Ice on the Overhead Line of AC Electrified Railways

Summary Report From the OHL Ice Team

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1 Summary and Conclusions

This note summarises and concludes the technical reports and other documents that have been collected within the framework of the OHL Ice Team under the ESC UserGroup. This team was formed in order to analyse, describe, and if possible suggest solutions the problems that are seen at conditions with ice on the overhead line of AC electrified railways. Amongst these problems are:

- The generation of DC components and even harmonics in the line current that may potentially interfere with track circuits operated by DC or by an even harmonic such as 100 Hz at 16.7 Hz supply frequency

- Generation of RFI (Radio Frequency Interference)

Participants in the OHL Ice Team are representatives of SBB, Banverket, The University in Luleå, Siemens, Bombardier, and others.

The main conclusions are:

- The DC components in the line current originates from the physical properties of the materials that are used for the overhead contact wire and the pantograph head (copper and carbon, respectively), in combination with the arc that is caused by the thin layer of ice. The voltage drop across this arc is polarity dependent, i. e., the voltage drop is higher in the negative half period when current flows from carbon to copper compared to the positive half period. This results in a net DC EMF across the arc. The polarity of this EMF is such that the current has its positive direction from the OHL into the generating vehicle.

- The even current harmonics originates from transformers that have been (partly) saturated by the DC. The RFI is generated by the arcing as such

- The magnitude of the DC EMF is up to approximately 20 V DC at less severe to normal conditions (hoarfrost, rime), but higher levels of up to 100 V DC can be expected at severe conditions with glaze. The current is determined by the resistances of the supply and OHL systems (typically 0.05 to 0.3 Ω/km) and of the primary winding of the main transformer (typically 0.5 to 10 Ω)

- The fact that the DC source is a voltage source and not a current source means that parallel connection of more sources (i. e., multiple operation of 2 or more vehicles) does not increase the magnitude of the direct current. On the contrary, the total DC emitted from a multiple formation is generally lower than the DC that is generated by a single vehicle. This is due to the fact that the leading pantograph sees the most severe ice conditions and generates a higher DC EMF than the following pantographs. In this way, only the leading vehicle becomes a net DC generator, while the following vehicles serve as return paths.

- There are full agreements between the predictions from the fundamental arc theory on one side, and the results from laboratory and field measurements on the other. No other DC generation mechanism that could possibly provide this degree of correlation has been identified.

The note does not treat the DC or even harmonic currents that can potentially be caused by other mechanisms, such as parallel DC electrified railways, failure conditions in the trains, etc.

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2 Introduction

2.1 The OHL Ice Team

The OHL Ice Team was kicked off at the ESC UserGroup workshop at UIC in Paris 2002-02-05, and formally formed as a working group 2002-03-14 by representatives of a number of different railway administrations and railway vehicle suppliers. The team has dealt with OHL ice problems in a common project, to the benefit of everybody.

This note summarises and concludes the technical reports and other documents that have been collected up to now within the framework of this Team.

2.2 References

[1] *CRREL Report 80-31, Icing on Structures.* L. D. Minsk, United States Army Cold Regions Research and Engineering Laboratory, December 1980

[2] *Icing on Overhead Lines of Electric Railway Lines, Metrological Conditions.* Thomas Berger, SBB, 2002-11-08

[3] *Origin of DC Components in Railway Line Currents Upon Operation With Iced Overhead Line. Theory, Experimental Results, and Conclusions*. Dierk Bormann, ABB Research, 2003-05-01 (draft, not yet to be published)

[4] *Analysis of OHL Ice Recordings.* Lars Buhrkall, 2002-08-05

[5] *PowerPoint Presentation at the ESC UserGroup Workshop, Paris 2002-02-05,* Lars Buhrkall, 2002-01-31

[6] *Working Group Meetings* (a folder of documents from the OHL Ice Team meetings), various authors

3 Early Observations and Field Tests

3.1 Experiences from England

The problem of DC line currents caused by ice on the OHL has been particularly important in England where very low interference current limits in combination with interference monitors have led to considerable difficulties with the safety approval of new generations of rolling stock.

It has been reported that Holec carried out a thorough study of the OHL ice problem as a part of their demonstration of compatibility of the class 323 EMU, but the details of this investigation cannot be (or at least, has not been) distributed outside its original scope.

Adtranz/Bombardier had OHL ice problems with the class 357 EMU ("Electrostar") during the winter 2000-2001, but unfortunately the critical weather conditions did not occur at any time when measurements and recordings could be carried out. Instead, OHL ice conditions were simulated at the tests in Cerhenice in the Czech Republic in July 2001, by reducing the upward force on the pantograph.

3.2 Experiences from Switzerland

The Swiss 16 2/3 Hz electrified railways are equipped with 100 Hz track circuits, i. e., they operate at the 6^{th} harmonic. This cause severe problems during wintertime, due to the fact that the existence of a DC component in the line current also leads to even harmonics.

3.3 Experiences from Denmark

During the winter 2001-2002, the operation with the new Oeresund Train Unit (OTU) EMUs had to be cancelled at some occasions. In contrary to other electric trains and locomotives in Denmark, the OTU is equipped with a DC supervision system. At conditions with ice on the OHL, this system reacted and stopped the OTU EMUs.

3.4 Experiences from Luxembourg

During 2 nights of testing with the locomotive class BR185 in Luxembourg, December 2001, rime was formed on the OHL. A brief analysis of some of the recordings from these tests were used in a presentation at the ESC UserGroup workshop at UIC in Paris 2002-02-05 [5], a presentation that kicked off the OHL Ice Team as a working group under the ESC UserGroup. The analysis show that the DC caused by the OHL ice is unidirectional, and always flowing into the generating vehicle. It is also characteristic that the DC seems to simply cause an offset of the line current, i. e., the line current wave shape is not affected in any other way than by this offset (10 A in the example in [5], but levels in excess of 20 A were seen).

(These and other recordings were later analysed in more detail. Please refer to section 5.4 below, and to [4].)

3.5 Experiences from Sweden

High DC line current components have been experienced with the IORE locomotive for the iron ore traffic in Northern Sweden.

4 Research Activities

The OHL Ice Team discussed and defined a number of research projects at its first meeting in Copenhagen 2002-03-14:

1. A description of the weather conditions that lead to icing, and of the characteristics of the different types of ice.

2. A theoretical explanation of the nature of the arc and of the observed phenomena, in particular:
   - The DC is unidirectional
   - Both undistorted and heavily distorted current wave shapes are seen

3. A test rig that could enable a direct measurement of the voltage across the arc

4. Tests with the OTU at the test track at Bombardier in Västerås

5. An uniform analysis of all available data, including an evaluation of different definitions of what is DC, i. e., of different methods for signal processing

In order to carry out the first point, each of the team members called their local meterological institutes and performed www-searches. The information that was collected in this way was later summarised and concluded by Thomas Berger, SBB (5.1 below, and [2]).

The 2nd and 3rd of the points above were ordered by Bombardier to be performed by ABB Corporate Research in Västerås (5.2 below, and [3]), while Lars Buhrkall has been looking at the 5th point (5.4 below, and [4]).

4.1 Weather Conditions and Ice Accretion

The CRREL report *Icing on Structures* [1] defines the following types of ice accretion:

Ice type	Air temp.	Wind speed	Mechanism
Hoarfrost	≤ 0°C	≈ 0 m/s	Water vapour in the air depositing on a surface, i. e., ice crystals are formed directly from the vapour phase
Soft rime	-5°C - -25°C	1 m/s - 5 m/s	Discrete supercooled water droplets freezing very rapidly upon depositing, resulting in a granular structure
Hard rime	-3°C - -8°C	5 m/s - 10 m/s	Discrete supercooled water droplets freezing relatively slowly upon depositing, thus allowing for some water flow before complete crystallization and resulting in a denser and harder structure
Glaze	0°C - -3°C	1 m/s - 20 m/s	Water droplets that have sufficient time to flow in a continuous film over the surface before freezing, forming homogeneous ice

Table 1. Types of ice accretion.

The basic requirements for ice accretion are that the surface temperature must be below 0°C and also below the dew point of the ambient air. This typically happens wintertime in one of the following ways:

- The air humidity is relatively high in the evening. During the night, the clouds disappear and the air is rapidly cooled down due to radiation to space
- The temperature is below zero. A quiet wind brings in air with a high humidity while the sky remains clear

The meteorological institutes can predict icing with a forecast of max. 8 hours. In particular, useful forecasts are made at all major airports.

The report from Thomas Berger [2] describes more details about the general mechanisms and weather conditions that can lead to ice accretion.

4.2 *Arc Theory and Laboratory Measurements*

In order to investigate the nature of the DC generation, Dierk Bormann at ABB Corporate Research in Västerås has carried out a theoretical study supported by laboratory measurements.

The results from this study are presented in [3]. This report is the property of Bombardier Transportation, but a short summary of the main points and conclusions can be given in the following sections.

4.2.1 Fundamental Arc Physics

Voltage drops. The arc consists of 3 zones: Thin layers 0.01-0.1 mm thick at the surface of each electrode, and the burning arc in between. The voltage drops across the electrode layers depend on the direction of the current (i. e., whether an electrode is anode or cathode), and different materials (in this case: copper and carbon) have different electrode voltage drops according to table 2 and figure 1 below.

	Anode	Cathode
Copper	*2-6 V*	*8-9 V*
Carbon	*11-20 V*	*9-11 V*

Table 2. Voltage drops across the electrodes.

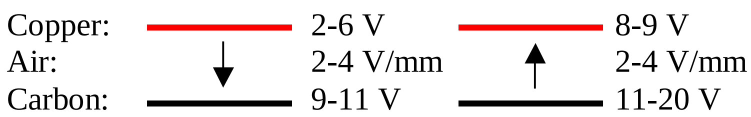

Figure 1. Arc voltage drops, positive and negative current direction.

The cathode spot. The electrons are emitted from a very small area called the cathode spot. It takes a certain voltage to ignite an arc in a new spot. This voltage is higher than the cathode voltage drop of the burning arc, and it depends on the electrode material, its shape, the ionization of the air, temperature, and of the polarity of the voltage.

4.2.2 Arc DC Generation Mechanisms

The theoretical considerations and the experiences from the early field measurements and other observations led to the suggestion of 3 possible mechanisms that individually or jointly may explain how DC is being generated by an arc at the interface between the pantograph and the OHL:

1. ***Continuously burning arc.*** The arc has a more or less constant length, i. e., it follows the pantograph as it moves along the OHL. Due to the sign reversals

of the alternating current and due the differences between the electrode voltage drops as explained above, a net DC EMF of approximately 5-20 V is generated across the OHL-pantograph interface.

2. ***"Jumping" arc.*** It takes a certain voltage to ignite an arc in a new cathode spot. The voltage drop across the burning arc depends on its length, and consequently, the arc needs to have a certain length before the voltage drop is higher than the ignition voltage such that an arc can be ignited at a new spot. This may cause the arc to move in "jumps" along the OHL. As the ignition voltage depends on the electrode materials and of the polarity of the voltage, the arc may be longer on average when the current flows in one direction compared to the other. This may lead to a considerably higher net DC EMF values than mechanism 1 above, up to 100 V.

3. ***Discontinuous arc.*** The arc may be completely extinguished at the zero-crossings of the current. For reasons similar to mechanism 2 above, the voltage that is required in order to re-ignite the arc is polarity dependent.

4.2.3 Test Set-up

In order to perform measurements at controlled conditions, a test rig was constructed (figure 2).

This rig comprises a rotating wheel with a diameter of 1250 mm. A piece of overhead copper wire is mounted at the periphery of this wheel. By adjusting the speed of the wheel from 0 to approximately 12 revolutions per second, equivalent train speeds of up to 160 km/h can be simulated.

A piece of pantograph carbon is mounted on a small carriage below the wheel in such a way that the distance (or the contact force at zero distance) between the copper and the carbon can be adjusted such that the severity of the arcing can be controlled[1].
The carriage moves from side to side in order to simulate the zigzag of a real catenary system.

By means of a set of brushes, a closed electrical circuit can be established through the wheel and the piece of carbon. The supply voltage as well as the amplitude and the phase angle of the load current can be adjusted.

[1] It should be noted that in the test rig, the arc is caused by this small air gap. No tests with real ice on the rotating wheel have been performed.

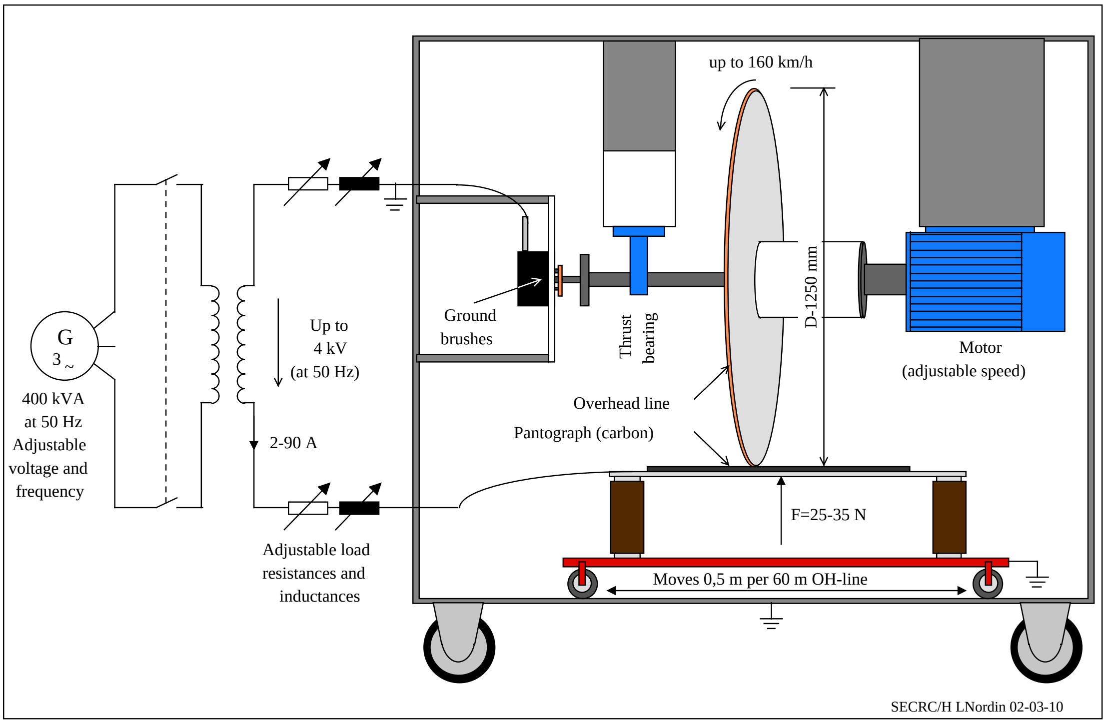

Figure 2. Test rig

One of the major advantages of this rig is the possibility of direct measurements of the arc voltage, a quantity that can hardly be measured at field tests.

An example of a recording made by means of this test rig is shown in figure 3 below.

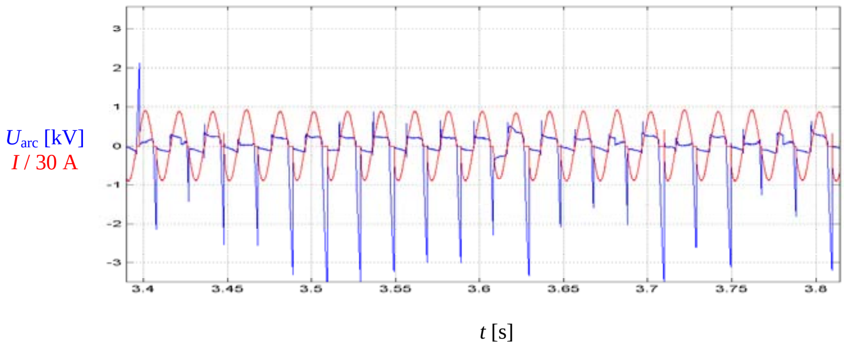

Figure 3. Arc voltage and load current wave shape examples

This example illustrates mechanism 3, i. e., the arc is extinguished at the current zero crossings, and the reignitions are polarity dependent. In this example, the net DC EMF is approximately -106 V.

4.2.4 Conclusions From the Laboratory Tests

During the tests, a wide number of parameters and conditions were varied in a systematic way:

- Voltage
- Load current
- Phase angle between voltage and current
- Distance between pantograph and OHL
- Speed of the rotating wheel

The measurements and analysis lead to the following conclusions:

- The arc end points move in discontinuous jumps along both electrodes, i. e., the tests show that mechanism 2 is also valid. Video recordings and visual inspections of the rotating wheel and the pantograph head after testing show that the arc has a clear preference for certain spots.
- The DC EMF decreases with increasing arc AC voltage and with increasing arc current. This is probably due to an increased ionization of the air.
- The DC EMF increases with increasing distance between the pantograph and the OHL, and with increasing speed of the rotating wheel. This is probably due to increased arc lengths.
- At low speeds, the DC EMF decreases with increasing phase angle, but it increases with increasing phase angle at high speeds.

4.3 Tests With OTU in Västerås

An OTU was tested at the Adtranz/Bombardier test track in Västerås March 23rd and 24th, 2002. OHL ice conditions were created artificially by means of a water spray. Both 50 Hz and 16 2/3 Hz supplies were tested, as well as different software settings.

In comparison to the tests with the BR185, it is characteristic that the line current wave shape became heavily distorted at the icy OHL section. It is likely that this is a result of the artificial ice, leading to a more glaze-like icing or a harder rime compared to the natural rime in Luxembourg.
An example is shown in figure 4 below, where the blue lines are the recorded pantograph voltage and current, while the dashed red line is an approximation of the purely sinusoidal line voltage. The difference between the two voltages is the voltage across the ice layer. This voltage reaches a level of approximately 2 kV during the intervals with zero current.

(Please notice that the current transducer has an offset of approximately 1 A, and that the pantograph voltage is maintained (with a small phase delay) by the 4-quadrant line converters during the intervals with zero current.)

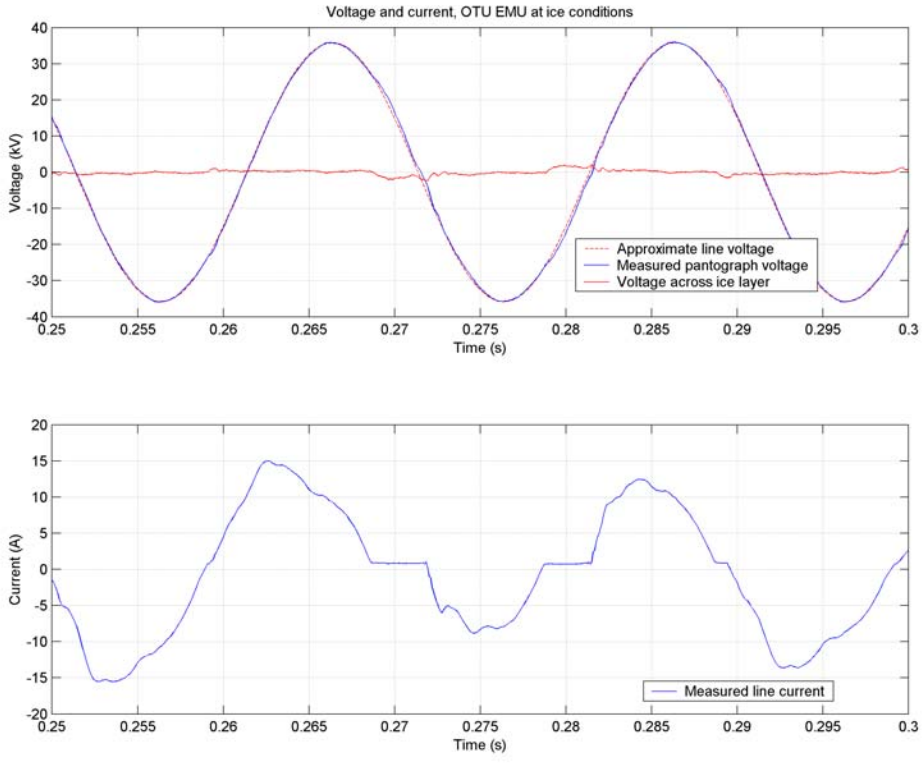

Figure 4. Pantograph voltage and current, OTU ice tests.

4.4 Analysis of Field Measurements

The report [4] 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. 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)

4.4.1 Single Traction

Single traction tests have been carried out with the OTU, the BR185, and the Electrostar ([4] chapter 5.1). These tests conclude the following:

- The DC generated due to OHL ice is unidirectional, and always flowing into the generating vehicle. DC levels in excess of 20 A are seen with the BR185
- 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 16.7 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

4.4.2 Double Traction

Double traction tests have been carried out with 2 BR185s ([4] chapter 5.2). These tests conclude that the total DC emitting from two 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.

4.4.3 More Vehicles

Tests with more vehicles have been performed with 2 BR185s in double traction, plus a CFL class 2000 EMU ([4] chapter 5.3). At these tests, also the substation current was recorded. The tests confirm the observations from the double traction tests, and they also show that 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.

The analysis supports 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.

5 System Analysis and Discussion

5.1 Discussion of Various Set-ups

5.1.1 Single Vehicle

The DC EMF across the arc is V_1. The current is determined by the total resistance in the circuit.

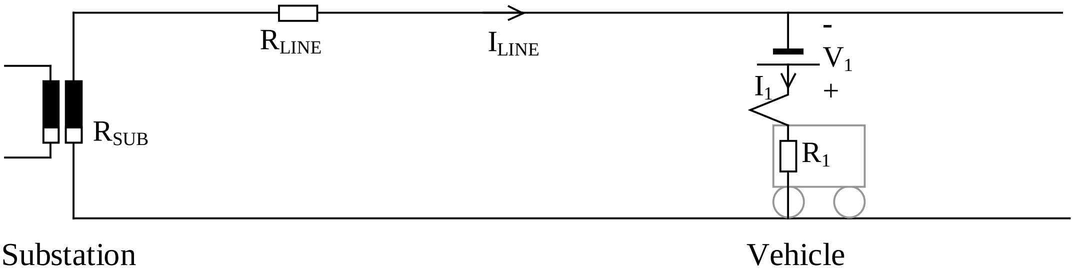

Figure 5. Single vehicle.

5.1.2 Two or More Vehicles in Multiple Operation

The DC EMF of the front vehicle is V_1, and that of the second vehicle is V_2 (figure 6 below).

In the normal case, $V_1 > V_2$ due to the scraping effect. In this case, the DC line current component I_{LINE} is lower compared to the level that would have been seen with only a single vehicle (figure 5 above), and I_2 is negative (current is circulating through the two vehicles). This is the situation seen in [4].

Only if V_1 and V_2 are approximately equal, then I_{LINE} will be marginally higher compared to the level that would have been seen with only a single vehicle (figure 5 above), due to the (in effect) parallel connection of the main transformer resistances R_1 and R_2.

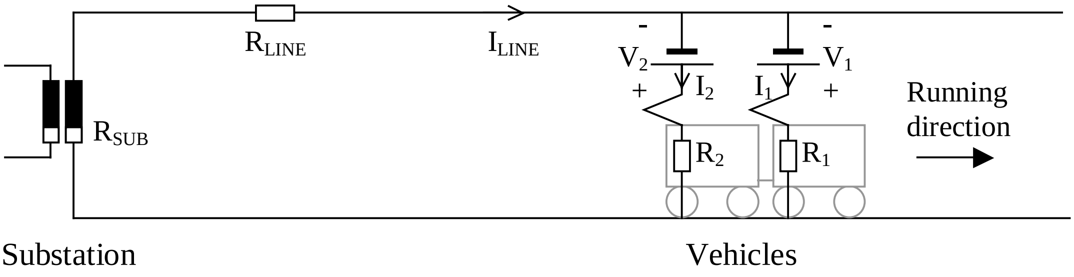

Figure 6. Two vehicles in multiple operation.

5.1.3 Two Separate Vehicles

If V_1 and V_2 in figure 7 below are approximately equal, then $I_{LINE1} \approx 0$ and I_{LINE2} is approximately equal to the level that would have been seen with only a single vehicle (figure 5 above).

If $V_2 \approx 0$, then I_{LINE1} becomes higher than the level that would have been seen with only a single vehicle (figure 5 above), due to the reduced overall resistance seen from vehicle 1.

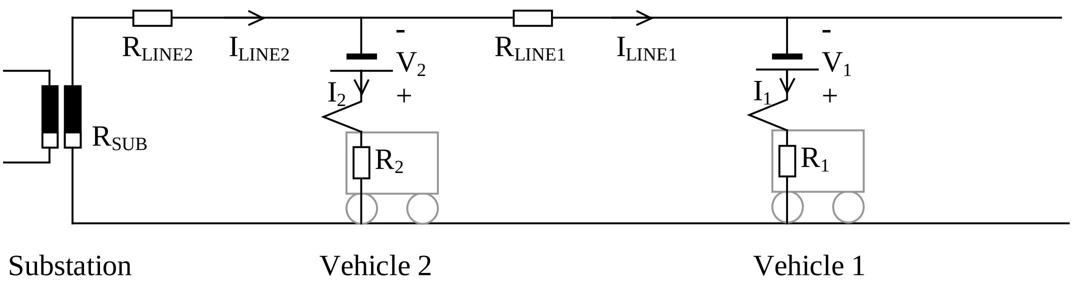

Figure 7. Two separate vehicles.

5.2 Alternative Causes?

This section discusses some alternative proposals regarding the origin of the observed DC components. However, as the section will show, none of the proposals are in agreement with the actual observations.

5.2.1 Other DC Sources in the Traction System?

The overall electrical system is characterised by (at least) 3 galvanically separated circuit loops, as shown in figure 8 below:

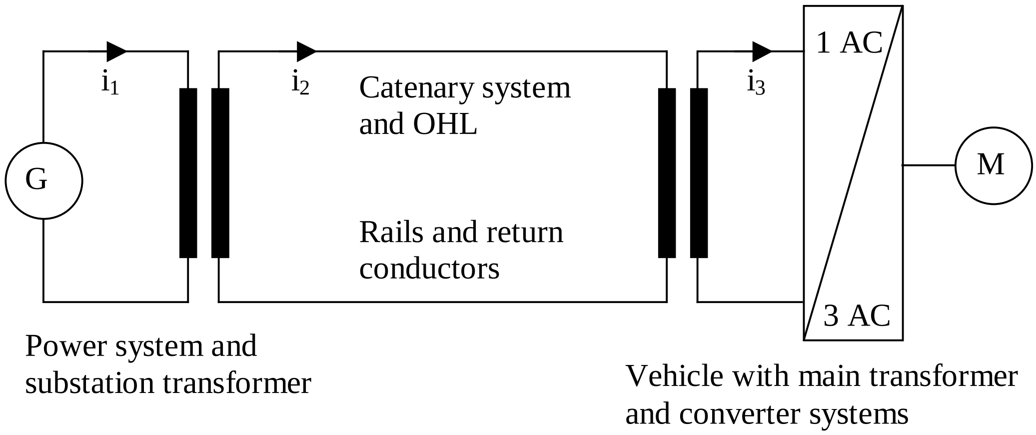

Figure 8. Overall electrical system

- The power supply system with generator, power grid, and substation transformer primary winding (normally the power system is separated in more loops by a number of effectively cascaded transformers)
- The railway system with substation transformer secondary winding, catenary and feeding system, main transformer primary winding, and rails and return current system
- The vehicle power system with main transformer secondary winding(s), power converters, traction motors, etc.

Due to the basic fact that transformation requires an alternating magnetic field, meaning that a transformer cannot transfer DC from the primary to the secondary winding or vice versa, it is evident that the DC components of i_1 and i_3, if any, do not cause any steady-state DC in i_2, they only cause even harmonics. This means that the source of the measured DC components in i_2 must be found within that current loop itself.

In other words, the DC components measured at the field tests cannot originate from the control of the power converters, wheel slip-slide, or other problems related to the systems at the secondary side of the main transformer. Such problems may cause "transient DC" lasting for some and maybe up to 10 seconds, but not the steady DC seen at the measurements. In addition, no mechanism is seen that correlates these problems to the existence of ice on the OHL.

5.2.2 Low Frequency Magnetic Fields?

It has been reported from Alaska and Northern Canada that the magnetic fields associated with the Northern Light induce currents with very low frequencies (fractions of a Hz) in the power grid. It is believed that the same phenomenon has been observed on the Iron Ore line in Northern Sweden and Norway.

However, this does not explain that the problems are also commonly seen in Central Europe where Northern Light is extremely rare.

5.2.3 Other Sources?

No mechanism has been identified that could, as an example, increase the leakage of direct currents from a nearby DC electrified railway whenever there is ice on the OHL. In addition, some of the measurements are from areas quite far away from DC electrified lines.