. Circuit model, multiple vehicles

In this example, the two vehicles in double traction could be the two BR185s in section 5.3.1, and the third vehicle could be the Z2000. With the shown running directions, the voltage source V_1 is normally stronger than V_2, meaning that a part of I_1 circulates back via V_2 and R_2 - i. e., I_2 is negative.
The direction of I_3 depends on the circumstances - it could be negative if V_1 is very high, or positive if it is lower.

6.2 Is Ice Removed by a High DC?

The lower plot in figure 5.3.1.1 showed a rather characteristic relationship between the direct currents of the two BR185s. This plot is shown again in figure 6.2.1 below.

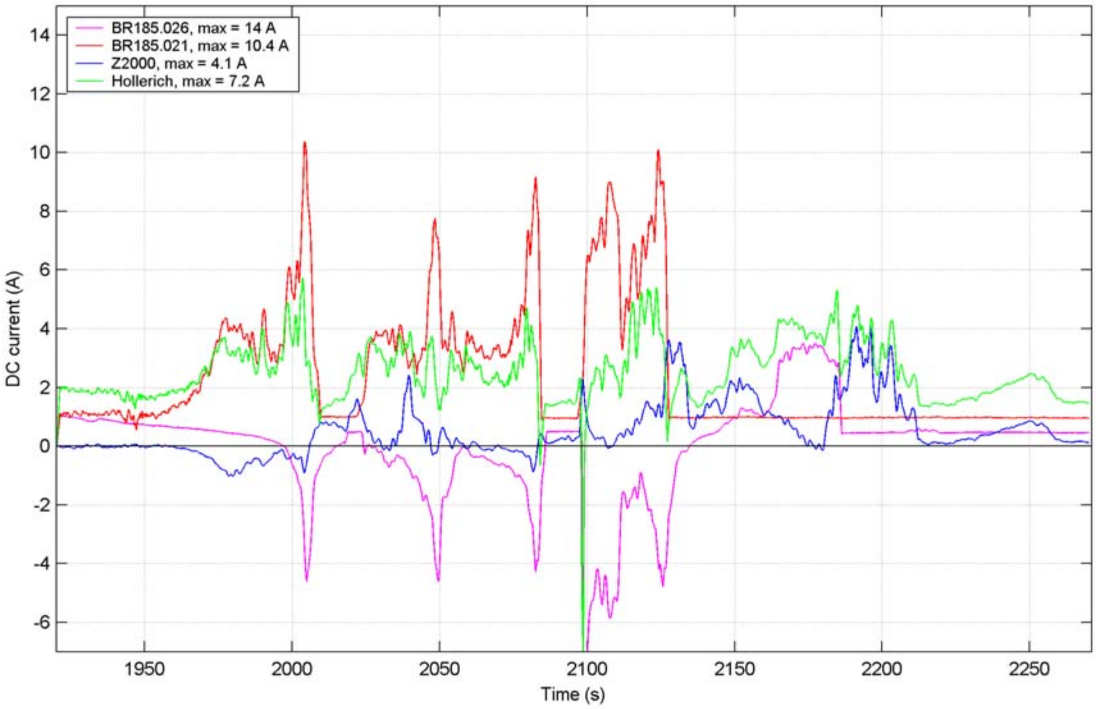


Figure 6.2.1. Direct currents, test 2.1-27 with 2 BR185s and Z2000 in Luxembourg

At at least 3 instants (t ≈ 2005 s, 2050 s, and 2080 s, respectively), the DC in loco no. 026 increases more or less exponentially in the negative direction, looking much like a system with positive feedback. The DC in loco no. 021 increases in the positive direction until the DC protection system reacts and inhibits the 4-quadrant converter.

At all 3 instants, the current in the Z2000 is rather close to zero. I. e., remove vehicle 3 from figure 6.1.1 above (or let $R_3 \approx \infty$). The primary transformer resistance of each BR185 is approximately 0.7 Ω (= R_1 and R_2), and let R_{SUB} be 2 Ω (20 km double track).

Assume now that the arc voltage of loco no. 1 is constantly = 15 V (V_1 in figure 6.1.1), and calculate the currents in the two locomotives and in the supply versus the arc voltage of the 2nd loco. The result of this calculation is shown in figure 6.2.2 below, with the arc voltage of the 2nd loco decreasing from 15 V to 0 V.

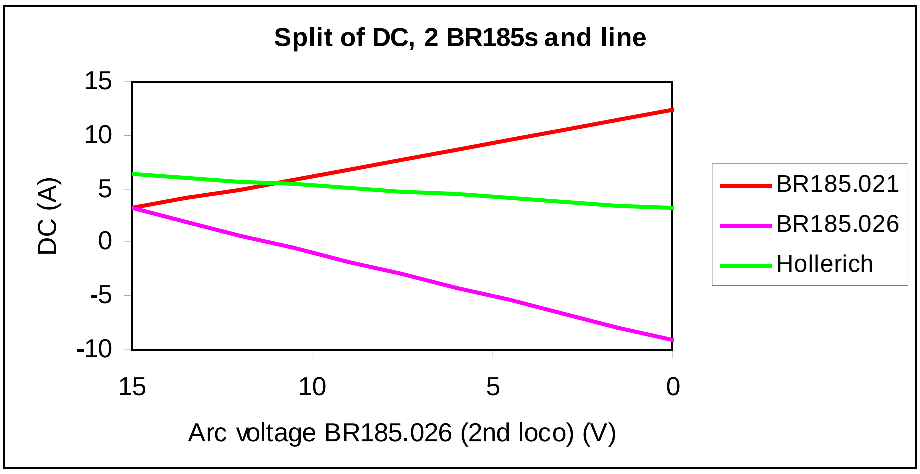


Figure 6.2.2. Direct currents versus arc voltage of the 2nd loco

It is reasonable to assume that the arc voltage of the 2nd loco would be approximately equal to that of the first loco if no ice at all had been removed by the passage of the first pantograph, and on the other hand that the 2nd arc voltage would be 0 in case the ice had been completely scraped off. In the latter case, a rather high DC would be circulating between the two locomotives, but the DC that returns via the substation would be rather low (3.2 A, to be compared to the 5.6 A that would be emitted from a single locomotive at identical conditions (15 V / 2.7 Ω)).

The curves in figure 6.2.1 indicate that as the DC in the first loco increases, more and more ice is being removed. This causes the arc voltage of the 2nd loco to decrease, in turn causing the circulating DC to increase even further. In other words, the DC itself seems to improve the way ice is being removed.

This leads to the theory that in case 2 electrically parallel pantographs were raised on one locomotive, even more ice could be scraped off. Given that the resistance in the loop pantograph 1 - roof busbar - pantograph 2 - OHL must be very low, a high level of DC would circulate in this loop, with the potential of efficient removal of ice.

This way of operating should be included in future tests, as should an investigation of the effect of scraping on the levels of DC that are generated by later trains.