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DOCTORAL THESIS

Measurements and Analysis of Electromagnetic Interferences in the Swedish Railway Systems

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Measurements and Analysis of Electromagnetic Interferences in the Swedish Railway Systems

by

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"Still confused, but on a higher level".
Enrico Fermi

PREFACE

The research work presented in this thesis has been carried out at the Division of Operation and Maintenance Engineering within the framework of Luleå Railway Research Centre (JVTC). During this time I have received generous support from a large number of persons, who in different ways have contributed in finalizing this thesis.

First of all I would like to express deep gratitude and thanks to my supervisor, Professor Uday Kumar, for his help and support and for being a source of inspiration and joy during my struggle up the hill of scientific indistinctness. I would also like to thank my co-supervisor, Assistant Professor Håkan Schunnesson, for his kind and supporting help.

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Finally, I would also like to thank Berith for her support, advice, nagging, and love, all of which has made this possible, as well as my near and dear friends and family, for supporting me and cheering from a distance.

Stefan Niska

Luleå, December 2008

ABSTRACT

Presently, the existing failure reporting system at Banverket (the Swedish Rail Administration), which handles reports on the failures of the railway infrastructures and possible causes of failure, is not optimum (or most suitable) when it comes to analysis of electromagnetic compatibility (EMC)-related failures and causes. This failure reporting system is reliant on correct reporting into the system, so that the right information can be sent back to the users, the maintenance and service personnel, in real time.

In general railway infrastructure operates in a complex and non-homogeneous environment where low power electronics has to function in the same environment as large voltages and currents from trains. The environment close to the railway tracks is heavily polluted by electromagnetic (EM) noise from the railway systems themselves. The reliability of railway signalling, communication, and control systems depends on the degree of galvanic isolation from EM noise. When new technologies are implemented into old installations, the complexity of the system increases, leading to new challenges which necessitate new forms of skill and competence to deal with these issues and challenges. The new technologies which are to be integrated into the old systems, or which are to be applied to build new systems, must meet the requirements for EMC in order to obtain a high degree of system reliability and ensure the problem-free operation of such systems.

The complexity of the infrastructure is not easy to simulate or calculate, and consequently it is important to observe the real systems and their characteristics in real situations. Therefore, measurements were performed on real systems in operation. To perform an audit of the problems in the railway systems leading to EM noises and failures, investigations were made by studying the real systems in operation and using the existing failure (and inspection) reporting system of Banverket. A large number of measurements were made on site at detectors and signalling systems and installations. By studying and analyzing the measured data and failure reports from the databases, an effort was made to understand the causes of faults related to EMI (electromagnetic interferences). Thereafter, visual inspection was carried out in the engineering constructions, i.e. signal and detector boxes, to verify if the recurring faults are caused by poorly designed installations and their physical environment. The visual inspections were concentrated on EMC and to the areas from where the power and communication cables entered the locations selected for study, by examining the areas where the sensitive equipment was placed.

Through the visual inspection it was found that there could be improvements in two problem areas, namely installations and instructions from the suppliers of equipment, which often result in wrong installations.

During this study, measurements were performed at sites which had extensive EMC and EMI problems. The measurements clearly show the erratic characteristics of the equipment and systems used in signalling and detector installations, mainly leading to EMC and EMI problems. For example, the measurements from detectors show that random transients appear even when a train is not present, and the measurements in the signal box show a completely different behaviour where the measuring equipment showed a reading of over -100 volts in a 27 V system. These measurements and the results from the subsequent analyses show EMI characteristics which are totally unexpected.

The detailed analysis of the failure reporting systems and databases shows that most of the failure causes are related to EMC problems. The fault reporting system is not configured to identify the failure causes as EMC or EMI problems. Therefore, this has to be investigated to identify the cause so that corrective actions can be initiated to restore the system to an operating condition.

The research study has helped in understanding the function of railway signalling and detector installations from an EMC and EMI point of view. The knowledge generated will be of assistance in designing new signalling and detector equipment which will have a higher level of reliability, leading to a smaller number of failures and EMC problems.

The study has made a contribution towards an understanding of the EMC and EMI characteristics of the signalling and detector infrastructure of the railway system. These characteristics often lead to failures resulting in train delays.

Keywords: Reliability of failure data, Railway systems, Signalling boxes, Detector systems, EMC, EMI, Analysis and Measurements of EMI.

LIST OF APPENDED PAPERS

This thesis includes an extended summary and the following five papers appended in full.

Paper A	S. Niska, Electromagnetic Interference: A major Source of Faults in Swedish Railway. Accepted for publication in the International Journal of Performability Engineering (IJPE), Vol. 5, No. 2, pp. 187- 196, January 2009
Paper B	S. Niska, H. Schunnesson and B. Nyström, Causes of EMC disturbance on the railway - a study of recurring faults in the signal box at Oxmyran Station in Sweden. Accepted for publication in the International Journal of Condition Monitoring and Diagnostic Engineering Management (COMADEM), 2008.
Paper C	Å. Wisten, S. Niska, J. Ekman, D. Björklöf and J. Delsing (2006). Experimental investigation of EM noise environment surrounding detector systems in Swedish railways. IEE Proceedings - Electric Power Applications, Vol. 153, No. 2, March 2006
Paper D	S. Niska and J. Ekman (2004). EMC Problems in railway Detector Systems. Nordic Rail, 12th Seminar on Nordic Railway Technique, Luleå., Sweden, 1-2 June 2004,
Paper E	S. Niska, Measurements and Analysis of electromagnetic interference in a railway signal box- A case study. Submitted for publication, 2008.

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INTRODUCTION

Background

The history of the railway in Sweden started in the middle of the nineteenth century. The first railway line was opened in 1856. When the train traffic commenced between Stockholm and Gothenburg in 1862 (on a line built by the Swedish Government), the journey took only 14 hours instead of three days by steamboat and stagecoach [1].

Since the start, the railway system has been upgraded continuously and it has been constructed to be in use for a long period of time. Many times the upgrading must be implemented without knowing what the future would look like. The electrification of the railway started in the late nineteenth century and involved a huge investment. This new technique was expected not only to function for a long period of time, but also to remain in such a state that it would function together with all the new equipment, communications and signals that would be developed in the future.

The Swedish rail network consists of approximately 17,000 kilometres of track, of which 80 per cent is administrated as the state rail network by Banverket (the Swedish Railway Administration) [2].

The European Rail Research Advisory Council (ERRAC) has set objectives for railway operation stating that the overall transport demand should grow by 40 per cent for passenger traffic and 70 per cent for freight traffic by 2020 compared with 2000 [3]. Banverket (the Swedish Rail Administration) has an overall maintenance strategy whose vision for the goals of maintenance activities is [4]:

- Maintenance operations shall lead to the achievement of established demands for reliability.
- The maintenance activities shall be a step in 'securing safety'.
- The cost-effectiveness of the maintenance activities shall be constantly improved.

With these demands in mind, knowledge and understanding of today's interruptions and faults in the railway infrastructure are important, as is awareness of the fact that acquiring this knowledge and understanding leads to more effective time for maintenance support personnel. A general trend towards increasing traffic flow, higher speeds, more trains per hour, longer trains and heavier axle loads demands more powerful engines and stronger currents in the supply lines. The complexity of the railway system increases when more and more electronics is used [5, 6, 7]. The environment of railway tracks is exposed to magnetic and electric fields from trains, the railway power supply systems, nearby electric power transmission lines [8], and other sources [9]. Consequently, the radiated and conducted electromagnetic emissions from railway systems are increasing over time [10, 11]. The combination of more sensitive electronic circuits [12], and stronger electromagnetic noise, containing higher frequencies, may make the railway system as a whole more sensitive [13]. Systems for traffic signalling are not only crucial for safe traffic, but also important for traffic efficiency. If anything goes wrong in the signalling systems, all the lights should switch to red, which is safe, but can cause delays in the timetables. Although traffic signalling systems have very high reliability, there have been unexplained phenomena, which may have been caused by disturbance from passing trains [14]. Because of very high goals for reliability, a continuous programme of work is going on, aiming at the highest possible security [15].

It is clear that the electromagnetic environment at the railway track is demanding and that electromagnetic interference (EMI) is likely to occur [13]. Electromagnetic compatibility (EMC) applied to railway traction systems covers a wide range of phenomena, such as inductive noise in parallel communication lines, impulse noise from lightning and traction transients, the production of hazardous voltages under step and touch conditions, and the appearance of stray current. The specific problems of interaction between power-electric-controlled rail traction drives, power systems and track signalling systems are important, since in-band harmonic interference current flowing in the signalling system can result in degradation of the system's performance, including, in the worst case scenario, unsafe failures [16]. Therefore, knowledge of how the railway system itself behaves is an important issue now, will be a major issue in the future, and will even lead to increased knowledge of EMC and EMC design in the railway [17, 18, 19, 20].

Research problem

In 0felia, the failure reporting system for the Swedish railway, fault categories like "no fault found" and "not able to detect" are significantly over-represented. It has been argued that the source of many of these faults is EM disturbances. However, other reasons for these faults are also possible, for example faults in the construction or disturbance sources that are unknown. The current lack of knowledge regarding EMC in the railway infrastructure hardly provides any guidelines either for the design and construction or for the maintenance of the railway system. A better knowledge and understanding of EM disturbance and EM compatibility are therefore required. This will facilitate the integration of maintenance needs arising due to EMC and related problems. This will also provide a basis for making trade-offs while improving design [21].

Research questions

Based on the above-mentioned research problem, the following research questions were formulated:

- What is the extent of EMC disturbance on the Swedish railway?
- What are the main causes of EMC disturbance on the Swedish railway?
- Could the cost for the maintenance support required to remedy the faults caused by EMC problems be traded off during the design and construction of electrical systems to minimise such EMC faults?

Purpose of the research

The purpose of this thesis is to study and explain the causes of EMC problems in electrical and electronic systems in the railway infrastructure, and also discuss how to use the knowledge of EMC problems in design and construction in future railway projects.

Scope and limitation

This research study deals with EMI problems related to railway infrastructure with special reference to signal boxes and detector systems.

The study does not cover any EMI problems on rolling stocks

THE SWEDISH RAILWAY SYSTEM

Railway systems

A railway system is a complex system and involves many subsystems. The subsystems that have been investigated in this thesis are the detector system, the power system, the train positioning system, a part of the signalling system and a specific subsystem, an RC circuit, which has been examined closely. The detector system that is described below is similar to the one at Sunderbyn and Notviken. The signalling system and RC circuit system described below are similar to the systems at Oxmyran and Öre Älv.

Detector system

The detector system is mainly used to uphold the safety of the track. This is achieved by monitoring the rolling stock. The detectors are located on the track and are in some cases even mounted on the rail. To uphold the safety of the track, different detectors give alarms when the signal is outside the defined levels. The specific detector systems that have been studied are the hot box, hot wheel, and flat wheel detector systems.

Hot box detector systems are used to ensure correct operating conditions through measurement of the temperature of the ball bearings. Hot bearings might jam, resulting in a possible derailment of the specific axle, personal injuries, and material damage.
Hot wheel detector systems measure the temperature of the wheel perimeter to detect falsely locked wheel brakes. Locked brakes can cause the same problems as hot bearings. Moderately higher temperatures can cause surface cracks that need to be repaired, while excessive temperatures can cause the outer ring of the wheel to detach, resulting in a possible derailment.

Flat wheel detector systems measure the vibrations in the rail when imperfect wheels give hard hits to the rail. A wheel flat arises when a brake locks a wheel and the wheel slides, locked, along the rail. Wheel flats can cause the rail to break, especially during colder periods.

For each alarm, the detector system notifies the Centralized Train Traffic Control (CTTC) office using a modem connection. The locomotive driver is then contacted by the CTTC and informed that there has been an alarm caused by his train and where on the train the problem is located. When receiving an alarm, the locomotive driver must stop the train at the next stretch of siding and make an ocular inspection. If the driver cannot find anything wrong, the train can continue. If the driver discovers damages, the specific wagon has to be disconnected and left at the siding. In the future, Banverket wants to be able to rely on the detector system so that the driver can automatically disconnect the indicated wagons at the next siding, without ocular inspections causing unnecessary time delays. Due to the many false alarms, the detector systems are currently not considered to be reliable.

Hot box detector

Hot box detectors measure the temperature on the box that contains the ball bearings for each wheel. To measure the bearings on each side of the axle there are two hot boxes, one on each side of the track. The boxes are galvanically isolated from the rail. Each box has an automatic opening that is controlled by a pair of axle detectors, see Figure 1. Four of the axle detectors are placed near the box and the other two are placed several metres away in both directions. The axle detectors that are placed further away register the presence of the train and open the lid of the detector box. The axle detectors close to the box activate an infra red (IR) sensor when a wheel is passing by. Between detector number 1 and 2 in Figure 1, the speed of the train is calculated. The third and the fourth axle detector do the same from the opposite direction. The analogue pulse, generated when a hot ball bearing is detected, is transmitted into the shed for analysis. The shed ground is connected with the return current rail (S-rail).

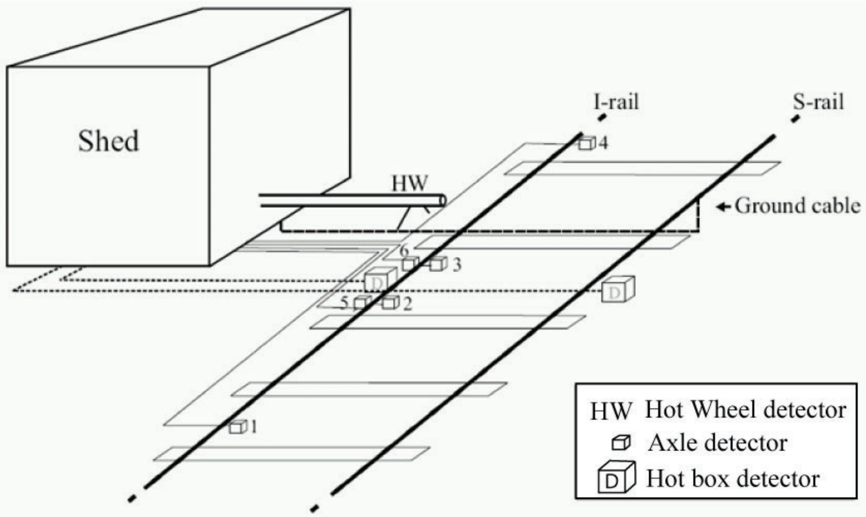

Figure 1 A schematic picture of the detector system at Sunderbyn.

Hot wheel detector

Hot wheel detector systems measure the temperature of the wheel's outer perimeter and have an axle detector that counts the number of the wheel or axle that is passing. If there is an alarm from a passing train, due to too high a wheel perimeter temperature, the detector calculates which axle is overheated. The detector system monitors the temperature of the perimeter of the wheel to avoid the contact surface being damaged. The wheel is painted with a special paint that flakes off when the wheel reaches the maximum allowable temperature. The driver can then make a visual inspection to see if the temperature has been high. The hot wheel detector uses an IR sensor that is placed in a tube going out from the shed. The temperature is measured on the outer edge (perimeter) of the wheel, since most of the brakes have brake blocks (brake shoes) that break through pressure on the contact surface of the wheel, see Figure 2. That means that the perimeter of the wheel becomes overheated if the brakes get locked. There are some locomotives that have disc brakes, but these are not common.

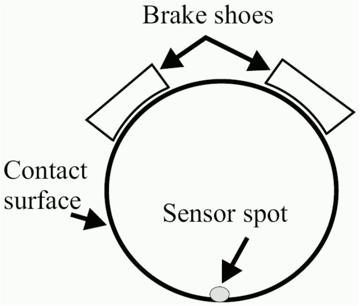

Figure 2 *A view of the wheel with the brake shoes and the spot where the hot wheel detector measures.*

Flat wheel detector

Flat wheel detectors measure the vibration in the rail that occurs when a flat surface on a wheel hits the rail over the detectors. A flat surface on a wheel appears when a locked wheel glides along and the wheel wears down at a spot on the wheel. According to [22], the rail-mounted strain gauges react to varying weights of freight equipment and sudden impacts caused by defects in wheels. Each gauge consists of two 350 Ω variable resistors. As the freight equipment passes over the gauges, their inherent resistance value changes, thus affecting the current flow through the circuit. Each set of gauges is connected to the input circuits in the module in the shed. The system measures the voltages across the gauge circuit as the wheel passes over the flat wheel detector system (the set of gauges), see Figure 3. The gauges are welded on both sides of the rail between the cross ties at specific locations along the rail's neutral axle. As a wheel passes between the ties, it applies pressure on the rail and bends it in a downward direction. As the rail bends, it distorts the gauges to varying degrees. The greater the distortion, the heavier are the loads from the rolling stock. The internal resistors of the gauges are mounted at a 45° angle to the rail. When a wheel enters the flat wheel detector system (the area between the gauges), those resistors which are mounted in parallel in the strain lines of force are compressed, while those which are mounted at a perpendicular angle to the lines of force are stretched. As the wheel moves across the detector system, the circuit shifts to maintain a constant voltage drop across the bridge dependent upon the weight of the rolling stock. When a defect rolls over the detector system, the strain forces increase proportionally to the degree of the defect and are picked up by the gauges. The bridge circuit is typically of the Wheatstone type, which requires a common source of electric current and a circuit to analyze the bridge voltage. The flat-wheel detector system therefore consists of four cables going between the detector system located by the rail and the analyzer unit inside the shed.

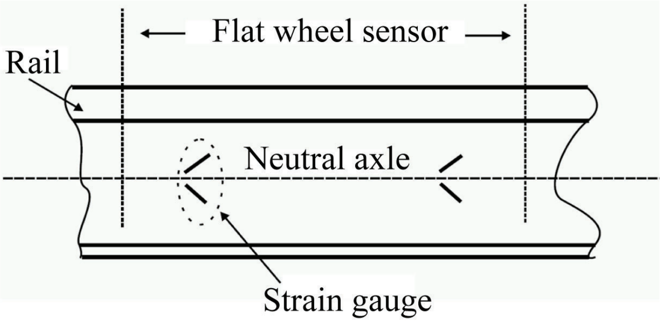

Figure 3 *Strain gauge configuration on the rail.*

Power system

In Sweden the building of the railway system began in the mid-nineteenth century. Electrification began in 1895, with DC (direct current) power, to meet the needs of the mining company, LKAB (Luossavaara-Kiirunavaara Aktie Bolag), located in the northern part of Sweden. This company transports iron ore from the mines in Kiruna and Malmberget to the harbours in Narvik and Luleå. A further set of demands from LKAB led to a change being made from DC to 16 kV AC (alternating current) with a frequency of 15 Hz. In the 1950s, the frequency again changed to 16 2/3 Hz, to bring it into line with the national electrical system, which has a frequency of 50 Hz [23].

Today the rolling stock has become heavier, with the axle load having increased from 22.5 metric tonnes to 25 metric tonnes. Furthermore, LKAB has now once again increased its demands by using axle loads of up to 30 metric tonnes [24]. Moreover, the power of the locomotive that is to pull such trains has increased to 10,800 kW [25].

The converters supply the railway system with 15 kV. The train uses the overhead catenary along the railway and the transformers help to transmit the current through the catenary system. The train obtains the current from the overhead contact wire and the return current is sent through the S-rail (continuous rail), which is used as the return circuit, back to the transformers along the track. The return current can reach several hundred amps. The S-rail is continuous along the track and is therefore ideal for use as a return circuit for the train power and for the current sent back to the transformers.

For the electric track there are two systems in use in Sweden: the booster transformer (BT) system and the autotransformer (AT) system.

Booster transformer system

The BT system is the most common system in Sweden. The ratio in the transformers between the primary side and the secondary side is 1:1, which forces the current to use the path through the transformers to the converter, and the current is therefore forced through the S-rail and cables. The transformers have been placed at an intermediate distance of 3 to 5 km, depending on the surrounding topography [26, 27], see Figure 4.

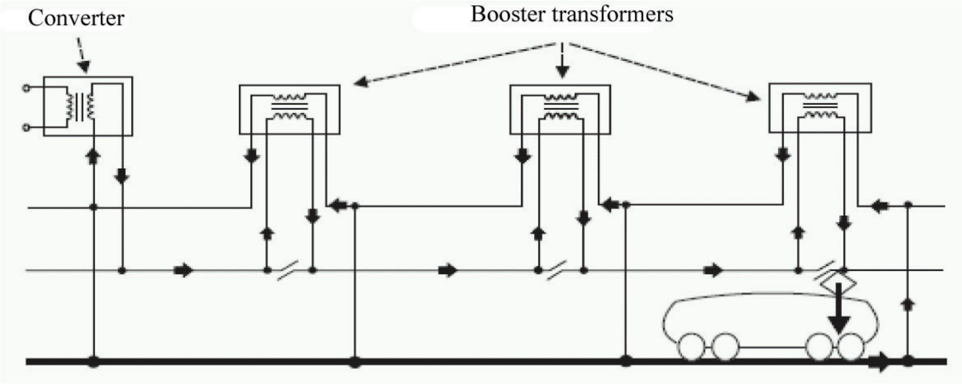

Figure 4 The current's path in the BT system.

Autotransformer system

The AT system uses 30 kV and divides the voltage in half in the transformers. The overhead contact wire has a 15 kV power supply and the return feeder, or negative feeder as it is called, has a phase different to that of the contact wire. The power of the return feeder is -15 kV, and it is therefore called the negative feeder. The output current from this system can be higher than that in the BT system. The AT system is used for tracks where more power, heavier loads or faster accelerations are needed. The return current is sent over the S-rail back to the transformers. The transformers can be placed at an intermediate distance of 10 to 20 km depending on the surrounding topography. The AT system has, compared to the BT system, a higher leakage of the return current to the ground [26, 27], see Figure 5.

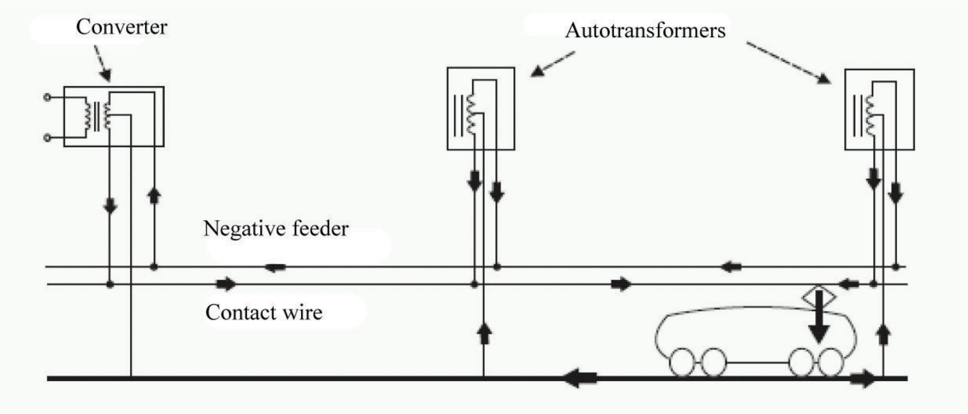

Figure 5 The current's path in the AT system.

Infrastructure systems

In addition to the high-voltage system used by the trains, the railway also uses low-voltage systems (< 1000 V, [28]) located in the same infrastructure. Examples of such systems are communication systems and detector systems that use 5 V DC.

The systems close to the tracks, e.g. signalling systems controlling the light signals for the locomotive driver, signals communicating the turnouts' position back to the CTTC office, and systems for reporting the position of trains along the track to the CTTC office, are all low-voltage subsystems. In the Swedish railway system, all these systems have traditionally been based on relay technology. To provide high reliability, the systems have a redundancy in every critical function.

The systems in the Swedish railway infrastructure are divided into three major subsystems based on the professional group responsible for the area of work covered by the subsystem, rather than the technical similarity of the components of the subsystem. The subsystems are:

- Electrical systems that deliver all the power to the stations, technical buildings or boxes. These systems transform the power from Banverket down to the required lower power and distribute it to the other subsystems.

- Signal systems making sure that all the signals in the railway system and in the infrastructure are working and checking that the right signals are being sent for different functions in the railway.
- Telecommunication systems, the purpose of which is to make sure that the communication from stations, technical buildings or boxes is functioning properly.

Electrical systems, signal systems, and telecommunication systems are mostly contained in the same physical location, e.g. a signal box, technical building, etc. The systems controlled by a specific professional group (electrical systems, signal systems, or telecommunication systems) are kept separate from those of other professional groups in different racks in a room or in different rooms. In larger technical buildings where several systems are located, not only are the systems of each professional area kept in separate rooms, but the equipment is also separately grounded. The location of the equipment belonging to the different professional areas is decided by the professional group in question and no thought is given to the interference level or the sensitivity of the installed equipment.

The design and construction of the grounding systems have varied over time. The telecommunication system has a separate ground, consisting of a loop of copper wire in the ground, around the building, and an iron bar connected to the loop to obtain a ground potential. The other systems use the S-rail as their ground potential. The old regulations dictated that only the S-rail was to be used as the ground. There also used to be an instruction stating that the grounding should be separated inside the buildings, but then reconnected before using the S-rail as the ground.

Train positioning system

The information as to where the trains are on the track is provided by the train positioning system. The train positioning system uses the two rails on a track, the common rail (S-rail) and the information rail (I-rail), to locate the position of the trains. The S-rail is continuous and is grounded. The I-rail, on the other hand, has galvanic gaps with an insulated block joint between different sections of the rail. Every other I-rail section has a positive potential (7 V) and the other sections have a negative potential (-7 V). The gaps isolate each section of the I-rail with a different potential. When no trains are on the line, there is a negative or positive potential between the rails, see Figure 6.

When a train moves into a new section (over a gap to a new rail section on the I-rail), the potential for the sector drops to zero, since the wheels of the train connect the two rails. The relay in this section holds the voltage drops indicating where the train is on the track.

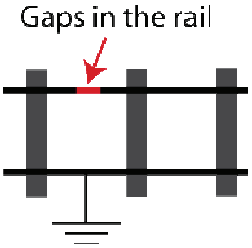

Figure 6 *An illustration of the train positioning system, where one rail, the information rail (I-rail), has galvanic gaps with an insulated block joint to split the rail sections. The other rail, the common rail (S-rail), has no gaps.*

Signalling system

The signalling system in the railway infrastructure ensures the safe operation of rolling stock, for example by providing lights for the locomotive driver, the positions of turnouts, and the localisation of train positions on the track to prevent the collision of rolling stock.

A "station" is the location of one or several turnouts. A station on a single track makes it possible for trains to meet and overtake, see Figure 7.

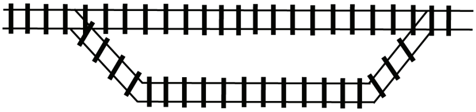

Figure 7 On a single track a station is used for meeting and overtaking trains.

The equipment for the signal system and other equipment that is needed by the track or the station are protected in a signal box located near the track. The signal boxes at Oxmyran and Öre Älv, for example, are 3 x 5 metres. Besides the signalling system, the signal box also contains electrical and telecommunication systems. The electrical system delivers power to the other systems, while the telecommunication systems are used for communication, e.g. a telephone, modem etc.

The signalling system controls the safety and informs the locomotive driver and the train traffic controller (who is located in a CTTC office) of the situation on the track. The detailed information is communicated from signal boxes that receive data by wires, from the signalling lamps, turnouts and positioning systems along the track. It is therefore essential that the equipment, cables and wires close to the track should send the right information and provide accurate signals from every position along the track.

Oxmyran Station

When a train enters Oxmyran Station from the south from Brattsbacka, the relay on section SIa is grounded and the potential drops to zero. The train positioning system indicates that there is a train in this section, see Figure 8.

When the train continues into the first section of Oxmyran Station, from the south, the potential of the S1a relay drops and affects the RS1 relay so that the RC circuit receives power, see Figure 9.

When the train moves over to the next section and the potential of the relay S1b or S1c, depending on the direction of travel, drops to zero, this indicates the presence of the train in this section. The RS1 relay is still pulling and makes sure that there is power to the RC circuit, see Figure 10.

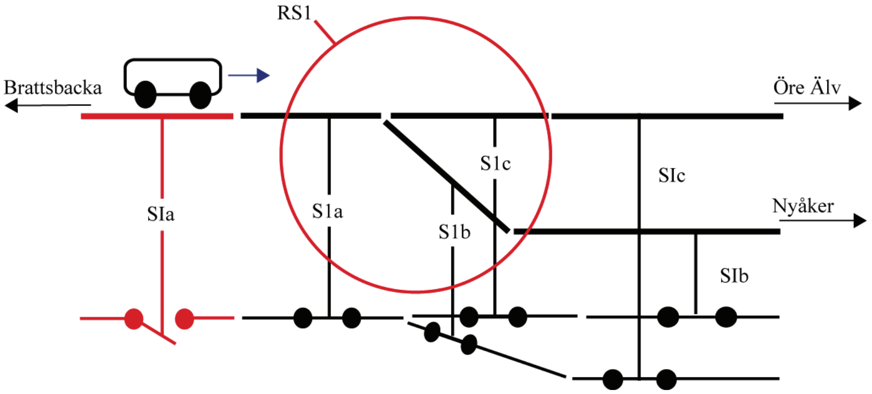

Figure 8 *The state of the train positioning system when a train is entering Oxmyran Station from the south via Brattsbacka; the potential of the section (relay) before the station has dropped to zero.*

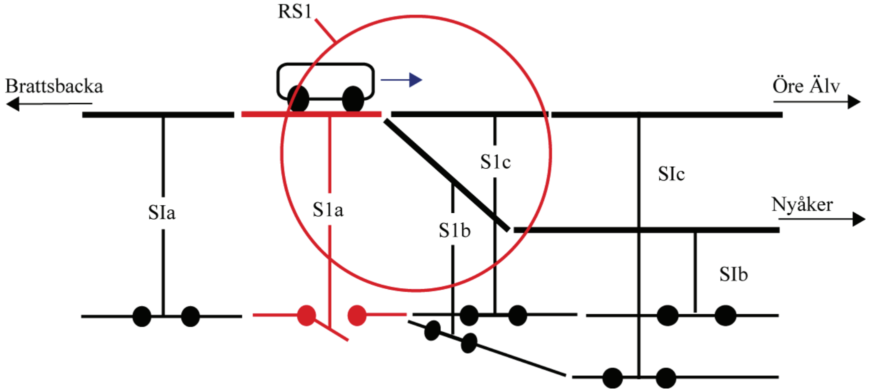

Figure 9 *The train is at Oxmyran Station. The potential of the relay S1a has dropped and therefore influences the RS1 relay.*

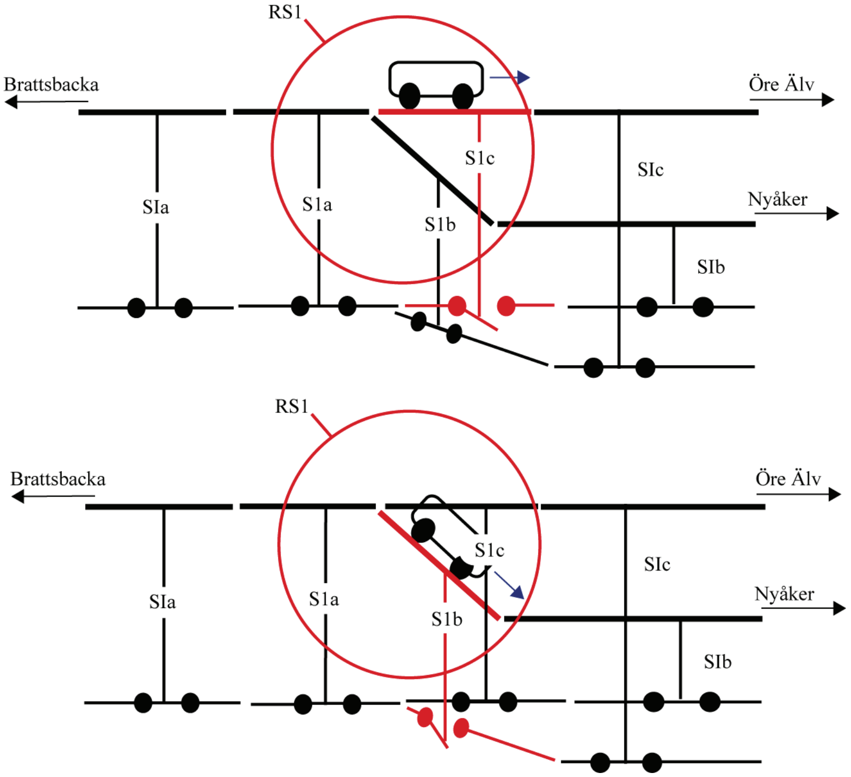

Figure 10 *The train is at Oxmyran Station and the potential of the S1b or S1c relay has dropped, depending on which way the train is going. The RS1 relay is still activated by the presence of the train at the station.*

When the last wagon of the train leaves the station, or, in this case, when the last wagon leaves the station section indicated by the S1a, S1b, or S1c relay, the power of the RS1 relay drops immediately. The next section SIb or SIc, depending on which way the train goes, indicates that the train is now in this section, see Figure 11.

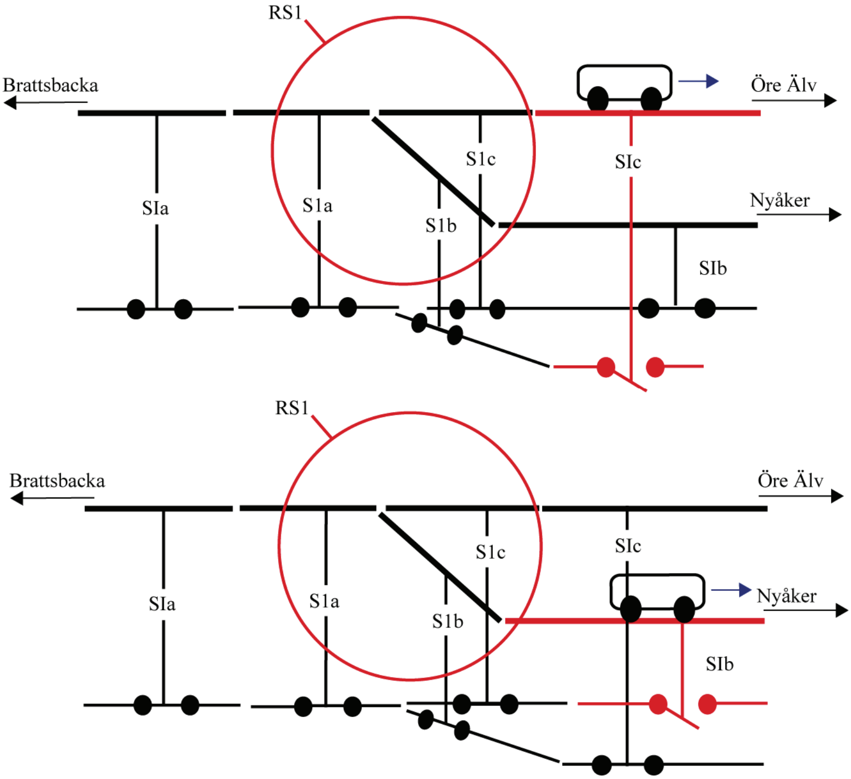

Figure 11 *When the train leaves Oxmyran Station and the potential of the relay SIb or SIc drops, depending on which way the train runs, this indicates that the train has left the station. The potential of the RS1 relay drops too.*

RC system

The relays are placed in a chain and are dependent on each other. Every relay that is in a chain is to make sure that every signal that has to be active receives the power in the same chain. When the RS1 relay cuts the power to all the other relays after it in the chain, these relays do not have the time to switch back. This power is supplied instead by the RC circuit, which can hold the power within a few milliseconds, and that is enough for the rest of the relays in the chain to switch back. If the RC circuit is broken, there will be no power to be supplied to the relays after RS1 in the chain and these relays cannot pull back, and consequently the system indicates that the train is remaining at the station. The RC circuit investigated in Paper E, has this sole function of supplying power to the relays and looks like that shown in Figure 12.

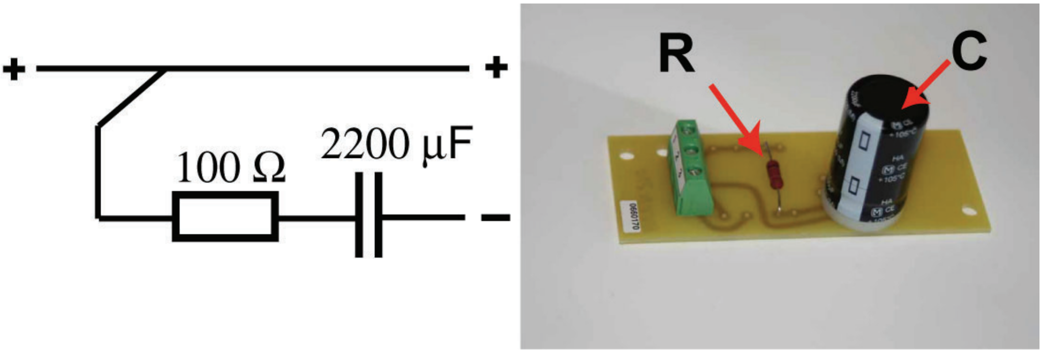

Figure 12 *The circuit is an RC circuit, has a resistance, marked R in the figure and photo, of 100 Ω and is connected in series with a capacitor, marked C in the figure and photo, of 2200 µF.*

The circuit is a printed circuit card with a resistor (R) and a capacitor (C), an RC circuit. The voltage level for the RC circuit is 27 V. A rectifier converts the power from AC 220 V to DC 27 V and delivers it to the system where the RC circuit is.

There is a fuse between the rectifier and the printed circuit card. The printed circuit card is connected on both sides with a 0.75 mm^2 solid wire. This wire goes to a negative wire loop joining other printed circuit cards that have the same function (but in different systems) and is grounded, see Figure 13.

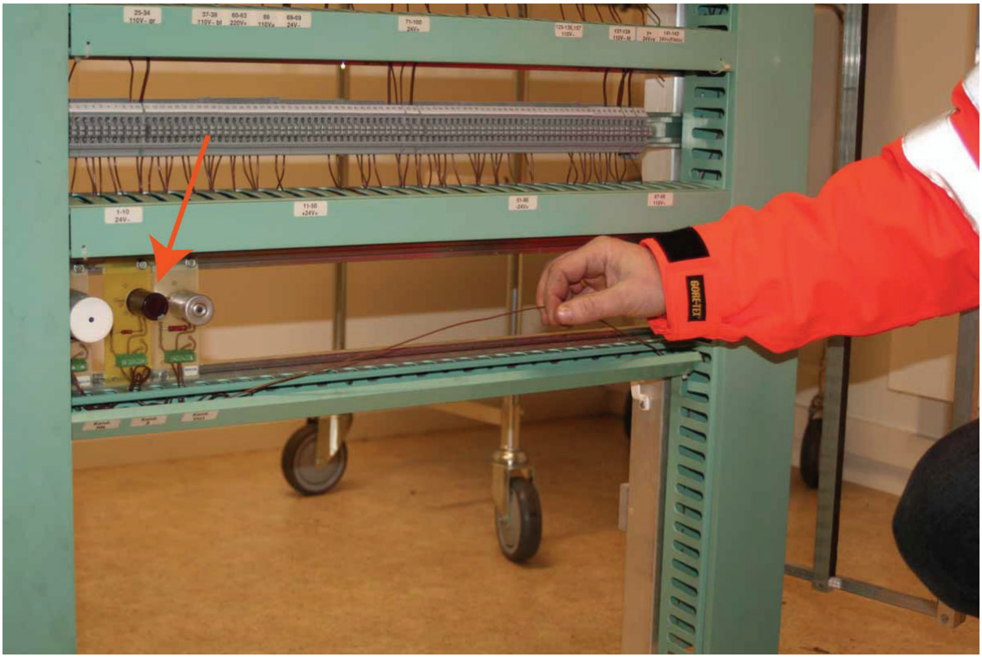

Figure 13 *The placement of the RC circuit in the rack (the middle RC circuit in the square indicated by the arrow) and the wire from RC circuits that have the same size both on the negative bound and on the voltage side. The area of the solid wire is 0.75 mm^2.*

At the station there are electrical circuits, computer systems like a PLC (programmable logic controller), and electrical relays for the equipment in the area which the station controls. The equipment that must be located close to the track is protected in boxes. The boxes are connected to the signal box via shielded twisted pair cables.

Between the stations the electrical signals are sent through a belted and shielded cable with 27 twisted pairs of copper wires that connect to the next station. All the systems, namely the electrical, telecommunication and signalling systems, use this cable for communication.

Bigger stations gather the signals and send them to the CTTC office via an optical cable.

ElectroMagnetic Compatibility (EMC)

EMC is “the ability of a device, unit of equipment or system to function satisfactorily in its electromagnetic environment without intruding intolerable electromagnetic disturbances to anything in that environment” [29].

The study of EMC is a "young old science". It started when the problem of radio frequency interference (RFI) arose nearly 100 years ago with the first use of radio waves as a communication medium. This makes it a rather old science, but in the last 30-35 years the progress in numerical computation has allowed scientists and engineers to propose models for the physical phenomena underlying this interference. Models have also started to be used to understand and visualize these phenomena better and to increase the knowledge of the effects of interference [30].

The EMC Directive came into force on 1st January 1992, and replaced all the existing legislation for the electrical and electronic equipment concerned, including fixed installations, from 1st January 1996 [31]. In 1996, CENELEC, the European Committee for Electrotechnical Standardization, an international association, published a corporate plan for 1996-2000 entitled Moving into the Twenty-first Century. An updated and more condensed plan called European Standardization in the Field of Electrotechnology was published by CENELEC in 1998 [32].

Electrotechnical standards are currently being developed in Europe, with the result that there exist no real technical barriers to trade due to electrotechnical standards in the European Economic Area.

Every producer, importer or seller of electrical equipment in the European Union (EU) has to test their products according to a specific standard, the European Standard (EN), before their products can be sold. The final responsibility for testing products lies with the product owner.

The product has to be authorized and marked with CE. With regard to electrotechnical equipment, the CE mark, apart from showing that the safety demands have been met, has to cover EMC approval. This means that the equipment is not allowed to disturb and/or be disturbed by the surroundings.

There are two categories of tests for EMC, the emission and the immunity test. The emission test measures the radiated emission within a frequency band of 30 MHz to 1000 MHz, and the conducted emission within 150 MHz to 30 MHz [33]. The immunity test is to verify that the product can handle, for example, the switching of electrical outlets, as well as verifying immunity to slow and high energy sparks that resemble current pulses from a stroke of lightning.

Standards describe how the testing is to be performed and the demands that apply to the product, e.g. the EN 50082-1 standard [34], which describes the general demands for immunity concerning equipment in houses, offices, stores and similar environments. The EN 50121 standard [35], is for railway applications.

The problem of EMC on the railway is, however, not solved by the EN 50121 standard.

METHOD

In general EM disturbances in the railway infrastructure are a very complex problem, and consequently the selection of the research methodology was a challenging task due to the great difficulty of narrowing the choice down to one or two established methodologies. Therefore, the approach adopted to obtain answers to the research problems consisted of many established methods used in engineering research. The results that are presented in this thesis are based on the following methods:

- Analysis of information from Banverket's fault reporting system “0felia”.
- Analysis of information from Banverket's system for traffic information (TFÖR).
- Analysis of information from the Swedish national strike statistics.
- Interviews with technicians responsible.
- Interviews with system and circuit suppliers.
- Interviews with installation supervisors.
- Interviews with maintenance personnel.
- Visual inspection on site.
- Measurements on site.

The railway sites which were investigated in detail are given in Table 1 and marked on the map in Figure 14. The locations were selected based on different criteria, namely different types of construction, traffic, etc. Visual inspection was made for different constructions or where problems had been reported which were likely to have been caused by EM field disturbance. The locations for in situ measurement were selected based on well-known problems as indicated by maintenance staff and the failure statistics reported in 0felia.

Table 1 The locations and types of construction where measurement or visual inspection was performed in this investigation.

Location	Construction	Measurement	Visual
Gransjö	Detector box		X
Kiruna	Converter		X
Kiruna	Technical building		X
Krokvik	Detector box		X
Notviken	Detector box	X	X
Oxmyran	Signal box	X	X
Sunderbyn	Detector box	X	X
Vassijaure	Detector box		X
Öre Älv	Signal box	X	X

Figure 14 Map showing the location of the sites that were investigated during this project.

Analysis in 0felia

Problems related to EMC in the railway should in one way or another be entered into the railway fault reporting system, 0felia. By analyzing these reports, the extent of EMC-related faults can be estimated. 0felia is a failure reporting system used by Banverket to report failures in the infrastructure [36]. When a fault appears in the Swedish railway infrastructure, it is indicated in the CTTC office by alarms from the signal and detector systems. The CTTC office staff then initially report the occurrence of the fault in 0felia, after which they call the contractor's contact person, who in turn instructs personnel to remedy the fault. Maintenance personnel receive a work order to check the alarm and perform repair work, if necessary, and then drive to the fault location. After the visit on site and the repair, the maintenance workers must report back to the CTTC office, which then finalizes the report in 0felia.

Visual inspections

To evaluate weaknesses in the construction or EMI protection in electrical and electronic systems, visual inspection was performed on sites that were selected on the basis of the construction type, see Table 1, and the failure statistics for the years 2005 & 2006, see Table 2.

Table 2 *Numbers of faults on the Swedish railway in 2005 and 2006. The table shows four separate categories of EM disturbance faults. The data have been taken from 0felia.*

Category	Year	
	2005	2006
Interruptions	11463	10374
Not able to define	16412	13534
No fault	6984	10366
Short circuit	4355	4198
Total no. of possible EM faults	39214	38472
Total no. of faults	57486	53677
Percentage	68	72

The visual inspection was initiated by checking every cable visually at the selected site and by examining where these cables entered the inspected installations. The barriers in the construction and the shielding of the cables were investigated, as well as how sensitive equipment was placed in relation to the other types of equipment. The barriers between the different types of sensitive equipment were checked, as well as the solution chosen for shielding the complete construction from the railway track nearby. Visual inspection was also made to examine the effectiveness of the grounding system for the inspected signalling installations and other electrical and electronic installations.

Measurements

The major aim in this thesis is to investigate EM disturbances, radiated or conducted emission from moving trains or from other sources, and to explore whether these emissions could disturb the detector or signalling systems. An additional aim is to suggest some approaches to characterize the EM environment at a railway track. One approach is to use existing standards like EN 50121 [35] for characterization purposes. However, for a detailed study of the EM environment close to the detector system at the railway, the existing standards are not sufficient. For the purpose of the investigation, additional methods have to be used and proposed. Therefore, a brief review of the EN 50121 standard and other methods feasible for EM characterization is presented.

The European standard EN 50121 describes in detail the measurement of radiated emission from a passing train. For instance, the measuring antenna should be placed at a distance of 10 m from the centreline of the track and at a height of 1 to 3.5 m above the top of the rails, depending on the receiving antenna. Furthermore, the standard states that it is not necessary to examine both sides of the locomotive, even if the locomotive contains different apparatus on the different sides. In the standard setup, a fixed antenna position is used to record the EM field from a passing train. There are limitations to how the available instrumentation can measure the emitted EM spectra. To obtain a good characterization of the EM environment, it is obvious that the measurements will be very lengthy. This is because repetitive measurements are required for the different levels of power usage of the locomotive, different speeds etc. Furthermore, due to the limited scanning speed of a spectrum analyser, there is clear evidence that this type of approach can miss spurious signals. This problem has been addressed by York EMC Ltd [37], which uses several spectrum analysers in parallel (up to 8 analysers) to speed up the measurement of the EM spectra [38, 39]. The York setup is shown in Figure 15 and Figure 16.

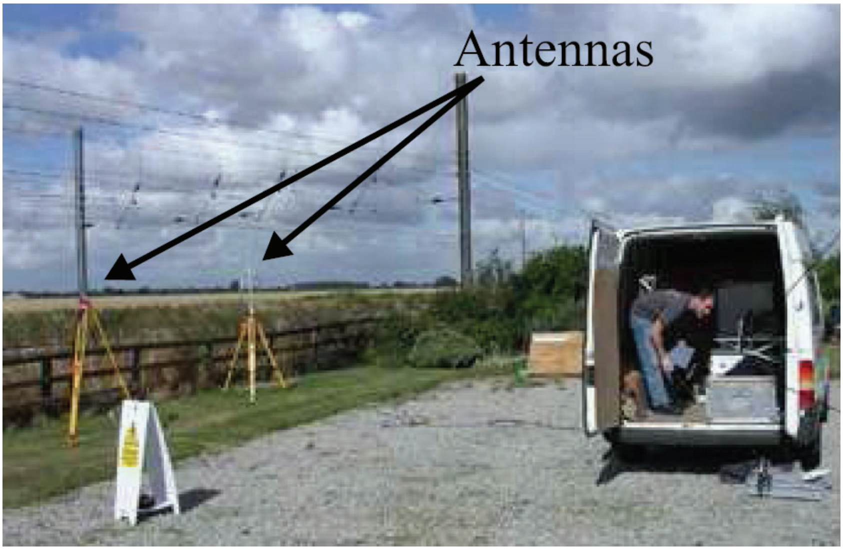

Figure 15 Overview of standard measurement set-up with several antennas. Figure from [37].

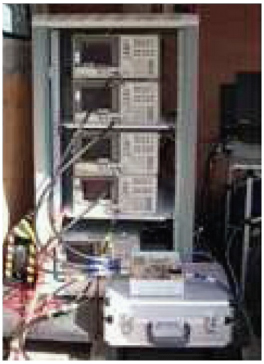

Figure 16 Overview of standard measurement set-up with multiple spectrum analysers for radiated emission. Figure from [37].

A completely different solution to the problem of measuring the EM environment has been proposed by Wisten and Mäkikaltio [40]. Here the measuring antenna is placed on a wagon in the train, see Figure 17. Thus it is possible to record the EM spectra for many different driving conditions from the point of view of load, speed and power usage. It is also possible to take the variation in ground conditions into consideration. One drawback of this method is, however, that it is not possible to determine the EM background.

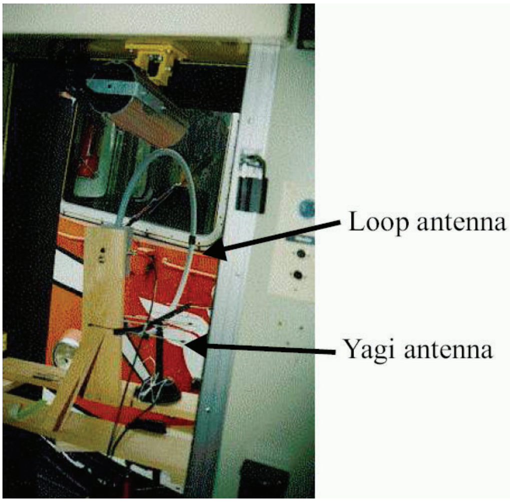

Figure 17 Antennas mounted in a wagon for measuring along a moving train [40].

Figure 18 shows a typical E-field spectrum, measured with the improved method proposed by Wisten and Mäkikaltio. It is obvious that EM energy above the background noise is present up to 500 MHz.

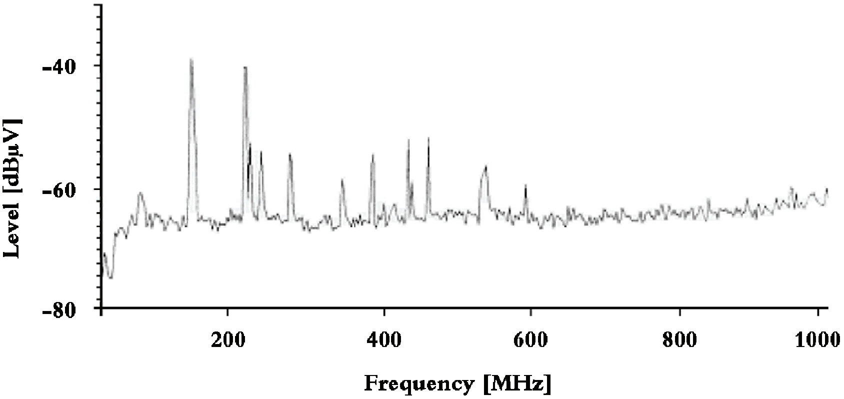

Figure 18 A typical E-field spectrum around a moving train. Frequencies up to 500 MHz have energies visible above the background noise.

Characterization of the EM environment at the detectors

There is a phenomenon called "ghost train" present at the measurement sites. The phenomenon occurs when the axle detector that counts in the numbers of axles and the axle detector that counts out the numbers of axles do not provide the same number, necessitating more detailed measurements than either of the above methods can provide, to analyse where the disturbance field enters the equipment in the shed. To avoid disturbing the detector system in operation, two additional measurements were performed. First, a measurement layout as illustrated in Figure 19 and Figure 20 was constructed using a similar type of cable to that used in the real detector system [41]. By measuring time series of noise data, using a high speed sampling oscilloscope, disturbances that make their way into the cabling of the detector system could be monitored. Secondly, measurements directly on the evaluation units inside the shed were performed. This gave indications of EM disturbances that could be conducted into the shed, see Figure 1, and potentially disrupt the operation of the detector systems.

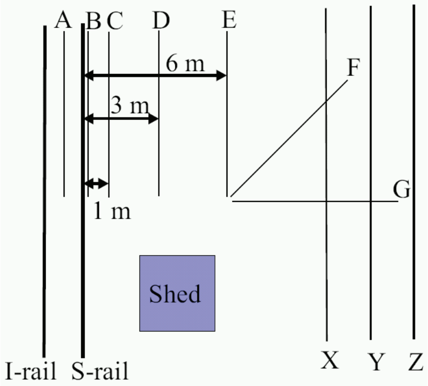

Figure 19 *The measurement location at Sunderbyn, with the rail, measurement cables (A–G) with F at 45° and G at 90° from the rail, and power lines (X–Z) from Vattenfall (a Swedish power distributor).*

For both measurement configurations, the measuring instruments were placed inside the shielded shed and the cables connecting the parallel cable setup penetrated a board of metal that covered the window opening.

To verify that the cables, RG223 inside and outside the shed connecting the two measurement setups, were not picking up disturbances, each RG223 was terminated in its characteristic impedance (50 **Ω**) and the signal levels were recorded. This simple test showed that no train-induced electromagnetic disturbances could be attributed to the instrumentation setup. Paper C details the measurements performed using this measurement configuration (see Paper C for details).

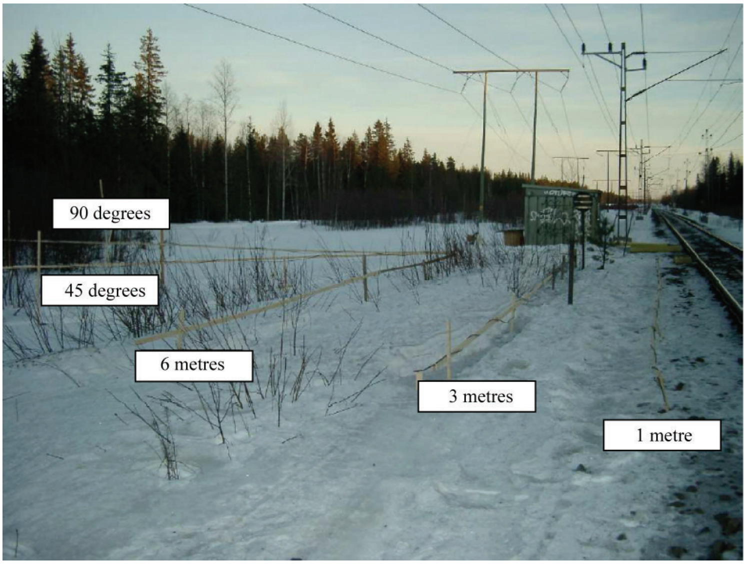

Figure 20 The set-up of the parallel cables at Sunderbyn.

Characterization of the EM environment at the signal station

For the purpose of characterization of the EM environment at a signal station, the signal station at Oxmyran was selected. This was mainly due to fact that this particular station has a large number of unexplained EM faults. Since the problem in the signal station at Oxmyran was mainly from a single RC circuit, the measurements done must be adaptable to the circuit. Therefore, a laptop computer and an NI USB-6251 DAQ (data acquisition) unit from National Instruments were used, see Figure 21. To control the measurements and collect the data from the DAQ, the software LabView from National Instruments was used. The probe measured voltages over the RC circuit. The DAQ unit had an input span of -10 V to +10 V and could not measure the 27 V DC that is supplied by the rectifier to power the RC circuit. Therefore, a probe that damped the signal by 10:1 was used to facilitate measurements with voltages up to 100 V. All the data presented in Figures 30-33 have been multiplied by 10 to restore the correct voltages. To start the measurement, the trigger level was set to 3 V, thus starting the recording every time the 30 V level was reached over the RC circuit. Levels below 30 V are common voltages for the system and do not cause any damages to the RC circuit, as the resistor and capacitor are specified for 64 V.

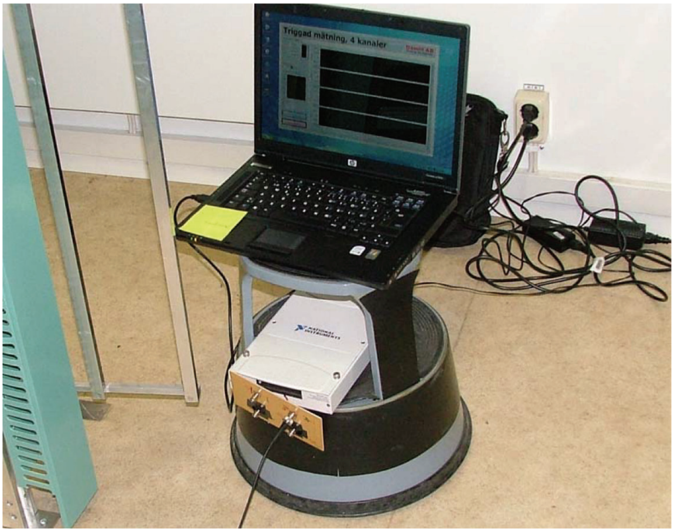

Figure 21 *The set-up during the measurements at both Oxmyran and Öre Älv.*

Two DAQ units and computers were used, with one set of equipment located at Oxmyran and the other one at Öre Älv, see Figure 22. Both the units were tested in the laboratory before the site test, to verify that they showed the same values from the same source and behaved in a similar way. They were checked with a Kiethley 2400 SourceMeter. To verify the function of the measurement programme on site, it was periodically tested by a measure every time the computer clock changed over to a new date. No train was passing at this time.

Figure 22 *The main railway line from Vännäs to Oxmyran via Öre Älv and over Nyåker, and further south to Brattsbacka. The new track that was built in 1995 between Öre Älv and Oxmyran is marked as a straight black line between Öre Älv and Oxmyran.*

RESULTS AND DISCUSSION

Analysis of fault statistics

To report failures in the infrastructure, a failure reporting system named 0felia is used by Banverket [36]. When a fault appears, it is indicated in the CTTC office by alarms from the signal and detector systems. The CTTC office staff then initially report the occurrence of the fault to 0felia, after which they call the contractor's contact person, who in turn instructs personnel to remedy the fault. After the visit on site and repair, the maintenance workers must report back to the CTTC office, which then finalises the report in 0felia.

In 0felia there is no specific category for EM failure. Since it is very difficult to designate EMC as a failure source and since the time for repair and evaluation is very limited, EMC-related faults will fall under other categories in 0felia. The possible codes in 0felia that may contain EM faults are: "interruptions", "not able to define", "no fault" and "short circuit". All these categories would include faults that occur due to EMC problems like EMI, EM disturbance or unknown electrical strain.

The argument in favour of the assumption that most of the faults in the above categories are EMC-related is that it has not been possible to find any software problems that have locked the system or any mechanical influence that has initiated the fault. If there had been a bug in the software, the system would have been locked every time the system was in the same state. If there had been a mechanical influence, there would have been signs of damage after the mechanical hit. Instead the electronics have for some reason been locked or put out of order and the fault has been fixed by resetting the system or replacing the faulty component. There has been no fault in the system function after the reset, which indicates that the source of the fault is EMI. In Table 2 it can be seen that the faults due to EM disturbance can be as high as 70% of all the faults reported in the Swedish railway system. Furthermore, even if all these faults are not due to EM disturbance, it cannot be excluded that EM disturbance is most likely a significant cause of faults in the Swedish railway system. Furthermore, it is also interesting to note that 70% of the faults in the railway system today have an unknown cause.

Visual investigation of installation sites

A variation in the building standard was invariably noticed during the investigation of installation sites. An interesting observation during the investigation of the sites was that EMC and related problems were not considered or prioritized while designing and building the constructions and installing equipment. However, it was noticed that, with the passage of time, the design and building of constructions have been improving increasingly and greater and greater focus has been placed on EMC and related problems. Nevertheless, there are still shortcomings in design and constructions from an EMC point of view. It is difficult to determine whether this is the result of a lack of information, task priority criteria or understanding of how important it is to install the electrical and electronic equipment in the right way.

For the detector system at Sunderbyn, a shed has been built to house the electronics taking care of the detector signals and the communication with the driver and the control centre. The shed is made of wood with a metal coating and has been placed on a foundation of concrete. The metal coating is not EM-protected or grounded in a satisfactory manner. The problem is that the ground of the shed is connected to the S-rail, where the return current in the AT system runs. The detector boxes are also connected to the S-rail, and the detector box cable shield has been taken directly into the shed (without filtering the EM noise). There is no other ground for the investigated shed.

Other important observation is that, instead of using the shield on the cable that is connecting the detector system to the analysis unit, the ground is connected to the cover of the box using a wire inside the cable, see Figure 23. This setup allows transients which exist on the S-rail and/or which are coupled to the detector box cover to be conducted directly to the analysis unit inside the shed. By using the cable shield as the ground conductor and by connecting the shield to the grounded exterior of the shed using through-put plates, the problem of directly conducted transients would be solved.

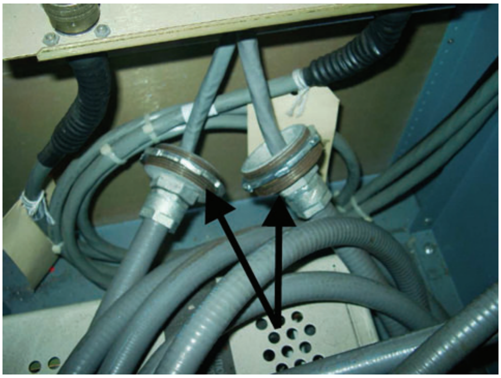

Figure 23 The shield of the cable from the hot box detectors is not in use.

The same issue arose when investigating the technical building in Kiruna railway yard, where problems were found with wrongly mounted cables entering control cabinets. Figure 24 shows an example of incorrect mounting in an advanced EMC-protected cabinet. Here no attempt was made to connect the cables correctly to the cabinet when they entered the bottom of the box, and the cables' shield was not connected anywhere in the cabinet. Instead, the filter for the cables and wires was simply thrown on the floor inside the cabinet. This shows how the use of expensive and advanced EMC-protected cabinets is meaningless if the installation is not performed correctly.

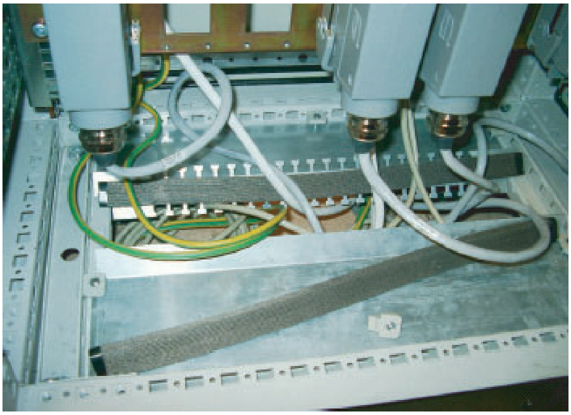

Figure 24 An intake of cables into an EM cupboard, where the incoming cables are not connected to the ground.

As mentioned in [42], many installations in the railway system are not performed according to the regulations. These deviations affect the EM environment for railway systems, and post-installation fixing has to be carried out to save the installed system, see for example Figure 25.

Figure 25 *A filter, indicated with an arrow, is mounted on an incoming signal. This filter has been mounted after the system started to be used.*

A general solution would be to separate the equipment into different zones, based on the sensitivity of the equipment, instead of separating it according to the professional area in question (telecommunications, signals and electric power supply), which is the common approach today for railway infrastructure. Equipment with similar sensitivity should be placed in the same zone. Between every zone there have to be barriers with filters. The number of zones depends on the variation of the sensitivity levels of the subsystems in the construction, as illustrated in Figure 26. It is also important that the cables and wires from different zones should be separated and not mixed up.

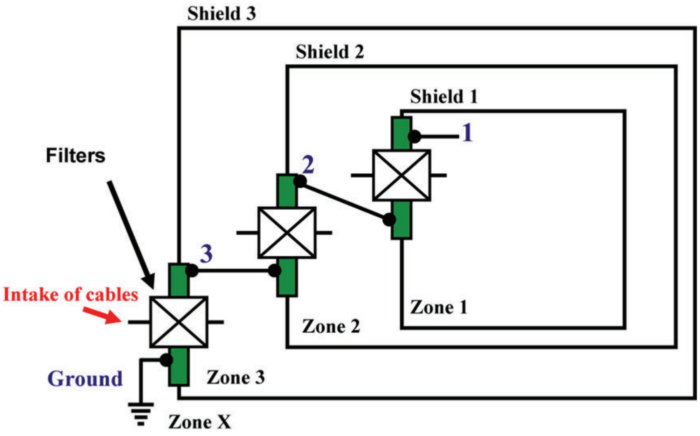

Figure 26 *Design of buildings, huts or cabins involving different zones, each of which has a specific level of allowed EM fields and cables which enter every zone through a filter.*

Utilising a grounding system that influences every subsystem is another important issue that must be considered. The ground used by the Swedish railway system is the S-rail, which is a solid and good potential, and the rolling stock uses the same rail as a return connection for the current in its power system. In general EMC problems start when electronics enters the same systems. Adequate filters can perhaps reduce the problems, but more knowledge and understanding of the railway system are required.

Detailed site investigation and measurement

Sunderbyn and Notviken

The results of the measurements on the flat wheel detector at Notviken show high transients when a train is present, see Figure 27. At Sunderbyn, on the other hand, a high transient occurred when no train was present. The recorded transients were saturated at ± 5 V, which was the limitation of the measurement system, see Figure 28. The exact location of trains on the stretch and the distance to the measurement location could, however, not be verified.

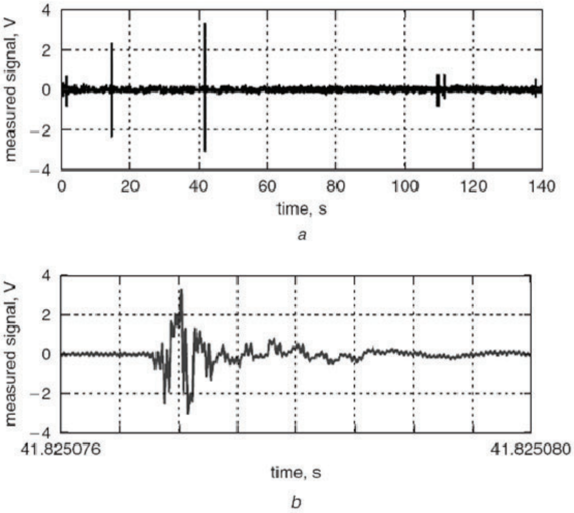

Figure 27 (a) Signal measured on the flat wheel detector at Notviken. (b) Close-up for the transients.

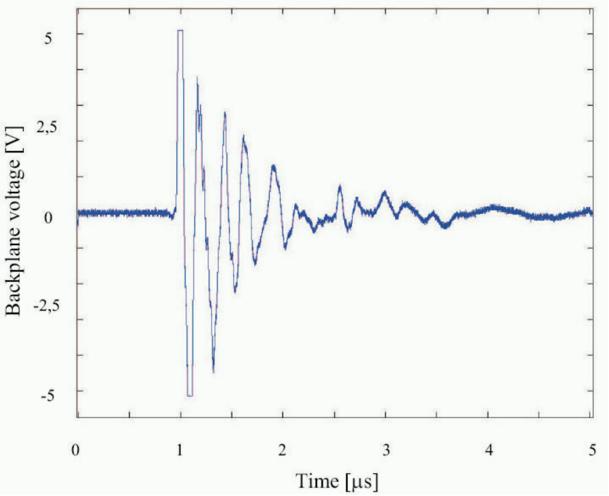

Figure 28 *Transient measured on the backplane inside the shed of the analyzing unit at Sunderbyn. The extremely high amplitude could not be registered by the measurement equipment.*

As a method of analysis, leaky dummy cables that could receive radiated noise were set up in order to separate radiated electromagnetic emissions from conducted noise. The measurements clearly show that electromagnetic emissions from the line–pantograph system, electric discharges, light arcs at the contact line and high-frequency emissions from the engine, when trains are passing, are not a direct threat to well-built and properly installed detector systems [43]. There are alarmingly high voltage peaks which have very short rise and fall times (~10Vpp/20 ns), and which do not necessarily occur when a train is close. These peaks are of the same size as the detector signals, and may generate malfunctions or indicate the presence of ghost trains. The sources of these voltage peaks are so far unknown. One hypothesis is that they occur when the engine enters or leaves isolated sections of the contact line.

Oxmyran and Öre Älv

To obtain an overview of the problems at Oxmyran and structure possible sources of the fault, a cause-and-effect diagram was made, see Figure 29. Every component in the diagram could influence and be a possible source of EMC failure in the infrastructure and in the signal box.

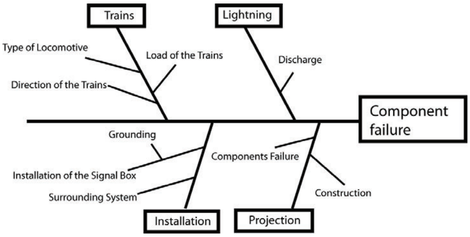

Figure 29 *Cause-and-effect diagram of possible error causes at Oxmyran.*

Lightning

Of the 35 RC circuit faults reported in 0felia during the period from 1 January 2001 to 1 May 2007, 13 reports have been filed stating the cause as “thunder”, see Table 3. For this to be the cause, lightning has to hit or discharge close to the railway infrastructure. After the discharge, a train has to pass the location in order to detect the failure, alarm the CTTC and generate a report in 0felia.

To verify the “thunder” causes reported in 0felia, the Swedish national strike statistics were used [44]. The accuracy of this discharge information is +500 - 1000 m. To be a possible cause, the dates and times that have been reported in 0felia should agree with the dates and times of the discharges, from clouds to ground.

The analysis shows that, out of the 35 reported faults, there were six occasions on which the location of the lightning strike was within a 25 km radius of Oxmyran. Five of these faults were reported as "thunder" and one as "uncertain electric disturbance". The time between the lightning strike and the alarm being triggered by a train passing Oxmyran was between 40 minutes and 3 hours and 36 minutes.

If the lightning strike is to be the fault cause, the alarm must be triggered by the first train passing Oxmyran after the lightning strike. According to the traffic control for trains passing Oxmyran, several trains passed between the time when the strike was registered and the time when the alarm occurred. Only on two occasions, out of six, was the alarm triggered by the first train that passed after the lightning strike. Only on these two occasions was it possible that a discharge, "thunder" or lightning could have caused the alarm.

Furthermore, if a discharge or strike was the cause, it would be reasonable to assume that the energy from a strike should affect more than one circuit or item at the station, and that more circuits should have been damaged at the station.

To conclude, only 2 out of 13 reported faults due to lightning in 0felia could be correct. Moreover, for the remaining 2 occasions it is doubtful if lightning was the true cause. For "thunder" or lightning, the accuracy of the fault reports and the cause of the fault are questionable.

Table 3 *The dates of the fault occurrences registered in 0felia concerning the RC circuits at Oxmyran; in 0felia the actual fault is registered under the column "the real fault" and the cause under the "cause" column*

Date Time	The real fault	Cause
2001-06-18 18:15	Material breakage	Broken component
2001-06-19 00:30	Unable to detect	Broken component
2001-07-04 22:28	Interruption	Thunder
2001-07-05 09:29	Interruption	Thunder
2001-08-11 16:13	Material breakage	Broken component
2002-06-07 17:45	Interruption	Thunder
2002-07-04 08:07	Interruption	Thunder
2002-07-12 08:42	Interruption	Thunder
2002-07-16 00:10	Interruption	Thunder
2002-07-24 09:12	Interruption	Thunder
2002-07-26 19:37	Interruption	Thunder
2003-06-25 17:12	Interruption	Uncertain electric
2003-07-21 16:24	Interruption	Thunder
2003-08-15 08:56	Material breakage	Thunder
2003-12-03 06:06	Interruption	Broken component
2004-05-10 06:01	Material breakage	Thunder
2004-07-17 05:40	Interruption	Broken component
2004-07-19 09:17	Unable to detect	Broken component
2004-08-20 11:18	Interruption	Broken component
2004-11-19 06:07	Interruption	Loose part
2004-12-22 16:34	Interruption	Uncertain electric
2005-04-09 22:29	Interruption	Broken component
2005-04-15 05:33	Unable to detect	Broken component
2005-05-25 09:40	Interruption	Broken component
2005-05-26 07:35	Interruption	Uncertain electric
2005-09-04 17:31	Interruption	Broken component
2005-09-09 22:31	Interruption	Thunder
2006-06-01 09:25	No fault	No fault found
2006-06-02 06:01	No fault	No fault found
2006-06-08 14:54	Unable to detect	Broken component
2006-06-21 07:11	Interruption	Thunder
2006-07-11 05:45	Unable to detect	Investigated the electronics
2006-09-07 13:33	Interruption	Uncertain electric
2006-09-14 13:05	Interruption	Broken component
2006-10-22 08:04	Interruption	Broken component

Trains

The train route passing Oxmyran and Öre Älv is the main route for the transportation of steel slabs from SSAB (Swedish Steel Inc.) in Luleå to SSAB in Borlänge, where sheet metal is made. Since the steel trains are very heavy and require higher power than most other trains, higher electromagnetic fields are generated [45]. Consequently, these trains, or a specific model of train or even a specific train, could be the cause of faults. Therefore, every train that was at the location before and at the time when the alarm went has been checked.

The steel trains always carry a heavy steel load when travelling south from Öre Älv to Oxmyran, whereas, when going north in the opposite direction from Oxmyran to Öre Älv, the trains are empty.

The elevation and slope of the track can also influence the disturbance. The lowest location is at Öre Älv, from which the elevation increases up to Oxmyran. The older track via Nyåker has a higher slope than the new track running directly to Oxmyran, see Figure 22. A train that starts after waiting for another train needs high power to accelerate, especially on an upward slope, and may generate a larger disturbance. This means that the direction of the train will influence the magnitude of the disturbance.

However, there is no correlation between the type of train passing Oxmyran Station and the faults that occur there. Different types of locomotive, types of train, travelling directions, or train weights cannot explain the faults. Faults have occurred with trains coming from both directions, passenger trains and steel trains.

Even if there is a possibility that a specific locomotive may disrupt the equipment at Oxmyran, similar faults do not occur at the reference station at Öre Älv, which has to be passed. The key of the problem is therefore not likely to be the trains.

Construction

The signal boxes at both Oxmyran and Öre Älv were built by the same company, Banverket's Industry Division, in Nässjö. The signal boxes were transported by truck to the locations at Öre Älv and Oxmyran. They were built according to the same instructions and drawings, and appear upon visual inspection to be alike, except for a wire from the RC circuit to the ground. However, this wire was not mixed with other wires or cables of different voltages. Nevertheless, a full investigation has not been made to verify that every single wire or cable in the signal box is identically located.

The constructions at Oxmyran and Öre Älv are similar, as far as could be seen in this investigation. Therefore, it is not likely that the construction has any impact on the frequent failure of the RC circuit at Oxmyran Station.

Installation

The same contractor, Banverket Production, installed the signal boxes at both Öre Älv and Oxmyran. The installation supervisor has been interviewed and there is no information pointing to the issuing of different instructions during the installation of the two signal boxes. On the contrary, all the available information indicates that both signal boxes should have been installed in the same manner. Here it is hard to evaluate how truthful this is regarding the grounding cables deep in the ground and to ascertain whether every screw at both locations is from the same supplier and of the same type.

Grounding

Since the same contractor has installed both boxes at Oxmyran and Öre Älv, according to the same drawings and instructions, the grounding system should be similar in both boxes.

In order to obtain a better grounding, both the Oxmyran signal box and the Öre Älv signal box, like every other signal box, have a ground loop around the box, connected to an iron bar that has been installed in the ground close to the box. The iron bar is connected to the S-rail to obtain a better grounding, especially for a lightning strike. However, since it is difficult to know the location of the ground cables from the signal boxes to the S-rail (the ground in the railway system), there is no guarantee that both the grounding systems are placed in a similar way.

There is no indication of any difference in the grounding of the signal boxes, according to the construction drawing and the interviews with the project manager. However, the grounding at Oxmyran has been checked and supplemented with double cables connected to the rail to obtain a low potential.

Grounding is, however, a very complex area, influenced by many parameters, and it is not easy to discount it as a fault source. Differences in the placement of the ground cable could be a possible cause in this case.

Surrounding system

At both Oxmyran and Öre Älv, the distances from the overhead contact wire to the signal box are approximately the same. Moreover, there is a transformer for reserve power (if Banverket's power breaks down), only 10 m away from the signal box at both Oxmyran and Öre Älv.

The older database that contained information on the reserve power switching on and off has been erased, but in the recent information, no correlation could be found between the reserve power switching on or off and the times of faults in the RC circuit.

Components

In each signal box there are six rectifiers. On the primary side each rectifier has 220 V, while on the secondary side there is a variation from 6 to 220 V. All the rectifiers installed at Oxmyran and Öre Älv were made by the same company. Moreover, for those subsystems that have been checked, the specifications are the same.

The visual inspection shows that the RC circuits are different, but follow the same specification.

There is no measurement result that indicates that the circuits behave differently or that differences in the rectifiers could be the source of the fault. In an interview, the supplier said that there had been no problem with the rectifier at all, and that they had not received any returns due to the rectifier breaking and causing similar problems to those at Oxmyran.

Quality assurance

Banverket conducts no quality control or inspection of circuits before they are taken into operation in the system. Instead they rely on the suppliers doing a good job, and on the RC circuits being built according to the correct specifications. The rectifier, however, is tested and inspected by the manufacturer.

Measurements at Oxmyran and Öre Älv

During the measurements at Öre Älv and Oxmyran the sampling rate was set to 10 kHz at first and then 1 MHz. The measurement at Öre Älv showed no recorded activity, which made further measurements uninteresting. The only recorded measurement at Öre Älv was the forced measure in the middle of the night when no train was passing the station. A comparison between the forced measurements at Öre Älv and at Oxmyran is shown in Figure 30 and Figure 31.

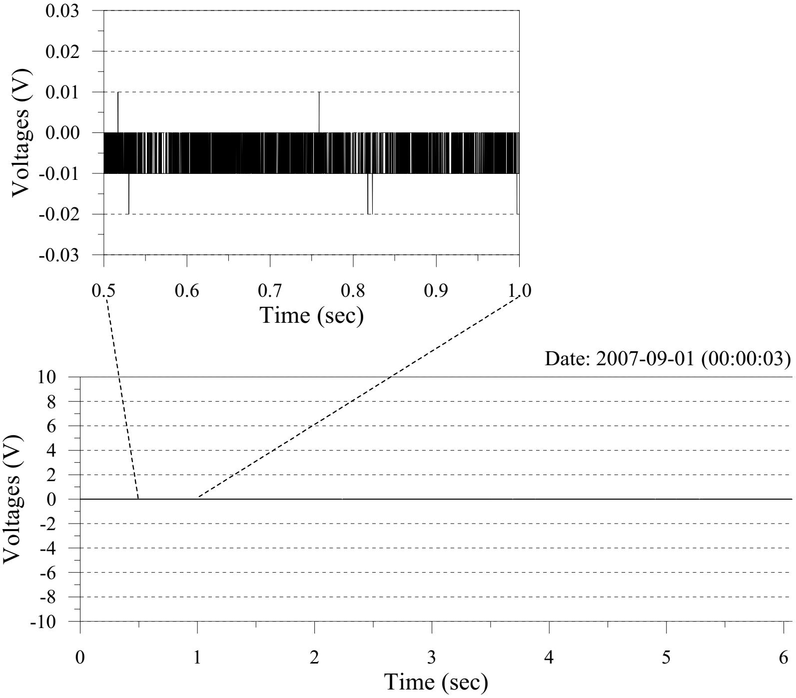

Figure 30 The forced trigger at Öre Älv at the date 2007-09-01 at the time 00.00.03.

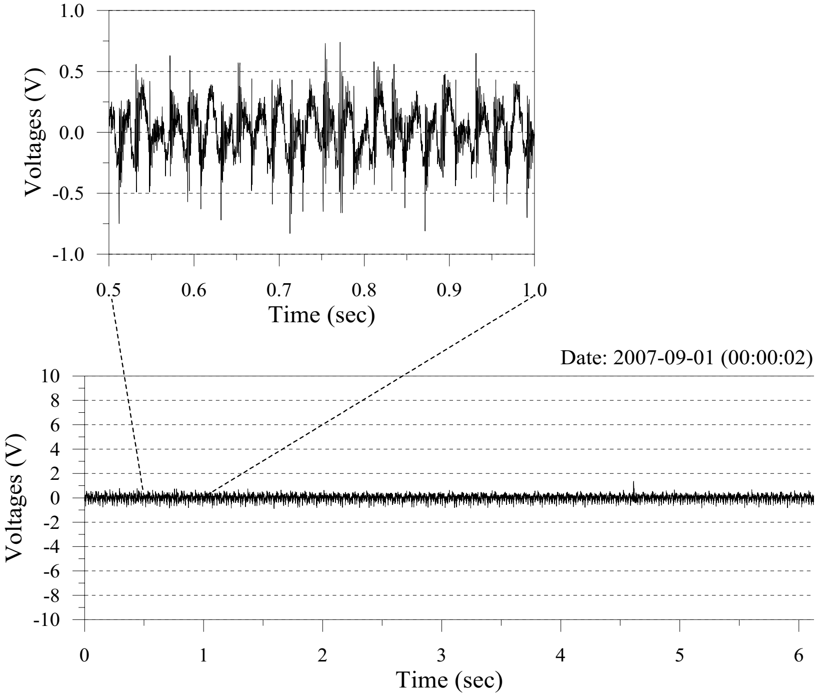

Figure 31 The forced trigger at Oxmyran at the date 2007-09-01 at the time 00.00.02.

The measurement system used was activated every time the trigger level (30 V) was reached. The system recorded data and saved it as a file, named after the time (year, month, day, hour, minute, second) when it was saved. In Table 4 the number of triggering events (i.e. voltages above 30 V) that occurred each day of the measurement period is shown. The table shows the variation in activity from no triggering event (the forced triggering event is not included) up to 689 triggering events in a single day. During the measurement period (21/9/2007 – 18/1/2008), there were 4 alarms showing that the RC circuit was out of order. The days when this happened are highlighted in the table, namely 30/9/2007 at 23.13 (11.13 pm), 1/10/2007 at 07.46 (7.46 am), 1/11/2007 at 15.12 (3.12 pm) and 8/11/2007 at 00.14 (12.14 am). In the table there are two big outliers, 1/11/2007 with 224 triggering events and 8/11/2007 with 689 triggering events. On both these two days the RC circuit was out of order. On 30/9/2007 the third highest number of triggering events occurred. On the evening of 30/9/2007, thunder occurred in the area. On the following day, 1/10/2007, an alarm was generated and the RC circuit was out of order, even though no triggering event had occurred.

Table 4 *Numbers of triggering events day and night every day during the period 20070921 to 20080118, except a small period of time between 20071204 and 20071218. The highlighted rows are the days when an alarm appeared.*

Date	**Number of triggering events**	**Date**	**Number of triggering events**	**Date**	**Number of triggering events**
20070921	3	20071027	0	20071202	2
20070922	7	20071028	0	20071203	2
20070923	0	20071029	1	20071204	3
20070924	0	20071030	2		
20070925	12	20071031	1	20071218	1
20070926	0	20071101	224	20071219	0
20070927	5	20071102	1	20071220	2
20070928	7	20071103	1	20071221	2
20070929	2	20071104	1	20071222	1
20070930	58	20071105	1	20071223	0
20071001	0	20071106	1	20071224	0
20071002	0	20071107	42	20071225	0
20071003	0	20071108	689	20071226	0
20071004	8	20071109	29	20071227	0
20071005	14	20071110	4	20071228	6
20071006	2	20071111	3	20071229	5
20071007	0	20071112	0	20071230	0
20071008	3	20071113	12	20071231	0
20071009	1	20071114	0	20080101	0
20071010	1	20071115	0	20080102	2
20071011	1	20071116	14	20080103	2
20071012	9	20071117	1	20080104	13
20071013	0	20071118	6	20080105	6
20071014	2	20071119	0	20080106	4
20071015	0	20071120	15	20080107	1
20071016	0	20071121	19	20080108	1
20071017	0	20071122	7	20080109	0
20071018	2	20071123	0	20080110	1
20071019	10	20071124	18	20080111	6
20071020	0	20071125	0	20080112	2
20071021	0	20071126	0	20080113	0
20071022	2	20071127	1	20080114	1
20071023	2	20071128	0	20080115	10
20071024	0	20071129	1	20080116	12
20071025	7	20071130	16	20080117	8
20071026	2	20071201	5	20080118	6

The results clearly indicate a correlation between the activity in the system and RC circuit faults, even though one fault occurred on a day when no activity at all was registered.

One explanation can be that the trigger was set to 30 V and not -30 V. Therefore, a drop of the potential in the system could not been seen in this measurement. Another explanation can be that, after a replacement of the RC circuit on 30/9/2007, the probe was not put back in the right way by the maintenance support personnel. After this replacement, data were collected and the system was checked on 4/10/2007. On this date there were no obvious faults registered for the connection to the RC circuit, but no check of the real connection was made. On 8/10/2007 the alarm was registered in the CTTC office at 00.14 (12.14 am), and still there were 689 recorded triggers during that day after the alarm had been registered. This alarm was not forwarded to the maintenance support personnel until 06.52 in the morning. The maintenance support personnel did not switch and repair the RC circuit until late that day, because the only spare system had been used a week before. On the day before, 7/10/2007, with 42 recorded triggers, 41 of these were recorded after 23.36, which can possibly explain the fault after midnight.

On the evening of 30/9/2007 the RC circuit was out of order and the alarm was registered at the CTTC office at 23.13. According to the maintenance support personnel, there was a thunderstorm this evening. There were 58 triggers during that twenty-four-hour period, see Table 1, and 56 of these triggers occurred between 19.43 and 20.46 (7.43 and 8.46 pm). There were no triggers at all when the fault occurred and the last trigger was recorded at 20.46 (8.46 pm). The last two curves that day, 30/9/2007, were recorded at 20.41.47 (8.41 and 47 seconds pm) and at 20.46.04 (8.46 and 4 seconds pm). The voltages dropped, or the whole system's potential was raised, see Figure 32. There is no evidence that the potential between these two measurements was saturated, but it is likely that it was saturated the whole time, approximately 5 minutes.

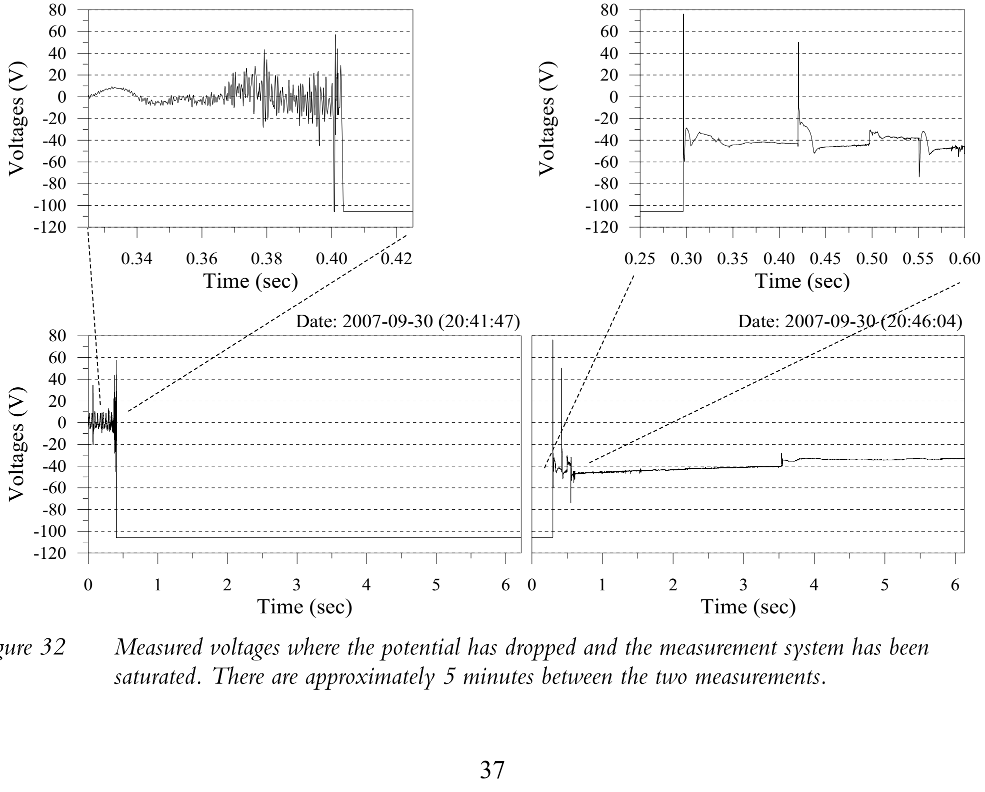

Figure 32 *Measured voltages where the potential has dropped and the measurement system has been saturated. There are approximately 5 minutes between the two measurements.*

The next day (1/10/2007) there was a new alarm sent to the CTTC office at 7.46 (am), showing that the RC circuit was out of order. During this day there were no triggers at all registered, except the forced trigger in the middle of the night. However, as explained before, the measurement system may have been malfunctioning because the probe was incorrectly connected.

The other two days when a fault was registered for the RC circuit were 1/11/2007, with 225 triggers, and 8/11/2007, with 690 triggers, see Table 4.

All the curves during this measurement period, using the fast sampling rate of 1 MHz, show a similar behaviour. The first transient in all the curves has the same value, - 56.25 V, as seen in Figure 33. The figure shows that the transient has very fast rise and fall times in the middle. In this transient there is no tail at all, as there was at 10 kHz or at Notviken and Sunderbyn.

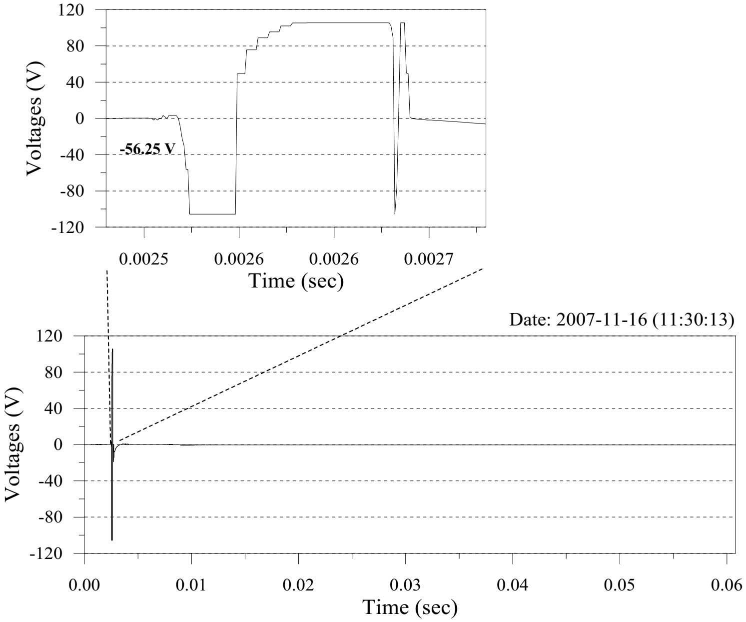

Figure 33 Voltage curve where the first transients are saturated. The sampling rate was 1 MHz.

The equipment was checked after the measurement and it behaved correctly in the laboratory environment.

To determine the specific frequencies that dominated the measurements, the data were analysed with an FFT (Fast Fourier Transform). The FFT was performed in MatLab. Table 5 summarises the dominant frequencies in each curve. The most recurrent frequency is 25 Hz, followed by other frequencies that can be divided by 8 1/3 Hz, which is half the frequency that Banverket employs in their power system, 16 2/3 Hz. The most dominant frequencies overall are 25 Hz and 50 Hz.

Table 5 The dominant frequencies for specific curves as obtained through FFT analysis.

Curves	***Frequency (Hz)***														
	8⅓	***11***	***14***	***25***	***41⅔***	***50***	***58⅓***	***61***	***64***	***75***	***91⅔***	***100***	***108⅓***	***125***	***141⅔***
2007-09-01		X	X	X		X		X	X			X	X	X	
2007-08 13	X	X	X	X			X	X	X	X	X		X	X	X
2007-09-25	X	X	X	X	X		X			X	X		X	X	X
2007-09-30				X		X						X		X	
2007-11-01	X			X	X	X	X			X	X		X		

During the measuring period at Oxmyran the RC circuit failed several times, resulting in alarms sent to the CTTC office. However, not on a single occasion was the measurement system triggered in direct connection to a failure. On the other hand, higher activity levels (numbers of triggering events) have been seen close to the time of many failures. High voltage levels were recorded during the period and some were so high that they saturated the measurement system used. However, in most cases the high transients were also very short. This means that the transients probably did not contain enough power to make the RC circuit go out of order.

The trigger level was set to 30 V and not -30 V. In Figure 32 both curves dropped below -30 V and were also saturated. The reason why these two curves were monitored was a short positive transient over 30 V before and after they were saturated. In this case it can be argued that the specific voltage levels and time would contain enough power to make the RC circuit go out of order. However, again the RC circuit was not out of order until much later that day, and no specific curve was recorded that could be the primary reason for the failure of the RC circuit.

Regarding the detailed analysis of the transients, see Figure 33, the supplier of the rectifiers controls and checks every delivered rectifier according to specific instructions. The supplier also states that there is not any internal or external source that could generate the voltage -56.25 V that is seen in Figure 33. It is not a normal behaviour that a high transient should drop that fast. To exclude faults or mistakes during the measurement, the measurement system was checked afterwards, and it was working correctly, even if there is no guarantee that the measurement is correct.

If the rectifier had been active and delivered the power, the level should have been around 26 to 27 V, which is what the rectifier delivers to its subsystem when it is active. This gives a clear indication that it was not a train or locomotive that was the primary cause of the interference. All the measurement curves are also centred on zero, which indicates that there were no trains located at the station.

In the analysis of the specific frequencies in the monitored data, it was surprising that the lowest frequency was 8 1/3 Hz and not 16 2/3 Hz, which is the frequency that Banverket employs in their power system. The converters used north and south of Oxmyran are both static and deliver 16 2/3 Hz in one phase. In Table 5 the frequencies 25 Hz and 50 Hz are dominant. One theory proposing that the 50 Hz system that is used in other systems at the station might influence the DC system after the rectifier is not that plausible, in spite of the fact that every system uses the same ground. However, both the frequencies 25 Hz and 50 Hz are multiples of 8 1/3 Hz, as are 41 2/3 Hz and 58 1/3 Hz.

CONCLUSIONS

This research has been able to present the investigation performed to assess the possible causes of EMC-related problems and has to a large extent answered the following question unambiguously, "What are the main causes of EMC in the Swedish railway system?" A number of conclusions drawn from the study are:

- EM disturbance is responsible for a significant number of faults in the Swedish railway infrastructure system. The presented statistics show that as many as 70 % of all the faults can originate from EMC disturbance.
- An analysis of the official national strike statistics show that thunder or lightning is not to any major extent responsible for the faults at Oxmyran Station. Thunder or lightning may also be overestimated as a fault cause at other places.
- It can be very difficult for the maintenance staff to define the cause of faults correctly, especially concerning EMC disturbance, during a short repair or maintenance visit on site.
- Demonstrably high transients occur in the system and can provide enough energy to interfere with the functionality of subsystems and hence the reliability of the system. Furthermore, in general, transients occur in the detector system independently of the presence of trains.
- The recorded ground frequency in the measurements is 8 1/3 Hz, which is half the frequency that is used in the railway, 16 2/3 Hz.
- To reduce EMC problems, the design and construction of critical systems must be improved. A new approach must be adopted, involving different zones, each of which contains equipment with the same sensitivity to EM fields. Between the zones there must be barriers and filters.
- To prevent crosstalk, the correct use of ground is very important. Separate grounds for the electronic equipment and the communication signals will prevent crosstalk from high power sources.
- The cables' shields are not properly joined when they are connected to the rack in the shed. The cables from the hot boxes are too long and they have been wound in circles on the floor because of their length. This results in an unnecessary deterioration of the shielding against EM disturbance.
- Post-installation fixing is common in the detector systems. This results in problems being solved by technical staff using a hands-on method that is not documented in a correct way. There is an apparent risk that new constructions are designed on the basis of incorrect operating conditions due to all post-installation fixing.

FURTHER RESEARCH

This thesis focuses on the EMC problem, aiming to estimate the magnitude and locate the major sources of EMC disturbance. Many probable sources have been eliminated from the list of possible causes for EMC-related problems, but the specific causes for EMC problems at Sunderbyn, Notviken and Oxmyran are yet to be located. Therefore, more research work is required in order to come closer to a solution for each site. The following research tasks are proposed:

- In order to investigate if trains in any way cause the problem at Sunderbyn and Notviken, the train position must be defined at that moment when a random transient is recorded. This can be accomplished by having, onboard the train, a GPS connected to the recording equipment.
- To continue the research task of trying to solve the problems at Oxmyran, other parts of the station should also be monitored, for example the 50 Hz systems or the grounding system.
- Since over 170 RC circuits are ordered by Banverket every year (2007), other similar problems must exist in other signal boxes in the Swedish railway system. Therefore, it would be very interesting to perform comparative measurement on other stations than Oxmyran to see if these systems behave in a similar way.
- In order to estimate the efforts involved in and the cost of the maintenance work, as well as the inconvenience that this creates, it would be very interesting to assign a cost, in terms of money, to every fault that is connected to the EMC problem. Comparing this with the cost of proper design and construction from the start could change the investment policy.
- Improvements should be made of the definitions in 0felia regarding EMC problems and of the reporting process, to ensure that the real problems are illustrated in a clear and correct way. This would not only increase the understanding of the problem, but also help the engineers to allocate correct resources and the maintenance support personnel to perform better work at the site.

REFERENCES

[1] Nilsson, I. et al., Fest på spår (Party on the track), Förspelet, Örebro, 1999.

[2] Banverket's annual report 2007. [Online] Available at: http://www.banverket.se/pages/1493/bv_2007_eng_webb-x.pdf, 9/11/2008.

[3] ERRAC (European Rail Research Advisory Council), Strategic rail research agenda 2020. [Online] Available at: http://www.errac.org/docs/SRRA-2007.pdf, 17/11/2008.

[4] Karlsson V., An overall view of maintenance, European Railway Review, Vol. 11, Issue 3, pp. 11 – 17, 2005.

[5] Cella, R. et al., Measurement of AT electric railway system currents at power-supply frequency and validation of a multiconductor transmission-line model, IEEE Transactions on Power Delivery, Vol. 21, Issue 3, pp. 1721- 1726, July 2006.

[6] Bourne, A. et al., Managing electromagnetic compatibility on the London underground system, EMC assurance in a railway environment, IEE, Vol. 8, pp. 1 – 11, 9 Sept. 2003.

[7] Midya, S. and Thottappillil, R., An overview of electromagnetic compatibility challenges in European rail traffic management system, Transportation Research Part C: Emerging Technologies, Vol. 16, Issue 5, pp. 515-534, Oct. 2008.

[8] Al Dhalaan, S.M. and Elirbawy, M.A., 'A quantitative study of the electromagnetic field coupling between the electric power transmission line and railway'. Proc. Canadian Conf. on Electrical and Computer Engineering, May 2003.

[9] Hill, R.J., Electric railway traction. Part 6 Electromagnetic compatibility – disturbance sources and equipment susceptibility, Power Engineering Journal, Vol. 11, Issue 1, 1997.

[10] Ruddle, A.R., 'Computation of electromagnetic fields in the vicinity of a railway catenary'. Proc. IEE Coll. on EMC in Electric Traction and Signalling, 1995.

[11] Solbiati, G.L., 'Managing the EMC between an AC railway line and the external world'. Proc. Electrotechnical Conf., May 1996.

[12] Holmes, R., 'Electromagnetic compatibility of electrified railways'. Proc. Int. Conf. on Electric Railways in a United Europe, March 1995.

[13] Hill, R.J., Electric railway traction. Part 7 Electromagnetic interference in traction systems, Power Engineering, Journal, Vol. 11, Issue 6, pp. 259-266, Dec., 1997.

[14] Allan, J. et al., 'Low frequency and radio frequency electromagnetic compatibility for rapid transit railways'. Proc. Fifth European Conf. on Power Electronics and Applications, 1993.

[15] Banverket research program. (December 2004) [Online] Available at: http://www.banverket.se/upload/pdf/om_banverket/fouprogram2.pdf, 10/12/2004.

[16] Brillante, S. et al., ‘Modelling for electromagnetic interference assessment in electric railway traction systems’. Proc. Int. Conf. on Electric Railways in a United Europe, March 1995.

[17] Holmes, R., ‘Electromagnetic compatibility of electrified railways’. Proc. Int. Conf. on Electric Railways in a United Europe, pp. 131-135, Mars 1995.

[18] Ogunsola, A., EMC assurance and management, EMC assurance in a railway environment, IEE, Vol. 5, pp. 1-8, Sept. 2003.

[19] Allan, J. et al., ‘Low frequency and radio frequency electromagnetic compatibility for rapid transit railways’, Proc. Fifth European Conference on Power Electronics and Applications, Vol. 7, pp. 106-111, Sep. 1993.

[20] Mariscotti, A. and Pozzobon, P., Determination of the electrical parameters of railway traction lines: calculation, measurement, and reference data, IEEE Transactions on Power Delivery, Vol. 19, Issue 4, pp. 1538 – 1546, Oct. 2004.

[21] Markeset, T. and Kumar, U., Design and development of product support and maintenance concepts for industrial systems, Journal of Quality in Maintenance Engineering, Vol. 9, No. 4, pp. 376-92, 2003.

[22] Banverket reference manual, WILD, Maintenance and troubleshooting, Chapter 2, September 1996.

[23] Banverket, Järnvägen 150 år (The Railway 150 Years), Informationsförlaget, Stockholm, Sweden, 2005.

[24] Nissen, A., Larsson, D. and Espling, U., ‘Vehicle classification based on wayside monitor data: a case study’. Proc. High Tech in Heavy Haul, IHHA Inc, 2808 Forest Hills Court, Virginia Beach, VA, USA, June 2007. International Heavy Haul Association, IHHA, Virginia Beach, Va., pp. 471-477, 2007.

[25] Nilsson L. and Diehl U., Svenska lok och motorvagnar (Swedish locomotives and rail cars), Förlagsstallet HB, Gothenburg, Sweden, 2006.

[26] Sollerqvist F.J. and Varjú, G., Comparison of Btrr, Btrc and At traction feeding systems in Norway, Technical report, STRI, Jernbaneverket, Norway, 2003.

[27] Schmieder A., Kießling, F. and Pushmann, R., Contact lines for electric railways, Publicis Corporate Publishing, Munich, Germany, 2001.

[28] European Committee for Electrotechnical Standardization, EN 50160, Voltage characteristic of electricity supplied by public distribution systems, CENELEC, Brussels, Belgium, 1999.

[29] International Electrotechnical Commission, IEC50 (161): (BS4727:Pt 1: Group 09) Glossary of electrotechnical, power, telecommunication, electronics, lighting, and colour terms: Electromagnetic compatibility, IEC, Geneva.

[30] Tesche, F.M., Ianoz, M.V. and Karlsson, T., EMC analysis methods and computational models, Wiley & Sons, New York, 1996.

[31] Council Directive, 89/336/EEC, Official Journal of the European Communities, May 1989.

[32] European Committee for Electrotechnical Standardization (CENELEC). [Online] Available at: http://www.cenelec.org, October 2007.

[33] European Committee for Electrotechnical Standardization, EN 50081-2 1993 Group 2 Class A, Electromagnetic compatibility - generic emission standard, Part 2: Industrial, Official Journal of the European Communities, 1993.

[34] European Committee for Electrotechnical Standardization, EN 50082-2 1995, Electromagnetic compatibility - generic immunity standard, Part 2: Industrial, Official Journal of the European Communities, 1995.

[35] European Committee for Electrotechnical Standardization, Railway applications - Electromagnetic compatibility, Part 2: Emission of the whole railway system to the outside world: EN 50121-2, CENELEC, Brussels, 2000.

[36] Nyström B. and Kumar, U., 'Analysis of train delay information'. Proc. of the World Congress on Railway Research, Edinburgh, September-October 2003, WCRR, pp. 253-261, 2003.

[37] York EMC Service Ltd. [Online] Available at: http://www.yorkemc.co.uk, September 2006.

[38] Konefal, T. et al., Potential electromagnetic interference to radio services from railways: final report (AY4110), for Radio Communications Agency, York EMC Services Ltd, York, 2004.

[39] Bozec, D. et al., Assessment of radiated electromagnetic interferences from moving rail vehicle using an innovative measurement system, EMC Europe 2004, Eindhoven, The Netherlands, Vol II, pp. 518-523, Sept.2004.

[40] Wisten, Å. and Mäkikaltio, P., Methods of measuring radiated electromagnetic emission from trains, Technical report, Luleå University of Technology, Luleå, 2002.

[41] Catalogue of Material. [Online] Available at: http://www.banverket.se, September 2004.

[42] Benda, S., EMC undersökning i Kiruna 2003-06-23--27 (EMC investigation in Kiruna 2003-06-23--27), Technical report, Luleå University of Technology, Luleå, 2004.

[43] Niska S., EMC in railway systems measurements, modelling, and analysis, Licentiate thesis, 2004:59, Luleå University of Technology, Luleå, Sweden, 2004.

[44] Uppsala University, Lightning research, Faculty of Science and Technology, Uppsala, 2007.

[45] Benda S., Interference-free electronics: electromagnetic compatibility, Studentlitteratur, Lund, 2001.

Paper A

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Electromagnetic Interference: A major Source of Faults in Swedish Railway

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Abstract: Industry and the railway sector are at present entering a new era. Increasingly, the systems in operation today use electronic components instead of relay technique and the railway sector now has the opportunity to improve current systems. However when new technology is installed into old infrastructure, new knowledge has to be taken into consideration. The new technology which is to be integrated into old systems or which is to be applied when building systems from scratch should meet the requirements for electromagnetic compatibility to fit into the infrastructure. To see whether there are any problems in this area, an investigation has been performed based on the failure reporting system used by Banverket (Swedish Rail Administration). Visual inspection has been carried out in the signal and detector boxes located close to the track. Measurements on site have been conducted to follow up the investigation into the failure reporting system and the visual inspections.

Keywords: *EMC, visual inspection, measurements, railway, design.*

1. Introduction

Today the Swedish railway industry, like many other industries, is following the general trend of replacing electromechanical relay technique with modern electronic systems. One argument in favour of this is that electronic systems, when compared to relay technique, are a less expensive investment. Moreover, the number of maintenance hours required is, in general, lower for new electronic systems. However, this is true only if the electronics are correctly installed and can withstand the surrounding interference [1]. To maintain high reliability and safety in this new technical environment, where different levels of voltage are used in the same system, and where many old relay-based subsystems are being replaced by new electronics, the demands for greater understanding and knowledge of electromagnetic compatibility (EMC) [2] need to be met. This is important since an electronic component is much more sensitive to electromagnetic interference (EMI) [3] than the older relay systems.

The railway infrastructure and then specific the environment close to the track has a number of noise sources [4]. Modern locomotives also produce significant interference in the power supply [5].

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Measurement show transients that reach over 300 V in a 230 V system [6] and measurements on the line-pantograph interface have also shown high frequency transients [7]. To install modern electronics in this environment, detailed knowledge is required of both the disturbance from the older system and the sensitivity of the new component. Therefore, EMC has today become a vital part of railway system design [8].

In this paper the extent to which EMC is a source of failure for the railway is outlined. Available statistical data show that up to 70 % of all the faults could be EMI or EMC problems. Measurements are provided and problems in the design and construction are evaluated as a source of disturbances. If these problems are not accorded due and serious attention, future railway systems are likely to face major difficulties.

2. Causes of Electromagnetic Interference

2.1 Railway power system in Sweden

In Sweden work began on building the railway system in the mid-nineteenth century. Electrification began in 1895, with DC (direct current) power. The mining company, LKAB (Luossavaara-Kiirunavaara Aktie Bolag), located in the northern part of Sweden get there track electrify in 1915. This company transports iron ore from the mines in Kiruna and Malmberget to the harbours in Narvik and Luleå. A further set of demands from LKAB led to a change being made from DC to 16 kV AC (alternating current) with a frequency of 15 Hz. And then, in the 1950s, the frequency was changed to 16 2/3 Hz, to facilitate easier conversion from the frequency of the national grid, which employs a frequency of 50 Hz [9].

Today the rolling stock has become heavier, with the axle load having increased from 22.5 metric tonnes to 25 metric tonnes. Furthermore, LKAB has now once again increased its demands by using axle loads of up to 30 metric tonnes [10]. Moreover, the power of the locomotive that is to pull such trains has increased to 10,800 kW [11].

The converters supply the railway system with 15 kV. The train uses the overhead catenary along the railway and the transformers help to transmit the current through the catenary system. The train obtains the current from the overhead contact wire and the return current is sent through the S-rail (continuous rail), which is used as the return circuit, back to the transformers along the track. The return current can reach several hundred amps. The S-rail is continuous along the track and is therefore good for use as a return circuit for the train power and for the current sent back to the transformers.

For the electric track there are two systems in use in Sweden: the booster transformer (BT) system and the autotransformer (AT) system.

2.2 Booster transformer system

The BT system is the most common system in Sweden. The ratio in the transformers between the primary side and the secondary side is 1:1, which forces the current to use the path through the transformers to the converter, and the current is therefore forced through the S-rail and cables from S-rail to the converter via the transformers. The transformers have been placed at an intermediate distance of 3 to 5 km, depending on the surrounding topography [12, 13], see Fig 1.

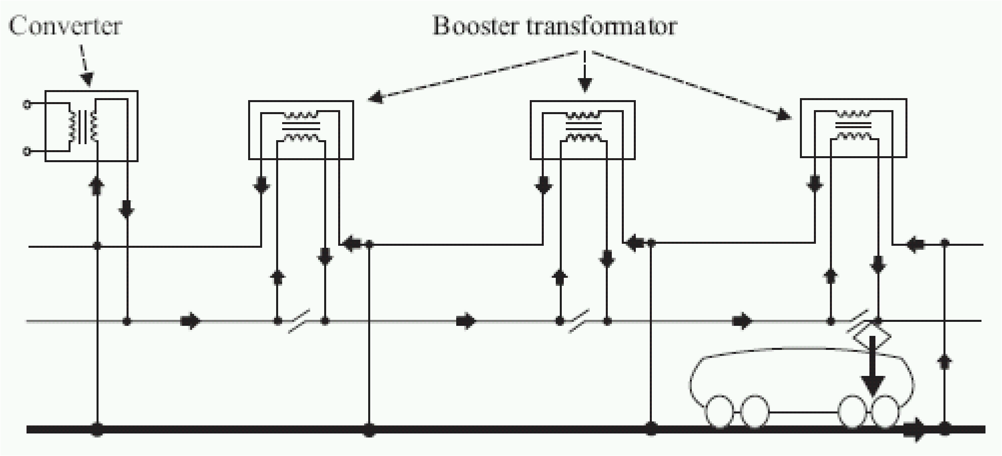

Figure 1: The current's path in the BT system

2.3 Autotransformer system

The AT system uses 30 kV and divides the voltage in halves by the transformers. The overhead contact wire has a 15 kV power supply and the return feeder, (or negative feeder), is provided with a phase shift in the contact wire. The voltage of the return feeder is -15 kV, and it is therefore called the negative feeder, see Fig 2. The output current from this system can be higher than that in the BT system. The AT system is used for tracks where more power is needed due to a desire for heavier loads or faster accelerations. The return current is sent over the S-rail back to the transformers. The transformers can be placed at an intermediate distance of 10 to 20 km depending on the surrounding topography. The AT system has, compared to the BT system, a higher leakage of the return current to the ground [12, 13].

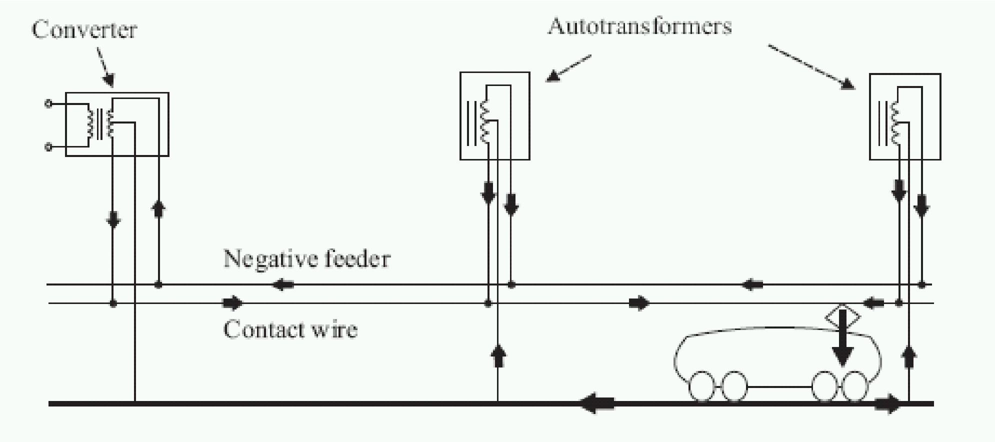

Figure 2: The current's path in the AT system

2.4 Infrastructure systems

In addition to the high-voltage system used by the trains, the railway also uses low-voltage systems (< 400 V) located in the same infrastructure. Examples of such systems are communication systems and detector systems that use 5 V DC.

The systems close to the tracks, *e.g.,* signalling systems controlling the light signals for the locomotive driver, signals communicating the turnouts' position back to the Centralized Train Traffic Control (CTTC) office, and systems for reporting the position of trains along the track to the CTTC office, are all low-voltage subsystems. In the Swedish railway system, all these systems have traditionally been based on relay technique. To provide high reliability, the systems have a redundancy in every critical function.

The systems in the Swedish railway infrastructure are divided into three major subsystems based on the technical group responsible for the area of work covered by the subsystem, rather than the technical similarity of the components of the subsystem. The subsystems are:

Electrical systems that deliver all the power to the stations, technical buildings or boxes. These systems transform the power from Banverket down to the required lower voltage and distribute it to the other subsystems.

Signal systems making sure that all the signals in the railway system and in the infrastructure are working and checking that the right signals are being sent for various functions on the railways.

Telecommunication systems, the purpose of which is to make sure that the communication from stations, technical buildings or boxes is functioning properly.

Electrical systems, signal systems, and telecommunication systems are mostly contained in the same physical location, *e.g.,* a signal box, technical building, etc. The systems controlled by a specific professional group (electrical systems, signal systems, or telecommunication systems) are kept separate from those of other professional groups in different racks in a room or in different rooms. In larger technical buildings where several systems are located, not only are the systems of each professional area kept in separate rooms, but the equipment is also separately grounded. The location of the equipment belonging to the specific professional areas is decided by the professional group in question and not to the surrounding interference level or the sensitivity of the installed equipment.

The design and construction of the grounding systems have varied over time. The telecommunication system has a separate ground, consisting of a loop of copper wire in the ground, around the building, and an iron bar connected to the loop to obtain a ground potential. The other systems use the S-rail as their ground potential. The old regulations dictated that only the S-rail was to be used as the ground. There also used to be an instruction stating that the grounding should be separated inside the buildings, but then reconnected before using the S-rail as the ground.

3. Data Collection Procedure

The data collection procedure used in the analysis of the faults caused by EMI consists of:

- Fault Reporting System, 0felia (zero=0, fault=felia), which is used by Banverket (Swedish Rail Administration).
- Visual Inspection of the design and construction at several railway sites.
- *In situ* Measurements at various railway sites.

3.1 Fault reporting system

Problems related to EMC on the railway should in one way or another be entered into the railway fault reporting system. By analyzing these reports, the extent of EMC-related faults can be estimated. 0felia is a failure reporting system used by Banverket to report failures in the infrastructure [14]. When a fault appears in the Swedish railway infrastructure, it is indicated in the CTTC office by alarms from the signal and detector systems. The CTTC office staff then initially report the occurrence of the fault in 0felia, after which they call the contractor's contact person, who in turn instructs personnel to remedy the fault. Maintenance personnel receive a work order to check the alarm and perform repair work, if necessary, and then drive to the fault location. After the visit on site and the repair, the maintenance workers must report back to the CTTC office, which then finalizes the report in 0felia [9].

In 0felia there is no specific category for EM failure. Since in general it is very difficult to designate EMC as a failure source and since the time for repair and evaluation is very limited, EMC-related faults will fall under other categories in 0felia. The possible codes in 0felia that may contain EM faults are: "interruptions", "not able to detect", "no fault" and "short circuit". All these categories would include faults that occur due to EMC problems like EMI, EM disturbance or unknown electrical strain.

The argument in favour of the assumption that most of the faults in the above categories are EMC-related is that it has not been possible to find any software problems that have locked the system or any mechanical influence that has initiated the fault. If there had been a bug in the software, the system would have been locked every time the system was in the same state. If there had been a mechanical influence, there would have been signs of damage after the mechanical hit. Instead the electronics have for some reason been locked, and the fault has been fixed by resetting the system. There has been no fault in the system function after the reset. This indicates that the source of the fault is EMI.

Table 1: Numbers of faults on the Swedish railway in 2005 and 2006. The table shows four separate categories of EM disturbance faults. Data is taken from 0felia.

Category	Year	
	2005	2006
Interruptions	11463	10374
Not able to define	16412	13534
No fault	6984	10366
Short circuit	4355	4198
Total no. of possible EM faults	39214	38472
Total no. of faults	57486	53677
Percentage	68	72

Table 1 show that faults due to EM disturbance can be as high as 70% of all the faults reported on the Swedish railway. Furthermore, even if all these faults are not due to EM disturbance, it can be concluded that EM disturbance is most likely a significant cause of faults in the Swedish railway system. It is also interesting to note that 70% of the faults in the railway system today have an unknown cause.

3.2 Visual inspection

Visual inspection was performed on site that was chosen because of varying constructions and building year to evaluate imperfection in the construction or EMI protection, see Table 2. The inspection was concentrated to the area from where the power cables entered the investigated location, and continued by examining where the sensitive equipment was placed in relation to the other equipment. In every investigated location, variation in the building standard was invariably found. However, the one feature that every location had in common was that EMC was not prioritized in the construction.

Table 2: The location, type of construction, where a performed measurement was done and where a visual inspection was done in this investigation

Location	Construction	Measurement	Visual
Gransjö	Detector box		X
Kiruna	Converter		X
Kiruna	Technical building with surrounding boxes and cabinets		X
Krokvik	Detector box		X
Notviken	Detector box	X	X
Oxmyran	Signal box	X	X
Sunderbyn	Detector box	X	X
Vassijaure	Detector box		X
Öre Älv	Signal box	X	X

Some examples of incorrect construction with respect to EMC that were found during the visual inspection were as follows:

The overvoltage protection was placed more than one metre in on the rack, as measured from the wall that is the barrier. The incoming cable was placed together with all the other cables in a cable channel for both the incoming and the internal cables, see Fig 3. If a transient enters this way through the cables, it interferes with all the closest cables before it enters the overvoltage protection after more than 1 metre.

In the instructions for constructing the technical buildings and signal boxes, the high-frequency grounding should be constructed as a low-ohm connection. However, in many cases this results in a long ground cable that does not give the EMI protection that it should. In order to provide a more effective grounding, the ground should instead be specified as a low-impedance ground.

Problems with wrongly mounted cables entering control cabinets. Fig 4 shows an example of incorrect mounting in an advanced EMC-protected cabinet. Here no attempt was made to connect the cables correctly to the cabinet when they entered the bottom of the box, and the cables' shield was not connected anywhere in the cabinet. Instead, the filter to the cables and wires was simply thrown on the floor inside the cabinet. This shows how the use of expensive and advanced EMC-protected cabinets is meaningless if the installation is not performed correctly.

As mentioned earlier, the equipment is often separated into different zones. However, this is not based on the sensitivity of the equipment, but instead on the professional area in question (telecommunications, signals and electric power supply). Instead it should be the sensitivity of the equipment that defines the zones, as in Fig 5.

Figure 3: Incoming cables in a technical building where the overvoltage protection filter is placed over 1 metre from the wall that is the barrier. The unfiltered cable is mixed with filtered cables before it reaches the overvoltage filter.

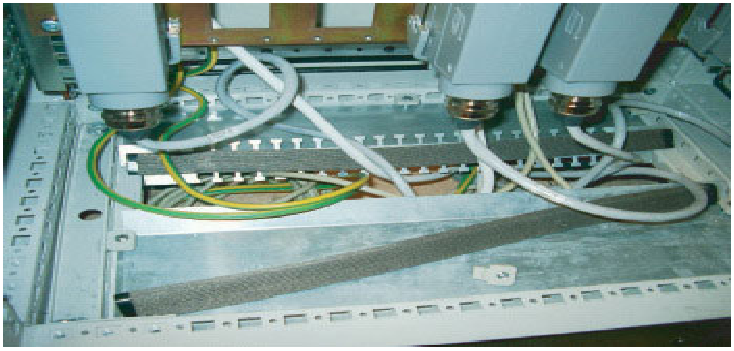

Figure 4: An intake of cables into an EM cabinet where the incoming cables are not connected to the ground.

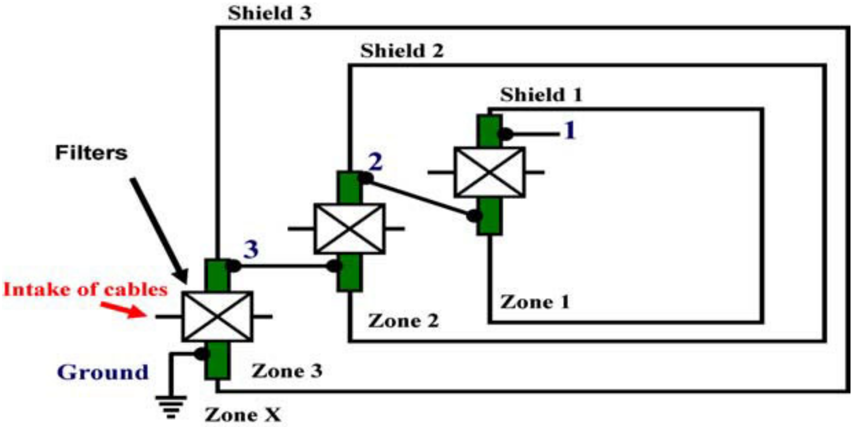

Figure 5: Design of the buildings, huts or cabins involving different zones, each of which has a specific level of allowed EM fields and the cables that enter every zone through a filter.

3.3 In situ Measurements

Measurements were made to verify that the problem was an EMC issue. The question was whether there were any transients that had enough power to disturb the subsystem in the infrastructure. This was investigated by measurements on site at several locations (see Table 2).

In almost all the constructions and locations where measurements were made, see Table 2, transients were registered in the infrastructure system. One example is the measurement at Notviken, see Fig 6.

This measurement was performed in the flat-wheel detector cabin situated at Notviken in Luleå, Sweden. The transients in this curve are saturated at ± 5 V, and consequently they are likely to be higher, see Fig 6. These transients occurred during a train passage. In this case the transients are larger than the 5 V, and therefore it can be concluded that the transients were not caused by the flat-wheel signal from the detector [15].

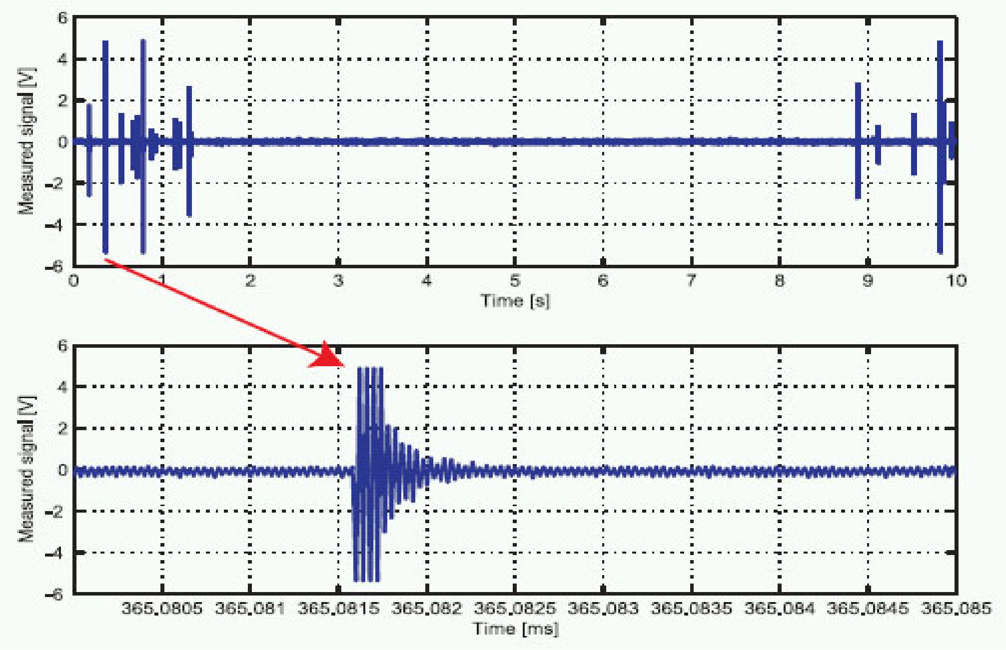

Figure 6: Measured transients on a flat-wheel detector during a train passage and the close-up picture for one transient. The signal shown in the lower close-up picture is saturated.

4. Remedial Measurements to minimize Interference

The analysis of fault data from the fault reporting system, 0felia, shows how difficult it is to verify EMC problems in the infrastructure. It is difficult to obtain a clear picture, partly because the reporting system has no category that specifies EMC problems or EMI. However, related fault categories where EMC problems are most likely to end up comprise a large portion (70 %, see Table 1) of all the registered faults in the Swedish railway infrastructure. It is assumed that if no mechanical source or software problem can be found, the fault has most likely been caused by an EMC problem.

Concerning the design and building of the telecommunication, signalling and electrical subsystems, during the past few years, have been an effort to solve EMC problems. However, its look like that the project managers, who control the building process, have not taken any consideration of EMC problems. In the examples presented here, it has been seen clearly how advanced equipment can be rendered useless, if the installation is incorrect. Moreover, designers sometimes lack understanding of EMC when they design new signal boxes with different zones. The main reason to have different zones is the variation of sensitivity of the components, and the design should not just be based on considerations such as the professional group currently responsible for the components. The number of zones should depend on the variation of the sensitivity levels of the subsystems' equipment, (see Fig 6). It is also very important that cables and wires from the different zones must not be mixed up.

The grounding is another important issue for EM problems. Telecommunication system must not use the S-rail as the ground, as is the case with signal systems and electrical systems. By using a loop of copper wire in the ground, around the specific building, and an iron bar connected to the loop to obtain a ground potential, the telecommunication system can deal with the grounding problem. This approach is necessary as the telecommunication system, which was installed decades ago, was sensitive to EMC and therefore this had to be taken into consideration to ensure less noisy communication. This initiative taken by the telecommunication department of Banverket is a beginning for solving EMC problems, though its appropriation is yet to be confirmed.

A number of measurements made show that there are transients in the railway system, as in Fig 6. These recorded transients can affect many subsystems on the railways, but the question is how these subsystems are affected and how big these effects can be. This is a matter of further investigation.

This paper clearly shows that EMC can pose a significant operational problem for the Swedish railways, and that operation and maintenance cost can be lowered if the EMC is given adequate attention.

5. Conclusions

The following conclusions can be drawn from the present study of electromagnetic disturbances in railway applications:

- EM disturbance of the equipment in the railway system infrastructure is likely to be responsible for a significant number of faults in the infrastructure in general.
- High transients occur in the system and can provide enough energy to interfere with the functionality of subsystems and hence the reliability of the system.
- To reduce these problems, design and construction of critical systems must be improved. The new approach involving different zones must be adopted, where every zone contains equipment with the same sensitivity to EM fields.

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References

[1] Benda S., *Interference-free Electronics: Electromagnetic Compatibility*, 3rd ed. Studentlitteratur, Lund, 2001.

[2] Tesche F. M., M. V. Ianoz and T. Karlsson, *EMC Analysis Methods and Computational Models*, John Wiley & Sons INC, New York, 1997.

[3] Williams T., *EMC for Product Designers*, 2nd ed. Newnes, Oxford, 1996.

[4] Hill R. J., *Electromagnetic Compatibility: Disturbance Sources and Equipment Susceptibility,* Power Engineering Journal, Vol. 11, pp.31–39, Feb. 1997.

[5] Pozzobon P. and P. Ferrari, *Railway Lines Models for Impedance Evaluation*, In: Harmonics and Quality of Power ICHQP, Athens, Greece, October 1998. IEEE/PES and NTUA, 1998, pp.14-16.

[6] Granström R., *Driftövervakning i signalanläggningar (Operation Supervision on Signal Constructions)*, Technical Report, Luleå Railway Research Centre (JVTC), Luleå, Sweden, 2004.

[7] Giannetti R., G. A. Antonacci, B. Tellini and M. Macucci, *Conducted and Radiated Interference Measurements in the Line-pantograph System*, Instrumentation and Measurement, Vol. 50, No. 6, pp.1661–1664, Dec. 2001.

[8] Holmes R., *Electromagnetic Compatibility of Electrified Railways*, In: Electric Railways in a United Europe, Amsterdam, Netherlands, March 1995. IEE, London, 1995, pp.131-135.

[9] Banverket, *Järnvägen 150 år (The Railway 150 Years)*, Informationsförlaget, Stockholm, Sweden, 2005.

[10] Nissen A., D. Larsson and U. Espling, *Vehicle Classification Based on Wayside Monitor Data: a Case Study*, In: High Tech in Heavy Haul, IHHA Inc, 2808 Forest Hills Court, Virginia Beach, VA USA, June 2007. International Heavy Haul Association, IHHA, Virginia Beach, Va., 2007, pp.471-477.

[11] Nilsson L. and U. Diehl, *Svenska lok och motorvagnar (Swedish Locomotives and Rail Cars)*, Förlagsstallet HB, Gothenburg, Sweden, 2006.

[12] Sollerqvist F. J. and G. Varjú, *Comparison of Btrr, Btrc and At Traction Feeding Systems in Norway*, Technical Report, STRI, Jernbaneverket, Norway, 2003.

[13] Schmieder A., F. Kießling and R. Pushmann, *Contact Lines for Electric Railways*, Publicis Corporate Publishing, Munich, Germany, 2001.

[14] Nyström B. and U. Kumar, *Analysis of Train Delay Information*, In: Proceedings of the World Congress on Railway Research, Edinburgh, September-October 2003. WCRR, 2003, pp.253-261.

[15] Wisten A., S. Niska, J. Ekman, D. Björklöf and J. Delsing, *Experimental Investigation of EM Noise Environment Surrounding Detector Systems in Swedish Railways*, Electric Power Applications, Vol. 153, No. 2, pp.191–196, March 2006.

[16] Benda S., *EMC undersökning i Kiruna 2003-06-23—27 (EMC Investigation in Kiruna 2003-06-23 –27)*, Technical Report, Luleå Railway Research Center (JVTC), Luleå, Sweden, 2003.

Stefan Niska is currently in his fourth year of a Ph.D. research program, sponsored by and working with Banverket, at the division of Operation and Maintenance Engineering at Luleå University of Technology. His focus of work is how the EMC design in railway subsystem affects the maintenance in the Swedish railways.

Paper B

S. Niska, H. Schunnesson and B. Nyström (2008). *Causes of EMC disturbance on the railway - A study of recurring faults in the signal box at Oxmyran Station in Sweden*. Accepted for publication in the International Journal of Condition Monitoring and Diagnostic Engineering Management (COMADEM).

Causes of EMC disturbance on the railway
A study of recurring faults in the signal box at Oxmyran Station in Sweden

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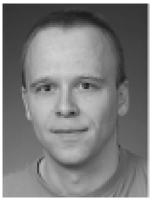
Håkan Schunnesson, PhD, have for a number of years been working for the Swedish mining equipment industry and as an independent consultant in the field of drill monitoring, exhaust purification, and vibration analysis for production control. In 2004 he joined Luleå University of Technology and the division of Operation and Maintenance Engineering as an assistant professor. His main interest is in mine automation, mining equipment monitoring, production control, maintenance and key performance indicators.



Birre Nyström has a PhD degree from the division of operation and maintenance engineering at Luleå University of Technology. His main research focus is in the field of maintenance of railway systems and its implication on punctuality.

ABSTRACT

Failure reporting systems in the railway industry are reliant on correct reporting into the system, so that the right information may be sent back to the user. This information is needed for correct decision-making in the maintenance process. For failure due to electromagnetic disturbance a correct classification can be very difficult to make in the field, with limited time available for the analysis of failure causes. Banverket (the Swedish Railway Administration) has a problem in a signal box at Oxmyran Station, where faults are reported frequently. The wide variation in the reported causes of the disturbance of the electromagnetic compatibility makes it very difficult to pinpoint the real causes of the events that lead to failure. In this paper a large number of causes are investigated, discussed and dismissed as reasons for the large number of faults at Oxmyran. Measurements on site, however, show that the electromagnetic interference is much higher at Oxmyran than at the reference station at Öre Älv. The main purpose of this study was to investigate the probable source and the subsequent sequence of events that result in faults that break the RC circuit at Oxmyran. This be completed and requires continued meticulous investigation of the system.

KEYWORDS: Maintenance process, railway, measurements, electromagnetic compatibility, signal box

1 INTRODUCTION

The most important task for a failure reporting system is to classify correctly the type and the causes of a failure [1]. The consequential maintenance planning performed and the decisions or action taken by maintenance staff or maintenance technicians out in the field are based on the information provided by the failure reporting system. Any error in the reporting system will influence the following maintenance process.

To document the numbers of faults, the type of faults and the time that it takes maintenance personnel to correct them, Banverket uses a failure reporting system called 0felia [2]. Every time a failure occurs in the Swedish railway infrastructure, the fault is registered in the 0felia database. 0felia has over time gradually been expanded to contain more and more information.

For the system to work, failures have to be reported correctly in terms of fault recognition, localization and cause identification. Erroneously reported failures provide an untrue picture of the behaviour of individual items or the entire infrastructure [3]. Correctly reported failures are also important if the right decisions are to be made for an effective maintenance management process. The responsible technician has to be precise in his reporting, to verify that the exact problem in the process is also entered in the maintenance reporting system, so that the failure reporting system may contain correct information which is useful for investigating, planning and even system improvement.

Today the Swedish railway, like other branches of industry, follows the general trend of replacing relay technique with modern electronic systems [4]. The arguments for this are that the investments in electronic systems are lower than those required for relay systems. The required hours of maintenance, in general, are also lower for new electronic systems compared to the older relay systems. However, one important drawback with modern electronic items is that, compared to the older relay systems, they are much more sensitive to electromagnetic (EM) disturbance. In this new technical environment where different levels of voltage are used in the same infrastructure and where many relay-based systems have been replaced by new electronics, an increased understanding and knowledge of EM disturbance and electromagnetic compatibility (EMC) [5] are a must for railway infrastructure management personnel and for external contractors.

In the present failure reporting system, EMC problems and EM disturbance are to some extent concealed. A correct classification of EMC disturbance can be very difficult to make in the field, with the limited time available for the analysis of failure causes. Nevertheless, a correct failure cause characterisation is the basic foundation for any improvement of the knowledge and design of the system and the maintenance required [6, 7]. Therefore, the technical personnel must have a good grasp of EMC if they are to report accurately the faults and the sources of the faults. In general, knowledge of the process becomes increasingly important for the maintenance staff and management, when equipment becomes complex, involving more areas that before, i.e. electronics.

This paper presents a detailed investigation of an electronic unit, an RC circuit, which has recurrently failed in the same failure mode without any reasonable explanation. The circuit is affected by EMC disturbance, which could be one reason for the registered problems. The difficulty of characterizing this type of failure and the consequent impact on the failure reporting system are evaluated and discussed.

2 TEST SITE, LOCATION AND DESCRIPTION

The site selected for this study is a station named Oxmyran, located on the main railway line in Västerbotten County in northern Sweden, see Figure 1. The closest bigger station is Vännäs and the closest city or town is Umeå.

According to the 0felia database, an RC-circuit in the signal box at Oxmyran has during the past six years failed remarkably often, compared to other similar circuits. This circuit failure has created large unnecessary costs for replacement of the circuit and a number of train delays. The cause of the failures is suspected to be electromagnetic interference.

Only 5 km away from Oxmyran, at Öre Älv, a similar signal box is located. The same type of RC-circuit at Öre Älv has no reported faults during the same period, even though the traffic is identical.

Figure 1. The location of Oxmyran, at the end of the arrow, on a map of Sweden with some of the railway lines and towns.

Both the Oxmyran signal box and the Öre Älv signal box were built in 1995. Before 1995 the old railway line made a big turn from Öre Älv to Nyåker and then back to Oxmyran. In 1995 Banverket built a new main line with a tunnel through Glödberget, running directly from Öre Älv to Oxmyran. The distance between the stations at Öre Älv and Oxmyran along the new route is 5 km. The old line was maintained, effectively resulting in a double track, see Figure 2.

For Banverket it is vital to understand the reasons behind the recurring faults at Oxmyran and explain why an identical signal box at Öre Älv has no similar problems at all. Is the problem related to the design, construction, operation or any external influences?

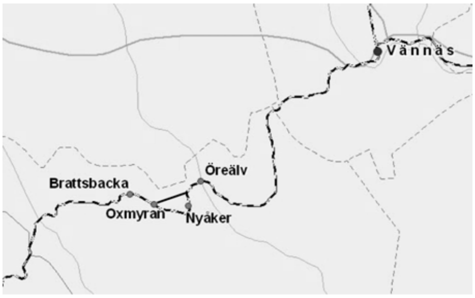


Figure 2. The main railway line from Vännäs to Oxmyran via Öre Älv and over Nyåker, and further south to Brattsbacka. The new track that was built in 1995 between Öre Älv and Oxmyran, marked as the straight black line between Öre Älv and Oxmyran.

3 METHOD

The results presented in this paper are based on:

- Measurements on site.
- Information from Banverket's fault reporting system “0felia”.
- Information from Banverket's system for traffic information (TFÖR).
- Information from the Swedish national strike statistics.
- Interviews with responsible technicians.
- Interviews with system and circuit suppliers.
- Interview with an installation supervisor.
- Interviews with maintenance personnel.
- Visual inspection on site.

Initially a cause-and-effect diagram, (see Figure 3), was made for structuring possible sources of the fault. Every problem in the diagram could influence and be a possible source of EMC failure in the infrastructure and in the signal box, see Figure 3.

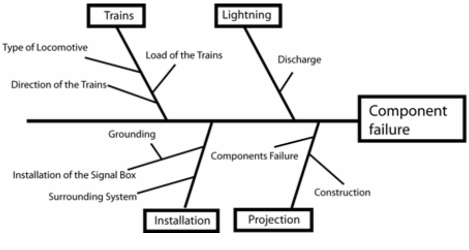


Figure 3. Cause-and-effect diagram of possible error causes.

4 SYSTEM FUNCTION

The signalling system in the railway infrastructure ensures the safe operation of rolling stock, for example by providing lights for the locomotive driver, the positions of turnouts, and the localisation of train positions on the track to prevent the collision of rolling stock.

A “station” is the location of one or several turnouts. A station on a single track makes it possible for trains to meet and overtake, see Figure 4.

Figure 4. On a single track a station is used for meeting and overtaking trains.

The equipment for the signal system and other equipment that is needed by the track or the station are protected in a signal box located near the track. The signal boxes at Oxmyran and Öre Älv are 3 x 5 metres.

Besides the signalling system, the signal box also contains electrical and telecommunication systems. The electrical system delivers power to the other systems, while the telecommunication systems are used for communication, e.g. a telephone, modem etc.

The signalling system controls the safety and informs the locomotive driver and the train traffic controller (who is located in a centralized train traffic control (CTTC) office) of the situation on the track. The detailed information is communicated from signal boxes that receive data by wires, from the signalling lamps, turnouts and positioning systems along the track. It is therefore essential that the equipment, cables and wires close to the track should send the right information and provide accurate signals from every position along the track.

4.1 Train positioning system

The information as to where the trains are on the track is provided by the train positioning system.

The train positioning system uses the two rails on a track, the common rail (S-rail) and the information rail (I-rail), to locate the position of the trains. The S-rail is continuous and is grounded. The I-rail, on the other hand, has galvanic gaps with an insulated block joint between different sections of the rail. Every second I-rail section has a positive potential (7 V) and the other sections have a negative potential (-7 V). The gaps isolate each section of the I-rail with a different potential. When no trains are on the line, there is a negative or positive potential between the rails, see Figure 5.

When a train moves into a new section (over a gap to a new rail section on the I-rail), the potential for the sector drops to zero, since the wheels of the train connect the two rails. The relay in this section holds the voltage drops indicating where the train is on the track.

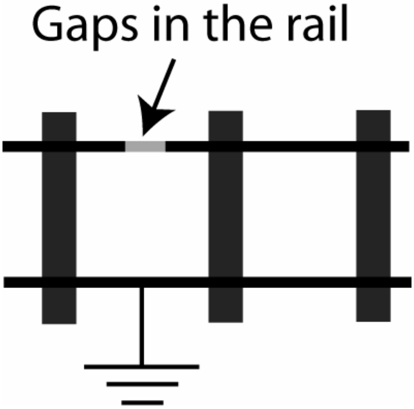


Figure 5. An illustration of the train positioning system, where one rail, the information rail (I-rail), has galvanic gaps with an insulated block joint to split the rail sections. The other rail, the common rail (S-rail), has no gaps.

4.2 Oxmyran Station

When a train enters Oxmyran Station from the south from Brattsbacka, the relay on section SIa is grounded and the potential drops to zero. The train positioning system indicates that there is a train in this section, see Figure 6.

When the train continues into the first section of Oxmyran Station, from the south, the potential of the S1a relay drops and affects the RS1 relay so that the RC circuit receives power, see Figure 7.

When the train moves over to the next section and the potential of the relay S1b or S1c, depending on the direction of travel, drops to zero, this indicates the presence of the train in this section. The RS1 relay is still pulling and makes sure that there is power to the RC circuit, see Figure 8.

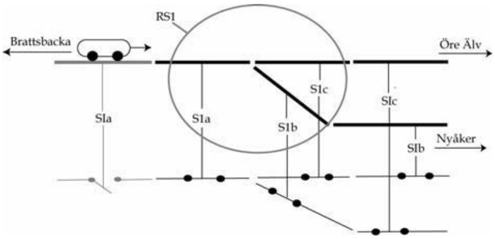


Figure 6. The state of the train positioning system when a train is entering Oxmyran Station from the south via Brattsbacka; the potential of the section (relay) before the station has dropped to zero.

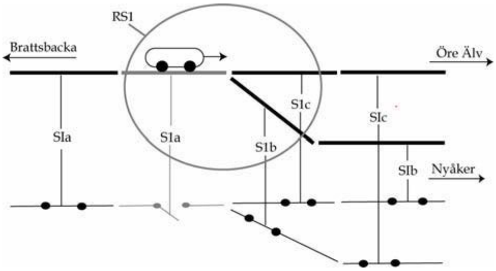


Figure 7. The train is at Oxmyran Station. The potential of the relay S1a has dropped and therefore influences the RS1 relay.

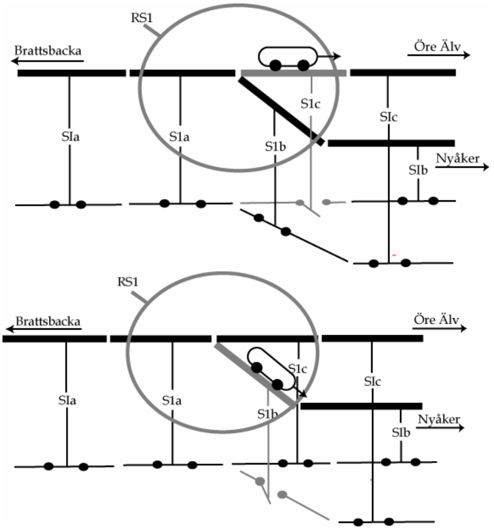


Figure 8. The train is at Oxmyran Station and the potential of the S1b or S1c relay has dropped, depending on which way the train is going. The RS1 relay is still activated by the presence of the train at the station.

When the last wagon of the train leaves the station, or, in this case, when the last wagon leaves the station section indicated by the S1a, S1b, or S1c relay, the power of the RS1 relay drops immediately. The next section SIb or SIc, depending on which way the train goes, indicates that the train is now in this section, see Figure 9.

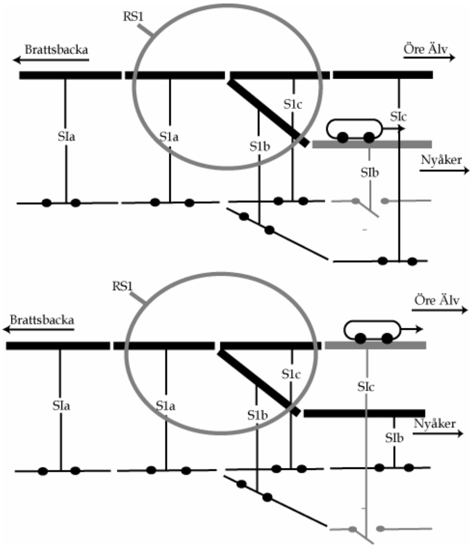


Figure 9. When the train leaves Oxmyran Station and the potential of the relay SIb or SIc drops, depending on which way the train runs, this indicates that the train has left the station. The potential of the RS1 relay drops too.

4.3 System description

The relays are placed in a chain and are dependent on each other. Every relay that is in a chain is to make sure that every signal that has to be active receives the power in the same chain. When the RS1 relay drops, the power to all the other relays after it in the chain does not have the time to switch back. This power is supplied by the RC circuit, which can hold the power within a few milliseconds, and that is enough for the rest of the relays in the chain to switch back. If the RC circuit is broken, there will be no power to supply the relays after in the chain and these relays cannot pull back, and consequently the system indicates that the train is remaining at the station. The RC circuit investigated in this paper has this sole function of supplying power to the relays and looks like that shown in Figure 10.

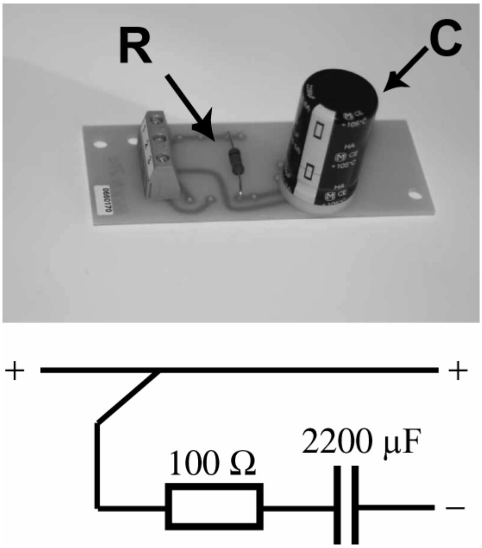


Figure 10. The circuit is an RC circuit, has a resistance, marked R in the figure and photo, of 100 Ω and is connected in series with a capacitor, marked C in the figure and photo, of 2200 µF.

The circuit is a printed circuit card with a resistor (R) and a capacitor (C), an RC circuit. The voltage level for the RC circuit is 27 V. A rectifier converts the power from AC 220 V to DC 27 V and delivers it to the system where the RC circuit is.

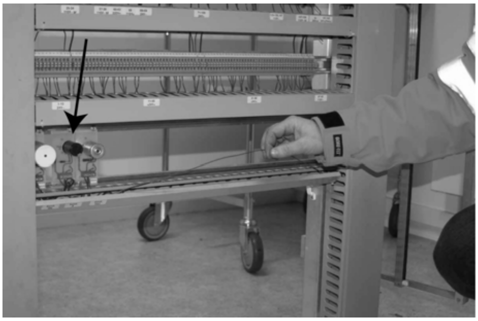


Figure 11. The placement of the RC circuit in the rack (the middle RC circuit in the square indicated by the arrow) and the wire from RC circuits that have the same size both on the negative bound and on the voltage side. The area of the solid wire is 0.75 mm^2.

There is a fuse between the rectifier and the printed circuit card. The printed circuit card is connected on both sides with a 0.75 mm2 solid wire. This wire goes to a negative wire loop joining other printed circuit cards that have the same function (but in different systems) and is grounded, see Figure 11.

At the station there are electrical circuits, computer systems like a PLC (Programmable Logic Controller), and electrical relays for the equipment in the area which the station controls. The equipment that must be located close to the track is protected in boxes. The boxes are connected to the signal box via shielded twisted pair cables.

Between the stations the electrical signals are sent through a belted and shielded cable with 27 twisted pairs of copper wires that connect to the next station. All the systems, namely the electrical, telecommunication and signalling systems, use this cable for communication.

Bigger stations gather the signals and send them to the CTTC office via an optical cable.

5 FAILURE REPORTING SYSTEM AND FAILURE HANDLING

Banverket uses a failure reporting system called 0felia (0 = zero; felia = faults). Every time a failure occurs at Oxmyran or in any other part of the railway infrastructure, it is to be reported and registered in 0felia.

When a fault appears, it is indicated at the CTTC office by alarms from the signal and detector systems. The CTTC office staff then initially report the occurrence of the fault to 0felia, after which they call the contractor’s contact person, who in turn instructs personnel to remedy the fault. Maintenance personnel receive a work order to check the alarm and perform repair work, if necessary, and then drive to the place of the fault.

After the visit on site and the repair, the maintenance workers must report back to the CTTC office, which then finalises the report in 0felia [2]. The report in 0felia includes several fields, e.g. the real fault, definition of the fault, cause of the fault, description of corrective action, etc. [2].

This report is therefore mainly dependent on the maintenance worker and on the fault analysis being correct and the reported source of the fault and cause of the failure also being correct.

When an RC circuit fails, the CTTC office personnel notice on their computer system that the train route on the track still remains red after the train has left the station.

With a working RC circuit the light switches back to green, in the computer system, when the train leaves the station. In the case when the RC circuit is broken, it is not possible to set a new train route in the CTTC's computer system and use the signalling lights for the locomotive driver out along the track. Therefore, the station must be visited (even remotely located stations like Oxmyran) and the RC circuit repaired before the station can again be available for traffic controlled by the CTTC's computer system. During the time when the circuit is broken, the signal can be overruled using mobile phone contact between the locomotive driver and the CTTC office staff to control the safety on the track.

During the period from January 2001 to October 2007, 35 faults concerning RC circuits, of a total of 77 faults, were reported at Oxmyran in 0felia, whereas no faults were reported for the RC circuit at Öre Älv. One example of a faulty RC circuit is shown in Figure 12. Here the resistor has been overloaded, causing a material breakage, see the arrow.

With this large number of similar faults, the first item checked by maintenance personnel when arriving at Oxmyran is the RC circuit. Normally the maintenance personnel have difficulty in obtaining a new RC circuit, since they only have one in stock locally. Obtaining a new one can take several days. In this case, anticipating that the RC circuit will fail again, the maintenance staff for Oxmyran today orders more than one RC circuit and place the stock of spare parts in the Oxmyran signal box.

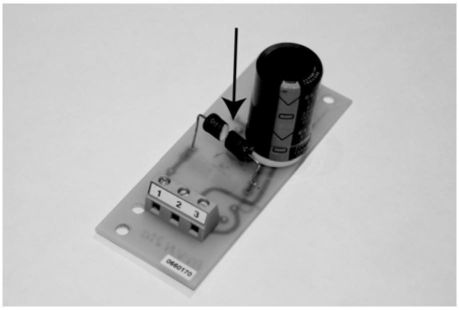


Figure 12. A faulty RC circuit.

6 POSSIBLE CAUSES

There are a number of possible causes of the fault that has been occurring in the signal box at Oxmyran Station. To find the actual cause, several possible causes have been studied in depth. These possible causes are as follows:

- ✓ Lightning
- ✓ Trains
- ✓ Construction
- ✓ Installation
- ✓ Grounding
- ✓ Surrounding system
- ✓ Components

6.1 Lightning

Oxmyran is not in an area where there is much lightning. In general lightning occurs mostly during the summer, and for Oxmyran most faults caused by "thunder" occur during the summer period, according to 0felia. Occasional faults have also occurred during the winter.

Of the 35 RC circuit faults reported in 0felia during the period from 1 January 2001 to 1 May 2007, 13 reports have been filed stating the cause as "thunder", see Table 1. For this to be the cause, lightning has to hit or discharge close to the railway infrastructure to cause interference in the railway infrastructure and its systems, especially the RC circuit system. After the discharge, a train has to pass the location, Oxmyran, in order that CTTC may detect the failure and generate a report in 0felia.

To verify the "thunder" causes reported in 0felia, the Swedish national strike statistics were used [8]. The accuracy of this discharge information is + 500 - 1000 m. To be a possible cause, the dates and times that have been reported into 0felia should agree with the dates and times of the discharges, from clouds to ground.

The analysis shows that, out of the 35 reported faults, there were six occasions on which the location of the lightning strike was within a 25 km radius of Oxmyran. Five of these faults were reported as "thunder" and one as "uncertain electric disturbance". The time between the lightning strike and the alarm being triggered by a train passing Oxmyran was between 40 minutes and 3 hours and 36 minutes.

If the lightning strike is to be the fault cause, the alarm must be triggered by the first train passing Oxmyran after the lightning strike. According to the traffic roll for trains passing Oxmyran, several trains passed between the time when the strike was registered and the time when the alarm went. Only on two occasions, out of six, was the alarm triggered by the first train that passed after the lightning strike. Only on these two occasions was it possible that a discharge, "thunder" or lightning could have caused the alarm.

Furthermore, if a discharge or strike was the cause, it would be reasonable to assume that the energy from a strike should affect more than one circuit or item at the station, and that more circuits should have been damaged at the station.

To conclude, only 2 out of 13 reported faults due to lightning in 0felia could be correct. Moreover, for the remaining 2 occasions it is doubtful if lightning was the true cause. For "thunder" or lightning, the accuracy of the fault reports and the cause of the fault are questionable.

Table 1. The dates of the fault occurrences registered in 0felia concerning the RC circuits at Oxmyran; in 0felia the actual fault is registered under the column “the real fault” and the cause under the “cause” column.

Date Time	**The real fault**	**Cause**
2001-06-18 18:15	Material breakage	Broken component
2001-06-19 00:30	Unable to detect	Broken component
2001-07-04 22:28	Interruption	Thunder
2001-07-05 09:29	Interruption	Thunder
2001-08-11 16:13	Material breakage	Broken component
2002-06-07 17:45	Interruption	Thunder
2002-07-04 08:07	Interruption	Thunder
2002-07-12 08:42	Interruption	Thunder
2002-07-16 00:10	Interruption	Thunder
2002-07-24 09:12	Interruption	Thunder
2002-07-26 19:37	Interruption	Thunder
2003-06-25 17:12	Interruption	Uncertain electric disturbance
2003-07-21 16:24	Interruption	Thunder
2003-08-15 08:56	Material breakage	Thunder
2003-12-03 06:06	Interruption	Broken component
2004-05-10 06:01	Material breakage	Thunder
2004-07-17 05:40	Interruption	Broken component
2004-07-19 09:17	Unable to detect	Broken component
2004-08-20 11:18	Interruption	Broken component
2004-11-19 06:07	Interruption	Loose part
2004-12-22 16:34	Interruption	Uncertain electric disturbance
2005-04-09 22:29	Interruption	Broken component
2005-04-15 05:33	Unable to detect	Broken component
2005-05-25 09:40	Interruption	Broken component
2005-05-26 07:35	Interruption	Uncertain electric disturbance
2005-09-04 17:31	Interruption	Broken component
2005-09-09 22:31	Interruption	Thunder
2006-06-01 09:25	No fault	No fault found
2006-06-02 06:01	No fault	No fault found
2006-06-08 14:54	Unable to detect	Broken component
2006-06-21 07:11	Interruption	Thunder
2006-07-11 05:45	Unable to detect	Investigated the electronics
2006-09-07 13:33	Interruption	Uncertain electric disturbance
2006-09-14 13:05	Interruption	Broken component
2006-10-22 08:04	Interruption	Broken component

6.2 Trains

The train route passing Oxmyran Station is used, for example, to transport steel slabs from SSAB (Swedish Steel Inc) in Luleå to SSAB in Borlänge, where sheet metal is made.

The steel trains are very heavy and require higher power than most other trains. Consequently, this generates higher electromagnetic fields [7].

The steel trains always carry a heavy steel load when travelling south from Öre Älv to Oxmyran, whereas, when going north in the opposite direction from Oxmyran to Öre Älv, the trains are empty.

The elevation and slope of the track can also influence the disturbance. The lowest location is at Öre Älv, from which the elevation increases up to Oxmyran. The older track via Nyåker has a higher slope than the new track running directly to Oxmyran, see Figure 11. A train that starts after waiting for another train needs high power to accelerate, especially on an upward slope, and may generate a larger disturbance. This means that the direction of the train will influence the magnitude of the disturbance.

From Table 1 it can be seen that there is no correlation between the type of train passing Oxmyran Station and the faults that occur there. Different types of locomotive, types of train, travelling directions, or train weights cannot explain the faults.

Even if there is a possibility that a specific locomotive may disrupt the equipment at Oxmyran, this is not very likely, since similar faults do not occur at the reference station at Öre Älv.

6.3 Construction

One possible explanation of the differences between Oxmyran and Öre Älv could be that the design and the construction of the signal boxes are different, and therefore influence the sensitivity to disturbance.

However, both signal boxes were built by the same company, Banverket's Industry Division, in Nässjö. The signal boxes were transported by truck to the locations at Öre Älv and Oxmyran. They were built according to the same instructions and drawings, and appear upon visual inspection to be alike. The only apparent difference is the location of the wire that is drawn to the ground, see Figure 10. However, a full investigation has not been made to verify that every single wire or cable in the signal box is identically located.

The constructions at Oxmyran and Öre Älv are similar, as far as could be seen in this investigation. Therefore, it is not likely that the construction has any impact on the frequent failure of the RC circuit at Oxmyran Station.

6.4 Installation

Differences in the signal box installation leading to better EM protection in one of the signal boxes could explain the registered differences between Oxmyran and Öre Älv.

However, the same contractor, Banverket Production, installed the signal boxes at both Öre Älv and Oxmyran. The installation supervisor has been interviewed and there is no information pointing to the issuing of different instructions during the installation of the two signal boxes. On the contrary, all the available information indicates that both signal boxes were installed in the same manner.

6.5 Grounding

Since the same contractor has installed both boxes at Oxmyran and Öre Älv, according to the same drawings and instructions, the grounding system should be similar in both boxes.

In order to obtain a better grounding, both the Oxmyran signal box and the Öre Älv signal box, like every other signal box, have a ground loop around the box, connected to an iron bar that has been installed in the ground close to the box. The iron bar is connected to the S-rail to obtain a better grounding, especially for a lightning strike. However, since it is difficult to know the location of the ground cables from the signal boxes to the S-rail (the ground in the railway system), there is no guarantee that both the grounding systems are placed in a similar way.

There is no indication of any difference in the grounding of the signal boxes, according to the construction drawing and the interviews with the project manager. However, the grounding at Oxmyran has been checked and supplemented with double cables connected to the rail to obtain a low potential.

However, grounding is a very complex area, influenced by many parameters, and it is not easy to discount it as a fault source. Differences in the placement of the ground cable could be a possible cause in this case.

6.6 Surrounding system

At both Oxmyran and Öre Älv, the distances from the overhead contact wire to the signal box are approximately the same.

Moreover, there is a transformer for reserve power (if Banverket's power breaks down), only 10 m away from the signal box at both Oxmyran and Öre Älv.

The older database that contained information on the reserve power switching on and off has been erased, but in the recent information, no correlation could be found between the reserve power switching on or off and the times of faults in the RC circuit in Table 1.

6.7 Components

In each signal box there are six rectifiers. On the primary side each rectifier has 220 V, while on the secondary side there is a variation from 6 to 220 V. All the rectifiers installed at Oxmyran and Öre Älv were made by the same company. Moreover, for those subsystems that have been checked, the specifications are the same.

The visual inspection shows that the RC circuit is different, but follows the same specification. The connections differ as mentioned; see Figure 11, which shows the placement of the wire from the RC circuit, on the negative side, at Öre Älv. At Oxmyran it is placed on the opposite side in the cable channel above.

There is nothing that indicates that the circuits differ or that differences in the rectifiers could be the source of the fault. In an interview, the supplier said that there had been no problem with the rectifier at all, and that they had not received any returns due to the rectifier breaking and causing similar problems to those at Oxmyran.

6.8 Quality assurance

Banverket conducts no quality control or inspection of circuits before they are taken into operation in the system. Instead they rely on the suppliers doing a good job, and on the RC circuits being built according to the correct specifications.

The rectifier, however, is tested and inspected by the manufacturer.

7 MEASUREMENT OF THE CIRCUIT

Measurements have been undertaken to determine if there are any differences between the systems at Oxmyran and similar systems at Öre Älv.

The measurements were made in both the signal box at Oxmyran and the signal box at Öre Älv. A laptop computer and an NI USB-6251 DAQ (data acquisition) unit from National Instruments were used. To control the measurements and collect the data from the DAQ, the software LabView from National Instruments was used. The probe measured voltages over the RC circuit. The DAQ has an input span of -10 V to +10 V and could not measure the 27 V DC that is supplied by the rectifier to power the RC circuit. Therefore, a probe that damped the signal by 10:1 was used to facilitate measurements with voltages up to 100 V. The trigger was set at 3 V; i.e. it started the measuring at 30 V. Levels below 30 V are common voltages for the system and do not cause any damages to the RC circuit. The resistor and capacitor has similar specification on 64V. The sample rate was set to 10 kHz.

Two DAQ units and computers were used, with one set of equipment located at Oxmyran and the other one at Öre Älv. Both the units were tested in labs before the site test, to verify that they show the same values from the same source and behave in a similar way. They were checked with a Kiethley 2400 SourceMeter. To verify the function of the measurement programme on site, it was periodically tested by a measure when the computer clock changed over to a new date. There was no train passing at this time.

Figure 13 (from Öre Älv) and Figure 14 (from Oxmyran) show measurements that were performed in the middle of the night.

The measurements clearly show that there are differences between the station at Öre Älv and the station at Oxmyran. The diagram from a measurement of the RC circuit from Öre Älv, Figure 13, is very stable with a low voltage and indicates the zero level. The diagram from a measurement at the same point at Oxmyran has a ripple signature and a different voltage level, 80 times higher than that at Öre Älv, see Figure 14. Both measurements were produced during the night and no trains were passing. The voltage level should be zero, but this clearly shows that there are differences between the systems. The presented difference may cause the problems in the subsystem that contains the RC circuit at Oxmyran.

Three measurement runs were triggered at Oxmyran and none triggered at Öre Älv. The trigger level is set over the normal level and differs from the specification in the system and the specific RC circuit. The levels of the transients are 50 V or more.

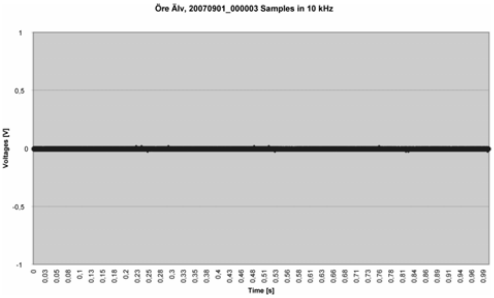


Figure 13. Measurement during the night when there were no trains at Öre Älv Station.

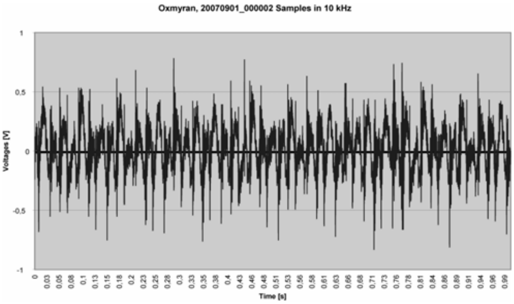


Figure 14. Measurement during the night when there were no trains at Oxmyran Station.

8 DISCUSSION

This paper describes a problem with the RC circuit at a station on the Swedish railway called Oxmyran. The RC circuit at Oxmyran failed 35 times during the period from January 2001 to October 2007. During the same period no failure of the RC circuit was reported in an identical signal box at Öre Älv only 5 km north of Oxmyran.

No differences between the stations can be found regarding the type of train, the direction of travel, or the load of the trains that could explain the differences in the occurrence of the faults. In terms of construction, installation, grounding, surrounding systems, and circuits, there are no differences between the stations that would explain why failure should occur more often at Oxmyran. As a fault source in Banverket’s failure reporting system, 0felia, “thunder” or lightning has been pointed out in 13 cases. However, the present analysis shows that this is possible in only 2 of the 13 cases. Furthermore, there is no possible explanation found as to why only Oxmyran is affected by “thunder” or lightning and not Öre Älv.

In 0felia, the cause of each fault must be reported. This information is provided by the maintenance staff visiting the station to repair the RC circuit after each failure. For the overall maintenance planning the 0felia data base provides an important input, and it is therefore of great importance that the data should be correctly reported. The failure reporting system to some extent conceals the fact that the circuit recurrently fails in the same failure mode. Inaccurate information in the reporting system makes it more difficult to study and understand the EM interference (EMI) problem and thus to improve the EM design and maintenance.

This study clearly demonstrates the difficulty of correctly defining the cause of the fault. In this case large resources and time have been spent to investigate the problems at Oxmyran, but the uncertainty remains about the true cause of the fault. The problem associated with defining the fault cause, for maintenance personnel visiting Oxmyran after each fault, is obvious. Instead the maintenance staff have today given up and found a temporary solution which involves leaving several spare circuits in a plastic bag in the signal box at Oxmyran.

Nevertheless, the presented measurements show that there are significant differences between the stations at Öre Älv and Oxmyran, and that the EMI is much higher at Oxmyran. However, there are no measurements during the period immediately before and during an RC circuit failure that can confirm this. The problems may also be influenced by the ground dampness, which in turn may affect the grounding system. However, according to this study, no differences have been found between the stations in this respect. Nevertheless, the EMI influence must be studied further to understand the impact on the railway control system.

The purpose of this paper and case study was to investigate the probable source of the fault that breaks the RC circuit at Oxmyran. This task remains to be completed and requires continued meticulous investigation of the system.

9 CONCLUSIONS

Even if the research work aiming to find the source of the failure at Oxmyran continues, some conclusions can already be drawn:

- It can be very difficult for maintenance staff to detect correctly the source of the fault during a short repair or maintenance visit on site.
- The difficulty seems to be even greater for EMC-related faults.
- Thunder or lightning is not the source of the faults at Oxmyran, and this cause may also be overestimated at other places.

10 REFERENCES

1. M. Kans. A holistic perspective of computerised maintenance management support. In U. Kumar, A. Parida, R.B.K.N. Rao, editors, Condition Monitoring and Diagnostic Engineering Management, p. 231–241, Luleå, Sweden, June 2006. Division of Operation and Maintenance Engineering, Luleå University of Technology.

2. B. Nyström, U. Kumar. Analysis of train delay information. In Proceedings of the World Congress on Railway Research, p. 253–261, Edinburgh, September-October 2003.

3. P. Söderholm. A system view of the no fault found (NFF) phenomenon. Reliability Engineering & System Safety, 92:1–14, Jan 2006.

4. L. Pintelon, N.D. Preez, F. Van Puyvelde. Information technology: opportunities for maintenance management. Journal of Quality in Maintenance Engineering, 5(1):9–24, 1999.

5. T. Williams., (1996), EMC for Product Designers, B.H. Newnes, Oxford.

6. F.M. Tesche, M.V. Ianoz, T. Karlsson, (1997), EMC Analysis Methods and Computational Models, John Wiley & Sons Inc., New York.

7. S. Benda, (2001), Interference-free Electronics: Electromagnetic Compatibility, Studentlitteratur.

8. Uppsala University. Lightning Research, Faculty of Science and Technology, 2007.

Paper C

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Experimental investigation of EM noise environment surrounding detector systems in Swedish railways

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Abstract: The close environment of railway tracks is heavily polluted by electromagnetic noise from the railway system itself. The reliability of railway signalling, communication, and control systems depends on good immunity to electromagnetic noise. There are sometimes false detector signals indicating non-existing flat wheels and ghost trains. A possible reason for detector failures is interference by transient voltage peaks in the detector system. Thus characterisation has been made of the electromagnetic environment around the detector system located at the track. The investigation shows that the typical electromagnetic environment is a combination of broadband low-level noise, and rare fast transients of potentially harmful amplitudes.

1 Introduction

The environment of railway tracks is exposed to magnetic and electric fields from trains, the railway power supply systems, nearby electric power transmission lines [1], and also from other sources [2]. A general trend towards increasing traffic flow, higher speeds, more trains per hour, longer trains and heavier axle loads demands more powerful engines and stronger currents in the supply lines. Consequently the radiated and conducted electromagnetic emissions from railway systems are increasing over time [3, 4].

The high-frequency content of the emitted fields [5] is also increasing owing to new methods of motor control. On the other hand, the switching voltages of electronic systems are decreasing, which is a consequence of a general demand for lower power consumption, and faster switching frequencies. The combination of more sensitive electronic circuits [6], and stronger electromagnetic noise, containing higher frequencies, may make the railway system as a whole more sensitive [7]. Systems of traffic signalling are not only crucial for safe traffic, but also important for traffic efficiency. If anything goes wrong in the signalling systems, all lights should switch to red, which is safe, but can cause delays in the timetables. Although traffic signalling systems have very high reliability, there have been unexplained phenomena, which may have been caused by disturbance from passing trains [8]. Because of very high goals for reliability, a continuous programme of work is going on, aiming at the highest possible security [9].

An investigation has been made in order to characterise train-induced electromagnetic noise in electronic systems in the close neighbourhood of railway tracks. For this aim, measurements on detector systems for flat wheels, hot brakes and hot bearings have been performed. Measurements on the signalling system have not been carried out due to the potential risks of harming important security functions. There are several reasons for choosing the detector systems for this investigation, for example:

- There have been false signals in detector systems, indicating passing axes and trains that did not exist, or just giving alarms for system down.
- It is important that the detector systems are so reliable that correct decisions can be made by the driver whether or not to stop a train and take a certain car out of operation.
- The cables used in the detector systems are of the same type as the cables used in the signalling system.

With the purpose of finding possible reasons for failing electronic systems in the railway environment, electromagnetic noise has been studied at two detector sites in northern Sweden. One detector site, Notviken, specialises in detecting flat wheels by means of strain gauge bridges. The other detector site, Sunderbyn, has two IR-detector systems: one for hot bearings and the other for locked brakes. The Notviken section is fed by a booster transformer (BT) system, while the section in Sunderbyn is powered by an autotransformer (AT) system. The electromagnetic noise at the detector sites was measured under winter and summer conditions.

2 Swedish railway system

2.1 Power supply

Swedish trains are powered by $16\frac{2}{3}$ Hz/16 kV alternating voltage. The railway power network is fed from the main Swedish 50 Hz power lines by converter stations. The converter stations are typically rated 50 Hz/6 kV at the primary, and $16\frac{2}{3}$ Hz/2.5 kV at the secondary. The secondary voltage of the converters is transformed to 16 kV to fit the train voltage. The power rating of the converter stations is 10 or 5.8 MVA. The distance between converter stations is about 100 km. The input voltage 16 kV is applied between the contact line and one of the rails, the ground (S) rail. Therefore, the return current from the engine passes partly through the S-rail, and partly to the ground. To minimise the current in the ground, there are booster transformers every 5 km, in the BT system, or in the AT system, about

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every 10 km. These transformers are designed to make the current in the rail equal to the current in the contact line (primary winding: contact line current; secondary winding: rail current). The BT system prevails in Sweden as a whole, but the modern AT system is installed at the ore track in northern Sweden, at the Öresund bridge to Denmark, and in parts of the western high-speed line. The AT system is fed with 32 kV from the converters, between the contact line at +16 kV and a support line at −16 kV, suspended at the poles, all along the track. The S-rail, i.e. the ground, is connected to the midpoint between +16 and −16 kV, which makes the train voltage still 16 kV, as it is in the BT system. The other rail, the so called I-rail, is divided into isolated sections, each section set at a 6 V DC voltage. The purpose of this arrangement is to detect the positions of the trains, i.e. traffic monitoring [8]. The wheel axes make short circuits between the S-rail and the I-rail, lowering the voltage of the I-rail to zero. A section where a train is located has zero voltage on the I-rail, while other sections have 6 V DC. Thus the position of the train is defined for the traffic control centre.

2.2 Detector systems for flat wheels, hot bearings and hot brakes

The principle for flat wheel detectors is that imperfect wheels give hard hits to the rail, which can be detected by strain gauges fixed on the rail. Strain gauges are set up in systems of Wheatstone bridges, covering a length of about 3 m of both rails. Each Wheatstone bridge is connected to two wires for the DC power supply, and two wires for measuring the voltage at the balance points of the bridge. The DC power supplies and the evaluation units are located indoors in a measurement shed, a few metres away from the track. The wiring from the strain gauge bridges is packed together in a tube leading to the rack indoors. The wiring distance is 6–10 m, see Fig. 1, depending on the position of the strain gauges. The detector for hot bearings is mainly a distance temperature reading unit, an IR detector at ground level, aiming upwards towards the passing wheel bearings. A mechanical lid protects the optics when no train is passing. The information and control signals are transported using shielded cables, type Belden 1250 A [10], with the main unit indoors, about 10 m away. The detector for hot brakes is also mainly a distance IR meter, monitoring the outer rim of the passing wheels. In this case the cabling to the indoor evaluation unit is shorter.

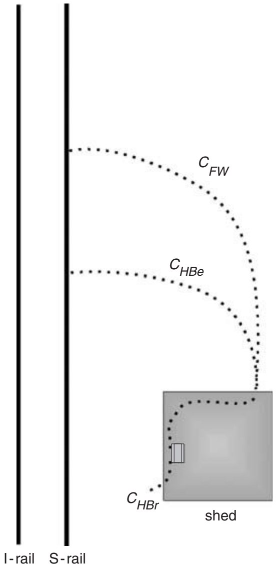

Fig. 1 *Measurements on detector transients performed inside shed*
Detectors connected to evaluation units inside shed by coaxial cables (RG223). Cabling for flat wheel (C_{FW}), hot bearing (C_{HBe}), and hot brakes (C_{HBr}) detector systems

3 Measuring methods

The electromagnetic environment in the neighbourhood of the railway track has been investigated by means of antennas, cables in the terrain and stationary equipment in the detector systems of flat wheels, dragging brakes and hot bearings. Two detector sites in northern Sweden have been thoroughly examined: Sunderbyn and Notviken, site characteristics of which are given in Table 1.

Table 1: Description of measurement sites

Site	Sunderbyn	Notviken
System	AT	BT
	$\pm 16\,\text{kV},\ 16\frac{2}{3}\,\text{Hz}$	$16\,\text{kV},\ 16\frac{2}{3}\,\text{Hz}$
Detectors	Hot brakes	Flat wheel
	Hot bearings	
Misc.	Parallel HV power lines	

Two types of engines have been selected for thorough examination: The freight train engine RC4 and the engine of the 6000 tonne ore trains, the heavy DM3. Electromagnetic fields from passing trains influencing measuring devices and cabling systems have been investigated by means of standard cables, used as antennas, set up close to the track, and by recording signals in stationary equipment for detecting flat wheels, hot bearings and dragging brakes.

3.1 Description of measuring site

The evaluation units of the detector systems are installed in small houses close to the railway track, the nearest wall being about 3 m from the nearest rail. The walls and roofs of these sheds have aluminium shielding, in order to reduce electromagnetic interference of the equipment inside. Our measuring instrumentation was set up inside the same sheds.

To register transients occurring in the detector systems, measurements were carried out inside the shed by connecting the measuring equipment directly to the evaluation units of the detector systems. The evaluation units are connected to each detector system by means of RG223 cables according to Fig. 1.

To be able to separate conducted and radiated transients, the detector system measurements were completed with a cable setup using shielded cables, type Belden 1250A, with two twisted pairs. The twisted pair receiving cables were set up parallel to the rails, at 1, 3 and 6 m distances from the nearest rail, at the same height as the upper level of the rails. At the far end, each twisted pair was loaded with 150 Ω resistors, weather-protected and electrically shielded. While testing for finding best possible locations, cable locations in the middle of the track and very close to one rail were also evaluated, but later not used, because of too low signal levels. A few tests with 15 m Belden-cables starting at a distance of 6 m from the rail, and running at 45 and 90°

angles to the track were also tested, but not further used owing to very low signal levels. The cable locations are detailed in Fig. 2. Each part of the twisted pairs was connected to the centre conductor of a 10 m RG223 cable that was running through specially made aluminium lids covering the window openings of the shed. The indoor length of the RG223 coaxial cables was 2.3 m, giving a total length of 12.3 m. Measurements were carried out using a Tektronix TDS 7254, 2.5 GHz, four channel, 32 Mbyte, oscilloscope, inside the shed, where the common-mode voltages of each part of a twisted pair could be recorded. The differential mode voltages were calculated by subtracting the two common-mode voltages of a twisted pair.

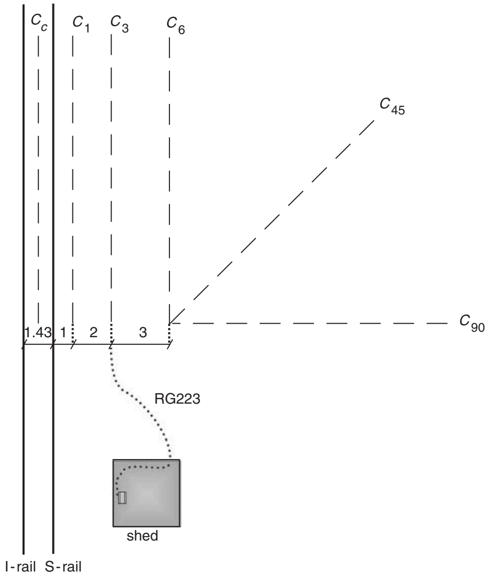

Fig. 2 *Measurements to detect radiated disturbances performed using parallel Belden 1250A cables contacted by RG223 cables*
Cable locations in middle of track (C_C), parallel to rails at 1 m (C_1), 3 m (C_3), and 6 m (C_6) distances from nearest rail, and cables starting at distance of 6 m from the rail, and running at 45° (C_{45}) and 90° (C_{90}) angles to track also tested. Distances in metres

3.2 Description of measurements performed

Earlier [11] measurements indicate that the power densities of frequencies above 500 MHz are relatively low. Based on this, the main efforts have been concentrated to the frequency interval 0–500 MHz. Initial experiments showed very clear evidence that potentially harmful signal energy is located in the frequency range below 10 MHz. Thus it was decided to use a 50 MHz sampling rate. In addition to this, some tests were made with 5 GHz sampling rate to catch higher frequency disturbances. All measurements was made with a Tektronix TDS7254 having a maximum sampling rate of 20 GSamples/s and a memory depth of 32 Mbyte.

A summary of the performed measurements, the conditions and the equipment used can be found in Table 2.

4 Results

This Section presents results for two cases. First, measurements are presented when no train is present. Secondly, measurements for actual train passages are presented. The last part presents box plots for a two-day measuring period for each detector system.

4.1 No train passage

Measurements presented below detail transients recorded by the measuring equipment when no train is present, approaching or leaving the measuring site, i.e. trains are more than 1 min away, corresponding to >800 m away for slowest train type:

(*a*) *Flat wheel detector system and parallel cable setup*: First, a 90 s measurement on one flat wheel detector in Notviken is shown in Fig. 3, together with measurements on a parallel passive cable in Fig. 4. At least one recorded transient, seen around 18 s, at the flat wheel detector is also seen at the passive cable indicating radiated electromagnetic disturbances.

Table 2: Description of actual measurements

Measurement object	Conditions	Equipment	Sampling
Flat wheel detector system		2.3 m RG223 (indoors), 7.0 m shielded, double pairs (outdoors)	50 M samples/s–5 G samples/s
Fig. 1, C_{FW}	No train, Fig. 3		
	DM3, 3 × 500 A, Fig. 7		
Hot bearing detector system		2.3 m RG223 (indoors), 10.0 m BELDEN (outdoors)	2.5 k samples/s–50 M samples/s
Fig. 1, C_{HBe}	No train, Fig. 6		
	RC4, idle, Fig. 10		
Hot brakes detector system		2.3 m RG223 (indoors)	2.5 k samples/s–50 M samples/s
Fig. 1, C_{HBr}	No train, Fig. 5		
	RC4, idle, Fig. 9		
Parallel cable setup		2.3 m RG223 (indoors), 10.0 m RG223 (outdoors)	2.5 k samples/s–50 M samples/s
Fig. 2, C_3	No train, Fig. 4		
	DM3, 3 × 500 A, Fig. 8		

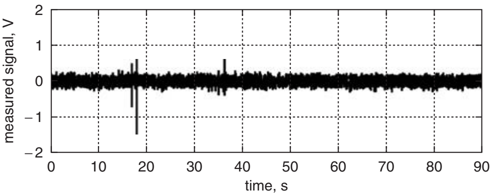

Fig. 3 *Measured signal on flat wheel detector for 90 s*

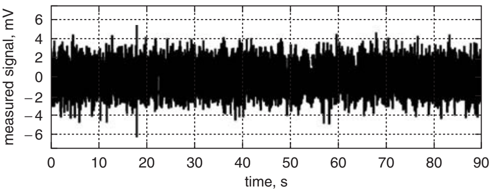

Fig. 4 *Measured signal on parallel passive cable 3 m from track for 90 s*

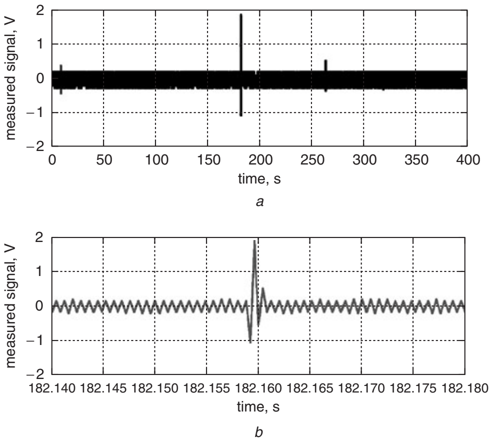

Fig. 6 *Measured signal*
a Hot bearing detector for 400 s
b Closeup for one transient

(*b*) *Hot brakes detector system*: Secondly, measurements on the hot brakes detector system in Sunderbyn is presented in Fig. 5*a* with a closeup of one large transient in Fig. 5*b*. Large transients of this type (Fig. 5) are often recorded by the measurement equipment when trains are absent.

(*c*) *Hot bearings detector system*: Finally, measurements on the hot bearing detector system are shown in Fig. 6*a* with a closeup of one large transient in Fig. 6*b*. Although these measurements are performed in parallel to the hot brakes measurements shown in Fig. 5, the transients is not occur at the same time, indicating conducting electromagnetic disturbances.

4.2 Train passage

This Section presents typical measurement results from various train passages:

(*a*) *Flat wheel detector system and parallel cable setup*: First, a 10 s measurement on one flat wheel detector in Notviken is presented (Fig. 7) together with measurements on a parallel passive cable (Fig. 8). As for the background measurements in the previous Section, transients observed at the flat wheel detector are also found at the parallel cable (0.365, 0.721, and 9.762 s) indicating radiated disturbances. Further, the closeup in Fig. 7*b* shows that the recorded transients, at the flat wheel detector system, are saturated at ±5 V, indicating the presence of larger transients.

(*b*) *Hot brakes detector system*: Secondly, measurements on the hot brake detector system are presented (Fig. 9). One transient at a fairly low magnitude (85 mV) is visible at 15.23 s. These results, indicating a relatively low disturbance on the hot brakes detector, are typical for the studied detector system.

(*c*) *Hot bearings detector system*: Finally, measurements during train passage on the hot bearing detector system are shown in Fig. 10*a* with a closeup of one transient in

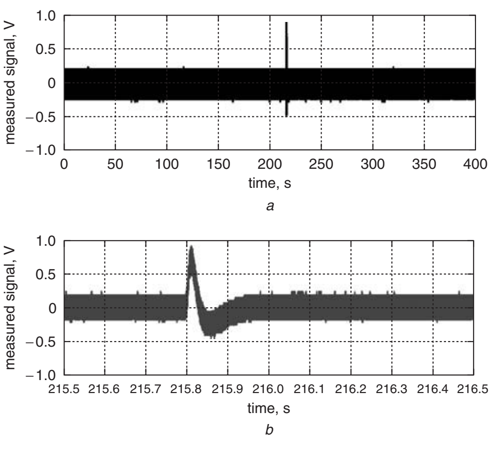

Fig. 5 *Measured signal*
a Hot brakes detector for 400 s
b Closeup for one transient

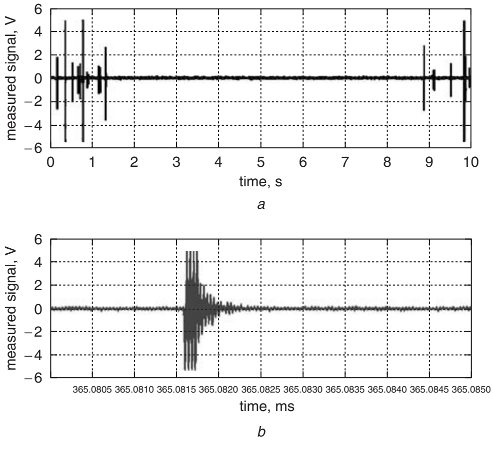

Fig. 7 *Measured signal*
a Flat wheel detector for 10 s
b Closeup for one transient

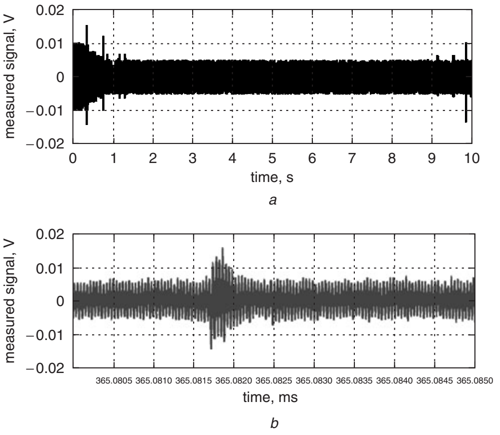

Fig. 8 *Measured signal*
a Parallel passive cable for 10 s
b Closeup for one transient
Four peaks can be identified at same time in both cable and flat wheel detector (shown in Fig. 7*a*)
Transient at cable as shown in *b* arrives 150 ns after same transient is seen at flat wheel detector in Fig. 7*b*

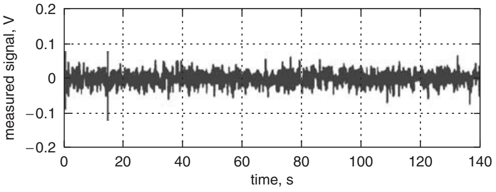

Fig. 9 *Measured signal on hot brake detector for 140 s*

Fig. 10*b*. These measurements are performed in parallel to the hot brake measurements shown in Fig. 9 and some transients are recorded in both systems at the same time (15.23 s) indicating radiated electromagnetic disturbances. However, there are several large transients recorded in the hot bearing detector system that are not present in the hot brake detector system indicating both radiated and conducted electromagnetic disturbances. Further, the transient shown in Fig. 10*b* is very similar (with regard to period) to transients resulting from the braking/closing of the line–pantograph system, as reported in [12].

4.3 Typical disturbance levels for two-day period

This Section presents boxplots [13] for typical disturbance levels measured at each detector system for a two-day period. The boxplot is convenient to visualise univariate data since it shows information about the location of the spread of the data by means of the median and the interquartile range. The boxes in Fig. 11 have lines at the lower, median, and upper quartile values for the measured detector voltages. The whiskers, dashed, on both sides of the boxes shows the skewness in the data. As in these measurements, the data is positively skewed (long upper tail) since large detector values are easy to separate from the low values that are mixed with the noise levels in the measurement systems (see Fig. 11).

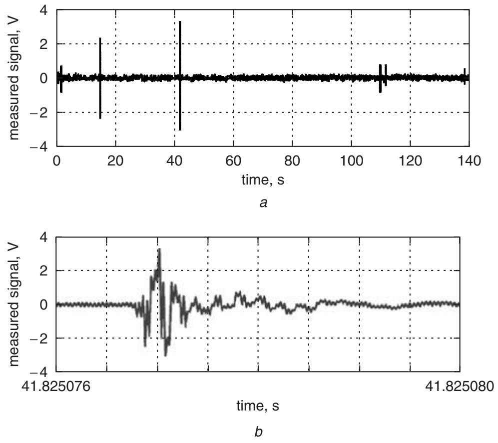

Fig. 10 *Measured signal*
a Hot bearing detector for 140 s
b Closeup for one transient

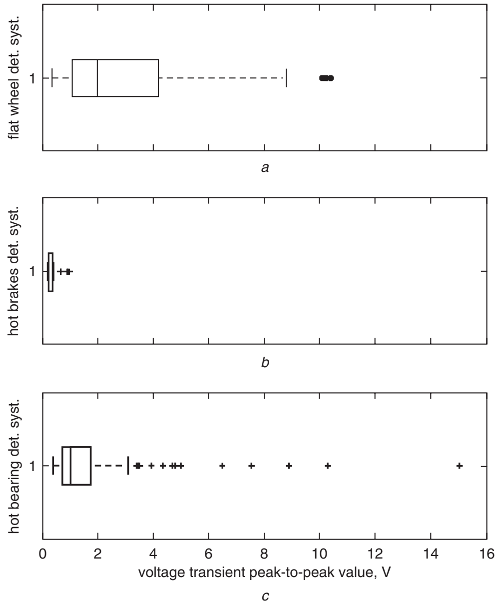

Fig. 11 *Boxplot for measured signals for a two-day period*
a Flat wheel detector system
b Hot brake detector system
c Hot bearing detector system

From the plots the following observations can be made:

(*a*) 25% of the measured transients are above 4.20 V for the wheel flat detector system (Fig. 11*a*)

(*b*) 25% of the measured transients are above 0.35 V for the hot bearing detector system (Fig. 11*b*)

(*c*) 25% of the measured transients are above 1.85 V for the hot bearing detector system (Fig. 11*c*).

Further, the wheel flat and the hot brake detector system have fewer outliners (‘wild data’) than the hot bearing detector system with measured transient peaks of 15.2 V.

Table 3: Worst case voltage peak to peak transient levels induced at the detector systems and parallel cables

Detector	Situation					
	DM3 engine with contact line current			RC4 engine with contact line current		No train passage
	113 A	338 A	450 A	108 A	237 A	
Flat wheel (V)	5.0	6.7	2.5	1.7	10.3	5.2
Hot brakes (V)	1.0	1.0		0.015	0.17	0.26
Hot bearings (V)	4.2	4.0		9.0	15.2	1.4
Parallel cable (V) BT	0.015	0.029	0.017	0.017	0.019	0.009
Parallel cable (V) AT	0.016	0.026		0.01	0.016	0.11

The measurements on the hot brakes detector system (Fig. 11*b*) confirm the conclusions from previous Sections showing maximal disturbance levels of 1.0 V. Further, the hot bearing detector system (Fig. 11*c*) shows the largest disturbance levels close to 15.2 V.

4.4 Malfunction due to transient disturbances

The examined detector systems indicate flat wheels, hot brakes, and hot bearings by a simple, damped sinusoidal signal [14]. The amplitude of the sinusoid gives the severity of the flatness or temperature. Since many of the voltage transients registered at the backplane of evaluation units have sinusoidal shape, the possibility for EMC problems to occur is high. However, the evaluation units only process information from the detectors while the train is present at the site. Thus, the presence of ghost trains can not be contributed to EMC problems in the investigated detector systems. However, if the sensors indicating the presence of trains are out of order, ghost trains might be indicated by the random voltage transients recorded (see Figs. 5–10).

5 Discussion

Voltage transients of substantial magnitude have been registered in detector systems close to the railway (see compilation in Table 3). A broad spectrum of frequencies within the transient pulses has been registered. Most transients show an oscillating behaviour. As a method of analysis, leaky dummy cables, which can receive radiated noise, can be set up in order to separate radiated electromagnetic emissions from conducted noise. The measurements show clearly that electromagnetic emissions from the line–pantograph system, electric discharges, light arcs at the contact line, and high-frequency emissions from the engine, at the very passing of the train, are not a direct threat to well built and installed detector systems [15]. According to our measurements, the signal-to-noise ratio is more than 40 dB in all cases (noise level of 10 mV between twisted pairs, at the train passage) But, on the other hand, there are alarmingly high voltage peaks, having very short rise and fall times ($\sim 10\,V_{pp}/20\,ns$), not necessarily when the train is close. These peaks are of the same size as the detector signals, and may generate malfunctions or indicate the presence of ghost trains. The sources of these voltage peaks are so far unknown. One hypothesis is that they occur when the engine enters or leaves isolated sections of the contact line. This clearly requires further work.

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7 References

1 Al Dhalaan, S.M., and Elirbawy, M.A.: 'A quantitative study of the electromagnetic field coupling between the electric power transmission line and railway'. Proc. Canadian Conf. on Electrical and Computer Engineering, May 2003
2 Hill, R.J.: 'Electric railway traction. Part 6 Electromagnetic compatibility–disturbance sources and equipment susceptibility', *Power Eng. J.*, 1997, **11**, (1)
3 Ruddle, A.R.: 'Computation of electromagnetic fields in the vicinity of a railway catenary'. Proc. IEE Coll. on EMC in Electric Traction and Signalling, 1995
4 Solbiati, G.L.: 'Managing the EMC between an AC railway line and the external world'. Proc. Electrotech. Conf., May 1996
5 Armstrong, D.S.: 'EMC aspects of electrified railways at high frequencies'. Proc. IEEE Coll. on EMC in Large Systems, 1994
6 Holmes, R.: 'Electromagnetic compatibility of electrified railways'. Proc. Int. Conf. on Electric Railways in a United Europe, March 1995
7 Hill, R.J.: 'Electric railway traction. Part 7 Electromagnetic interference in traction systems', *Power Eng. J.*, 1997, **11**, (6)
8 Allan, J. *et al.*: 'Low frequency and radio frequency electromagnetic compatibility for rapid transit railways'. Proc. Fifth European Conf. on Power Electronics and Applications, 1993
9 Banverket research program. (December 2004) [Online]. Available: http://www.banverket.se/upload/pdf/om_banverket/fouprogram2.pdf
10 Belden CDT. (December 2004) [Online]. Available: http://www.belden.com/
11 Wisten, Å., and Mäkikaltio, P.: 'Methods of measuring electromagnetic emission from trains'. Tech. Report 2002:20, Luleå University of Technology
12 Tellini, B. *et al.*: 'Conducted and radiated interference measurements in the line-pantograph system', *IEEE Trans. Instrum. Meas.*, 2001, **50**, (6)
13 Tukey, J.W.: 'Exploratory data analysis' (Addison-Wesley, 1977)
14 Banverket, Varmgångsdetektorer, Beskrivningar och anvisningar. Varmgångsdetektor 8909, 1993-10-01. Systembeskrivning
15 Benda, S.: 'EMC Undersökning i Kiruna, 2003-06-23-27'. Tech. Report 2004:10, Luleå University of Technology

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EMC Problems in Railway Detector Systems

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Abstract— **This paper details measurements, analysis, and modeling of electromagnetic compatibility problems in detector systems used in the Swedish railway systems. The partial element equivalent circuit method has been used to recreate transient waveforms, captured by a measurement system, and to evaluate possible coupling paths to the detector system. A detailed analysis shows that the detector systems are, in their actual setup, prone to transient coupling of considerable magnitude. Further, suggestions on how to improve the installation of the detectors are given.**

I. INTRODUCTION

A general railway section includes signaling systems, catenary supply systems, rail current return systems, and several detector systems to locate trains, detect wheel damage, and measure the temperature of the wheel perimeter and ball bearing temperature. It is clear that the electromagnetic environment at the railway track is demanding and that electromagnetic interference (EMI) is likely to occur [1]. Electromagnetic compatibility (EMC) applied to railway traction systems covers a wide range of phenomena, such as inductive noise in parallel communication lines, impulse noise from lightning and traction transients, production of hazardous voltages under step and touch conditions and the appearance of stray current. The specific problems of interaction between power-electric controlled rail traction drives, and power systems and track signalling systems is important since in-band harmonic interference current flowing in the signalling system can result in degradation of systems performance including, in the worst case, unsafe failures. [2].

Banverket (The Swedish Railway Association) is working together with the operators to reduce train delays. For this purpose, Banverket have installed detectors along the track to detect train operating conditions. The detectors are measuring: (1) the temperature of the ball bearings to ensure correct operating conditions, (2) the temperature of the wheel perimeter to detect falsely locked wheel brakes, and (3) vibrations in the rail to detect flat wheels. When the detectors give the alarm, a manual inspection is required to decide the correct action. If a serious damage has occurred, the trains speed is reduced and a careful inspection has to be made. If a false alarm is given, the train has stopped for no reason, with delays and disturbances in the schedules as a consequence.

Electromagnetic modeling opens up many possibilities for designing railway stretches and for analyzing electromagnetic characteristics in local railway systems. In the design for operating conditions, assuring line currents and voltages, a 2D transmission line (TL) technique is usually applied [3]. The 2D transmission line techniques are computationally fast and accurate and are applicable under certain TL conditions [4]. When analyzing the effect of electromagnetic coupling to detector systems, the transmission line modeling technique becomes unsuitable due to the three dimensional nature of the problem. More suitable techniques are Method of Moments [5] type of techniques and equivalent circuit descriptions. This paper uses the partial element equivalent circuit (PEEC) method [6]-[8] for the electromagnetic modeling of the railway geometry and the detector system. The PEEC method is a 3D, full-wave equivalent circuit method which is numerically equivalent to a full-wave Method of Moments solution with Galerkin matching, see further Sec. V.

This paper focus on the detector systems at an autotransformer (AT) stretch in Sunderbyn and at a booster-transformer (BT) stretch in Notviken, both located near Luleå, Sweden. Initial measurements in the attached detector shed showed, in both locations, a large number of transients occurring at these specific locations. The first part of this work is to find the coupling paths from the rail to the cable, detector system, and detector analyzing shed. The second part is to investigate the intra-system electromagnetic disturbances in the analyzing shed Further, it is interesting to find the source of the recorded transients (train generated or generated by add-on equipment). The specific system in Sunderbyn contains a construction of hot ball bearing- and hot wheel- detector. The main investigation in this paper concerns the hot ball bearing detector.

II. DETECTOR SYSTEM

The detector systems are mainly used to uphold the safety of the track. Current detector systems monitor:

1) The temperature of the ball bearings to ensure correct operating conditions. Hot bearings might jam, resulting in a possible derailment on the specific axis, personal injuries, and material damage. This detector system is the focus of this study and will be referred to as the hot-box detector.
2) The temperature of the wheel perimeter to detect falsely locked wheel brakes. Locked breaks can cause the same problems as hot bearings. Moderately higher temperatures can cause surface cracks that needs to be repaired while excessive temperatures can cause the outer ring of the wheel to detach resulting in a possible derailment.

This detector system will be referred to as the hot-wheel detector system.

3) vibrations in the rail to detect flat wheels. Wheel flats arises when a break locks a wheel and it slides locked along the rail. The wheel flats can cause the rail to break, the axis pressure is exceeding 25 tons. on regular trains sets, without effecting the driving conditions.

Due to the many false alarms, the detector systems are currently not considered to be reliable [9]. For each alarm, the detector system sends the alarm to the control center (CC) using a modem connection, then the locomotive driver is contacted by the CC and told that there is an alarm and where on the train the problem is. When receiving an alarm, the locomotive driver must stop the train at the next siding stretch and make an ocular inspection. If the driver can not find anything wrong, the train can continue. If the driver discover damages, the specific wagon has to be disconnected and left at the siding. In the future, Banverket wants to be able to rely on the detector system so that the driver can automatically disconnect indicated wagons by the next siding without ocular inspections causing unnecessary time delays.

A. Hot-box detector

The hot-box detector measure the temperature on the ball bearings for each wheel. There are two hot-boxes, each on every side of the track, to measure both bearings of the current axis. Hot bearings can be caused by a broken ball or by dirt. The temperature is measured under the wagons with a infra red (IR) sensor to have a reference temperature. This temperature shows the air temperature in the surrounding of the place where the detector box is. When the axes are passing, the sensor is checking the temperature to the reference. If the temperature is to high, the hot-box detector will alarm. The IR sensor is placed in a heated box, kept at 20 °C, for protection from snow and dust. The boxes are isolated from the rail. The box has an automatic opening that is controlled by a pair of axis detectors, fig. 1. Four of the axis detectors are placed nearby the box and the other two are placed several meters away in both directions. The far away axis detectors register the presence of the train and opens the lid to the detector box. The close axis detectors activates the IR sensor when a wheel is passing by. Between the detector number 1 and 2 in fig. 1 the speed of the train is calculated. The third and fourth axes detectors does the same from the opposite direction. Axel detector five and six are there to compensate the rail current from the train and they are placed on the opposite side of detector two and three on the same rail [9], fig. 1.

The analog pulse, generated when a hot ball bearing is detected, is transmitted into the shed for analysis. The shed ground is connected with the return current rail (S-rail). The S-rail is continuous and used as a return line of the current drawn by the train back to the auto transformer [10] (that is in use at the investigated stretch). The other rail is the I-rail and is broken every 1 km and is used for signaling purposes. The AT system has a contact line where the train draws the current while the return current splits up and goes through the S-rail forward and backward to the nearest auto transformer. The negative feeder run parallel between the auto transformers [10].

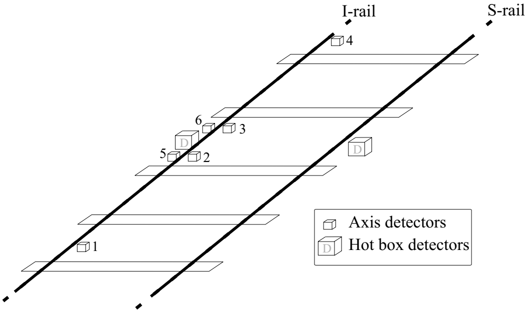

Fig. 1. Hot-box detectors with corresponding axis detectors.

An important observation is the instead of using the shield in the cable connecting the detector system to the analysis unit, the ground is connected to the cover of the box using a wire inside the cable. This setup allows transients that exist on the S-rail and/or that are coupled to the detector box cover to be conducted directly to the analysis unit inside the shed. By using the cable shield as the ground conductor and by connecting the shield to the grounded exterior of the shed using through-put plates, the problem of directly conducted transients would be solved. The lack of EM topology in the studied railway detector systems is contributing to the problems with false detector alarms.

From the study regarding the hot-box detector system, we found a problem with the system detecting the position of the trains on the stretches. The train positioning system uses both the rails to decide the train position on the stretches. Since the I-rail is kept constantly at 6 V. (DC) the train will connect (short circuit) both the rails when entering a 'new' I-rail stretch and the positioning system can decide the position of the train. A very important observation is that the hot-box detector have the S-rail as ground, the detector box cover is directly connected to the S-rail. And, since the hot-box detector is placed only 5 cm from the I-rail it is very easy to short circuit to the cover of the box and I-rail. This will cause a false alarm (since the I- and S- rails are short circuited) regarding the position of the train.

B. Hot-wheel detector

The hot-wheel detector system measures the temperature of the wheel outer perimeter and have an axis counter that is counting the number of the wheel axes that are passing. If there is an alarm from a passing train, due to a too high wheel perimeter temperature, it calculates which axis that is overheated. The detector system monitors the temperature of the perimeter of the wheel to avoid the contact surface to be damaged. The wheel is painted with a special paint that is flaking off when the wheel reaches the maximum allowable temperature. The driver can then make a manual inspection to see if the temperature have been to high. The hot-wheel detector uses an IR sensor that is placed in a tube going out from the shed. The temperature is measured on the outer edge (perimeter) of the wheel since most of the brakes have brake-shoes that breaks through pressuring against the contact surface of the wheel. That means that the perimeter of the wheel gets overheated if the breaks gets locked. There are some locomotive that have disc breaks, but that is not common.

From an EMC point of view, the hot-wheel detector system is somewhat better than the hot-box detector system. The IR sensor is placed in a metal tube extending from the shed in the direction towards the wheel perimeter. The magnetic axis counters are connected to the shed using a cable. The only coupling path for, radiated, transients is through a sensor connected through the cable into the shed.

C. Flat-wheel detector

According to [11], the rail mounted strain gauges react to varying weights of freight equipment and sudden impacts caused by defects in wheels. Each gauges consists of two 350Ω variable resistors. As the freight equipment passes over the gauges, their inherent resistance value changes thus affecting the current flow through the circuit. Each set of gauges connect to the input circuits in the module in the shed.

The system measures the voltages across the gauge circuit as the wheel passes over the crib (set of gauges), see fig. 2. The gauges are welded on both sides of the rail between the cross ties at the specific locations along the rail's neutral axis. As a wheel passes between the ties, it applies pressure on the rail and bends it in a downward direction. As the rail bends, it distorts the gauges to varying degrees. The heavier the rolling equipment, the grater the distortion. The internal resistors of the gauges are mounted at 45^o angle to the rail. When a wheel enters the crib (area between the gauges), those resistors that are mounted in parallel in the strain lines of force are compressed while those that are mounted at a perpendicular angel to the lines force are stretched. As the wheel moves across the crib, the circuit shifts to maintain a constant voltage drop across the bridge dependent upon the weight of the rolling stock. When a defect rolls over the crib, the strain forces increase proportionally to the degree of the defect and are picked up by the gauges. The bridge circuit is typically of Wheatstone type which requires a common source of the electric current and a circuit to analyze the bridge voltage. The flat-wheel detector system therefore consists of four cables going between the detector system located by the rail and the analyzer unit inside the shed. Since the gauges are welded on the rail there is a direct path for conducted disturbances from the detector into the shed if not the appropriate EMC actions are taken. For example, it is necessary to use a low-pass filter for each of the conductors connected to the detector and also through-put panels where the cables enter the shed.

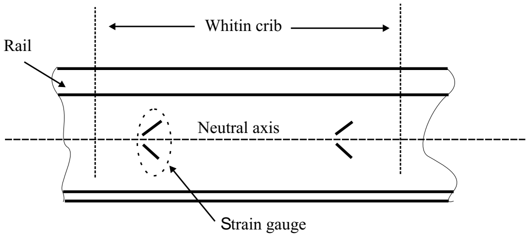

Fig. 2. Strain gauge configuration on the rail.

III. INSTALLATION IN THE SHED

To the detector system, a shed is built to house the electronics, to take care of the detector signals, and the communication with driver and control center. The shed is made out of wood with a metal coating on a foundation of concrete. The metal coating is not completely tight, at the window for example, or grounded in a satisfactory manner. The problem is that the ground of the shed is connected to the S-rail, where the return current in the AT system conducts, which is also connected to the detector boxes and detector box cable shield directly taken into the shed (without filtering). There is no other ground to the investigated shed.

The train detector system uses both rails. The system gives an indication when the axes of a train connects the S-rail to the I-rail since there is a constant voltage, 6 V., on the I-rail that will be grounded to S-rail when the train axis connects them. This train detector system is a possible source of transients and a realistic coupling path into the shed.

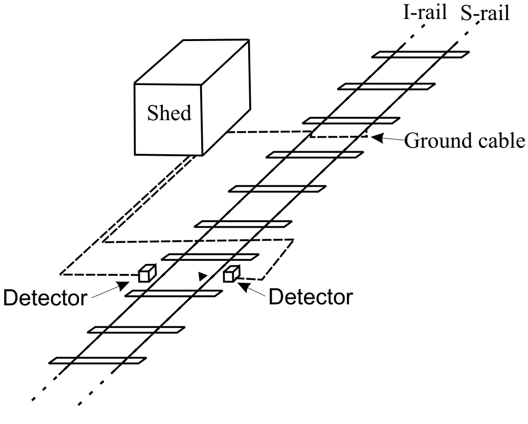

Fig. 3. Schematic over detector installation in Sunderbyn.

An important observation, as pointed out earlier, is that the cable shield from the hot-boxes does not have a connection to ground, instead the ground is one of the wires inside the cable with crosstalk between cables as a possible consequence. From an EM point of view, the cables are not used as they are intended to. With this solution of the grounding, it is an inductive connection, with a low potential that is sensitive for current.

The length of the cable connecting the hot-box to the analysis unit is too long and is currently collected in a bundle lying at the floor in the shed. For the last part of the cable, connected to the terminal block, the wires are separated and openly assembled. The ground is separated in the cables and the protection from the ground is missing. The terminal block have no cover over the connections so the EM protections are incomplete from any electromagnetic fields in the shed.

There is a filter, EMI-filter EMIGUARD type DSS710 [12], mounted on the cable that connects the hot-wheel detector to the analyzing equipment. This filter has been mounted in this shed at the time of installation to filter away voltage transient disturbances. This typical emergency solutions shows that many problem have been tried to be solved as they occur.

The shed is equipped with an electric heater to keep the temperature around 20 °C. Since there is only one ground for all the equipment in the shed, it is a possible way for transients to conduct from the thermostat of the heater to the analysis unit sensitive equipment. The transients from the 230 V. heater can be severe for the rest of the electronic equipment. The energy in thermostat generated transients could interfere with signals from detector systems causing false alarms.

IV. MEASUREMENTS

Measurements have been carried out to register the transients near the track when the trains are present. One set of measurements where using a loop antenna, an EMCO Model 6512 used in the interval 10 kHz - 30 MHz, that was placed 3 m. from the outermost rail and 1,2 m. above the top of the rail. The loop antenna measures the vertical magnetic field, antenna voltage, using an oscilloscope.

A second set of measurements where carried out inside the shed, to verify the presence of transients that could cause false alarms to the analyzing unit. The measuring point was on the backplane of the analyzing rack where the cables from the hot-wheel and hot-box detectors enter.

An important observation, from the performed measurements over a period of one and a half year (May 2002 - November 2003) in about 20 occasions, is that when the train is present at the measurement location it generates very low noise levels. However, measurements could show very high amplitude randomly occurring transients, see for example fig. 4, that had no correlation with the presence of trains at the measurement location. The train's exact position on the stretch and the distance to the measurement location could not be verified due to various communication problem. Possible sources of the observed large transients could be lightning strikes, switching operations, arching etc.

The results shows that there were no high transient recorded when the train was passing. Even the newest train, the IORE that MTAB (a Swedish ore operator) operates with, which is the most powerful train, among locomotives that operates at the investigated stretch, with a power of 10,8 MW (14,700 hp) and a starting traction force on 1,200 kN.

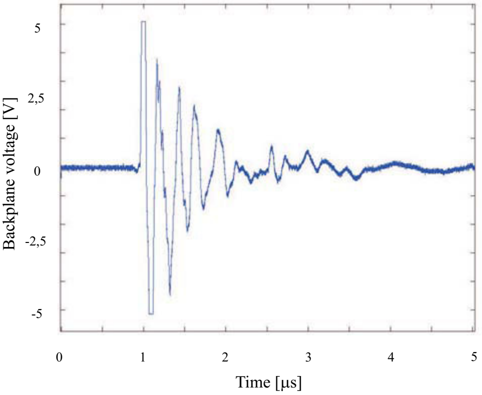

Fig. 4. Measured transient on the backplane inside the shed of the analyzing unit in Sunderbyn. The extremely high amplitude could not be registered by the measurement equipment.

V. COMPUTATIONAL MODEL

To help in the analysis of the transient coupling, an electromagnetic model of the different coupling situations has been created using the PEEC method. The PEEC method was developed by A. E. Ruehli [6]-[8] for VLSI inductance calculations in the early 1970s. The approximate integral equation solution pursued in this method is based on the proper electromagnetic interpretation of the various terms in the equation describing the sum of all the sources of electric fields at any point in space according to

$$\vec{E}^i = \frac{\vec{J}(\vec{r},t)}{\sigma} + \frac{\partial \vec{A}(\vec{r},t)}{\partial t} + \nabla \phi(\vec{r},t) \qquad (1)$$

where $\vec{E}^i$ is an incident electric field, $\vec{J}$ is a current density, $\vec{A}$ is the vector magnetic potential, and ϕ is the scalar electric potential at observation point $\vec{r}$. By defining a suitable inner product with a weighted volume integral over the cells, 1 can be interpreted as Kirchoffs voltage law over a PEEC cell shown in fig. 5. In the figure, fig. 5, the magnetic and electric field couplings have been collected in equivalent voltage sources V^L and V^C respectively, $Lp_{\alpha\beta}$ is the partial self inductance of the volume cell between node α and β, $R_{\alpha\beta}$ is the DC resistance of the same volume cell, and $p_{\alpha\alpha}$ and $p_{\beta\beta}$ is the self coefficient of potential for surface cell α and β respectively. The equivalent circuit transformation enables the combined modeling of electronic functionality and electromagnetic effects, the usage of the same model for time- and frequency domain analysis, the use of equivalent circuit

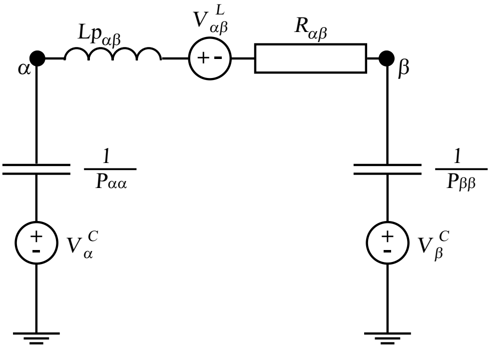

Fig. 5. Basic PEEC cell.

descriptions, and combined two- and three- dimensional models, i.e. transmission line models and 3D PEEC models. The PEEC method is traditionally used for electrical interconnect and package modeling but is geometrically scalable to handle larger structures. For general information on the PEEC method see [13] and for using the PEEC method on railway structures see [14].

In the computational model for the AT system, the local track section including the detector systems can simplified to contain two rails, a contact line and a negative feeder. The rails are separated 1,435 m. the contact line is 5,5 m. above the rails, the negative feeder is located 7,5 m. above and 2,2 m. horizontally spaced from the outermost rail. To model the transient coupling to the detectors, the model was totally 24 m. long with the detectors in the center of the section. Fig. 6 shows the basic setup for the computational model.

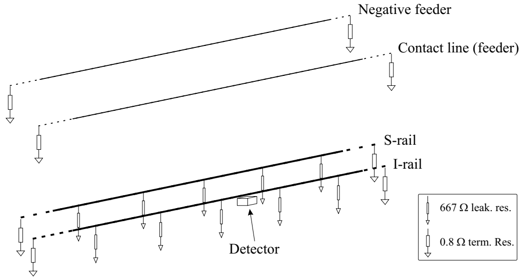

Fig. 6. Basic description of PEEC model for transient coupling to detector system.

The contact line, negative feeder, I-rail and S-rail is terminated using 0.8 Ω at the end of each line. The rail leakage, through the ballast to the ground, is 0,8 Ω/km [10]. This leakage was modelled using discrete resistors at the I-rail and the S-rail with a space of 1.20 m. These resistances have a value of 667 Ω to be equivalent to 0,8 Ω/km. The structure is excited using a current source in parallel to the terminating resistances on the I-rail. This model uses a discretization of $\frac{10 \text{ cells}}{\lambda}$ where $\lambda = 3$ m (corresponding to $f_{max} = 100$ MHz).

A PEEC model was crated to model the loop antenna voltage for a large transient. In this way we could determine the magnitude of the transient occurring at the rail. The EMCO loop antenna was modelled using a staircase approximation using very thin conductors. The I-rail was excited using a Gaussian pulse with different rise time and magnitude until a satisfactory agreement between the measured and modelled pulse was found. Fig. 7 shows the comparison of measured and modelled loop antenna voltage for a gaussian pulse causing a rail transient current with a 1 A. amplitude. In the PEEC model, the electric field couplings to the loop antenna are excluded to model the loop antenna more accurately (the EMCO loop antenna has a thin conducting shell to minimize the effect of the electric field coupling). It is clear that there is a difference in frequency content of the modelled and measured pulse. However, this model gives a good indication on the magnitude of the randomly occurring transients in the rail system. The loop antenna modeling results indicate that there are transients, on the I-rail, on the order of 2 A. that was recorded by the loop antenna measurements.

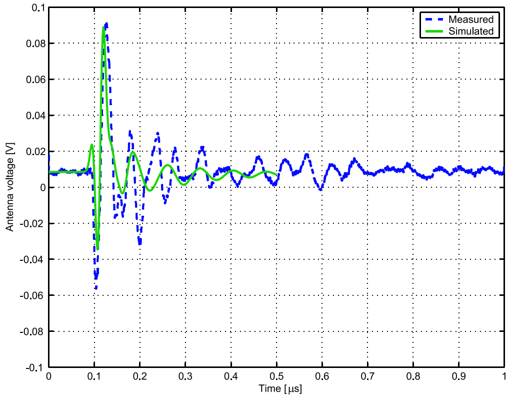

Fig. 7. Comparison between measured and modelled loop antenna voltage.

To model the coupling to the hot-box detector cover from the S-rail, the PEEC model is not necessary since the two systems have a direct connection through the grounding. However, the transient coupling from the I-rail to the S-rail is shown in fig. 8. The use of the PEEC method to model transient coupling in a local railway stretch is straightforward and, for this model situation, computationally efficient. However, electromagnetic modeling of the investigated railway stretch is not required to substantially improve the performance of the detector system (including the shed). Modeling can give important results after improving the overall electrical environment in the detector system.

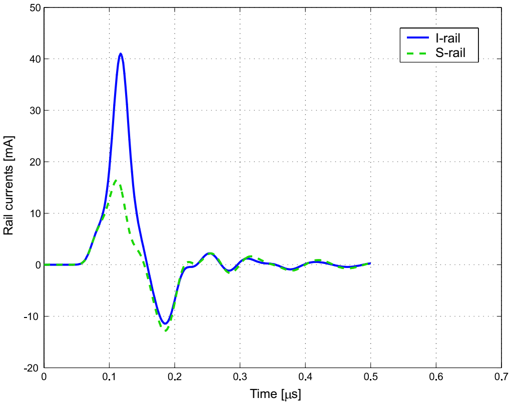

Fig. 8. Crosstalk between the I- and S- rail.

VI. CONCLUSIONS

From this study some important conclusions can be drawn:

1) In general, the transient are occurring in the detector system independently of the presence of the train.
2) To prevent crosstalk, the correct use of ground is very important. A separate ground for the electronic equipment and the communication signals will prevent crosstalk from high power sources.
3) The cables shield are not properly joined when they are connected to the rack in the shed. The cables from the hot-boxes are to long and they have been inclined in circles on the floor because of the length. This give an unnecessary deterioration in the shielding of EM disturbance.
4) Post installation fixing is common in the detector systems. Different problems has been solved by technical staff using hands-on methods that has not been documented in a correct way. There is an apparent risk that new constructions are designed on incorrect operating conditions due to all post installation fixing.
5) The shield of the cables must be grounded to protect low voltages signals. The cables must be grounded to the shed coating where it is penetrated into the shed. It is also important to be aware of the EM topology when constructing the detector system and use appropriate barriers at each zone border.

VII. FURTHER WORK

This study of EMC problems in railway detector systems has shown that the current situation, with false alarming in the detector systems, can be improved by adopting basic EMC design including separating the grounding systems, use of the cable screen, and through-put plates for example. However, other EMC related problems with the detector systems needs further investigation. Here the use of electromagnetic modeling together with measurements can give further information on how to improve the overall electronic performance of the detector systems.

Lightning induced effects using 2D computational models has been studied in the Swedish railway system over the past years [15]. We see the possibility to combine the 3D method used in this study with 2D methods from the lightning study to enable the analysis of a complete stretch, or even multiple stretches, including electronic ad-on equipment (detector systems, etc.) for improving EMC characteristics.

REFERENCES

[1] R. J. Hill, ”Electric railway traction. Part 7 Electromagnetic interference in traction systems”, *Power Engineering Journal*, pp. 259-266, Dec., 1997.
[2] S. Brillante, R. J. Hill, A. Pozzobon and G. Sciutto, ”Modelling for electromagnetic interference assessment in eletric railway traction systems”, *IEE electric railway in a united Europe*, 27–30 March 1995.
[3] A. Pleym and J. Ma, ’A study on interference from AC electrified systems to nearby earth return currents’, in *Proc. IEEE*, 1999.
[4] C. A. Balanis, *Advanced Engineering Electromagnetics*, Wiley, 1989.
[5] R. F. Harrington, *Field Computation by Moment Methods*, Robert E. Krieger, 1987.
[6] A. E. Ruehli, ”Inductance calculations in a complex integrated circuit environment”, *IBM Journal of Research and Development*, 16(5):470–481, September 1972.
[7] P. A. Brennan and A. E. Ruehli, ”Efficient capacitance calculations for three-dimensional multiconductor systems”, *IEEE Transactions on Microwave Theory and Techniques*, 21(2):76–82, February 1973.
[8] A. E. Ruehli, ”Equivalent circuit models for three-dimensional multiconductor systems”, *IEEE Transactions on Microwave Theory and Techniques*, 22(3):216–221, March 1974.
[9] Tech. report, Banverket, ”Varmgångsdetektor 8909, systembeskrivning”, 1993-10-01.
[10] Gy. Varjú and F. J. Sollerkvist, ”Comparison of BTRR, BTRC and AT traction feeding systems in Norway”.
[11] Banverkets Reference Manual ”WILD Maintenacne and Troubleshooting”, Chapter 2, Sep 1996.
[12] (2004) Murata Maunfacturing Co., LTD. [Online] Available: http://www.murata.com
[13] J. Ekman, ”Electromagnetic modeling using the partial element equivalent circuit method” Ph. D. dissertation, Luleå University of Technology, Sep. 2003.
[14] J. Ekman and S. Niska, ”PEEC based formulation suitable for electromagnetic analysis of raiway structures”, in *Proc. of EMC Europe 2004*, Eindhoven, The Netherlands, 2004.
[15] N. J. Theethayi, ”Electromagnetic interference to electrified network caused by lightning: developments of computation models”, Lic. thesis, Uppsala Univeristy, 2004.

Paper E

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Measurements and Analysis of electromagnetic interference in a railway signal box- A case study

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Abstract

Today the railway industry, together with many other industries, has to examine the maintenance support procedure. Maintenance has to be as cost-effective as possible, as does the whole industry process, and the traffic on the railway has to function without interruptions. Electromagnetic compatibility is being prioritised to an increasing extent, since interruptions cause major inconvenience in the process. The knowledge of how the system works and reacts in different situations has to be investigated. *In situ* measurements must be performed on systems that have obvious problems show increasingly fast and high transients in a DC signalling subsystem. The statistics also show an increased activity of transients during a period before a certain circuit in this system gets out of order. The presented results clearly show how the electromagnets interference effects he signalling system in a signalling box. The measurements in this case study have provided new information on a railway subsystem and have revealed frequencies that are difficult to explain at this moment.

Introduction

The European Rail Research Advisory Council (ERRAC) has set objectives for railway operation stating that the overall transport demand should grow by 40 per cent for passenger traffic and 70 per cent for freight traffic by 2020 compared with 2000 [1]. Banverket (the Swedish Rail Administration) has an overall maintenance strategy whose vision for the goals of maintenance activities is [2]:

- Maintenance operations shall lead to the achievement of established demands for reliability.
- The maintenance activities shall be a step in ‘securing safety’.
- The cost-effectiveness of the maintenance activities shall be constantly improved.

With these demands in mind, knowledge and understanding of today’s interruptions and faults in the railway infrastructure are important, as is awareness of the fact that acquiring this knowledge and understanding leads to less available time for maintenance. Therefore, knowledge of how the railway system itself behaves is a major issue now and in the future. The complexity of the railway system increases when more and more electronics is used [3, 4, 5]. A contributory cause of this development is the use in the railway industry of highly integrated high level systems where there can be interactions between many of the components [6]. The railway environment contains numerous sources of electrostatic noise and electromagnetic and electrical disturbance, and it is a hostile environment for low power circuits, e.g. signalling systems [7]. Therefore, it is an important issue to increase the knowledge of electromagnetic compatibility (EMC) and EMC design in the railway industry [8, 9, 10, 11, 12,]. The impact of electromagnetic interference (EMI) in the railway system has been simulated and is commonly known [13, 14, 15, 16]. Furthermore, there are experimental measurements where EMI from the pantograph has been minutely investigated [17, 18, 19]. Bad system design and inadequate understanding of disturbance caused by included sub-systems will generate mal-functions that are difficult to understand and which are causing many maintenance actions in order to maintain high availability for the railway [10]. To avoid bad design that generates costs in maintenance support, it is important to monitor, analyse and understand the system.

This paper presents an investigation of a specific component (an RC circuit) at a station called Oxmyran in the Swedish railway signalling system. The component has failed a considerable number of times over the past few years. The failures have caused a number of train delays and a large number of unnecessary maintenance support actions. The failures have been without any obvious cause, although electromagnetic (EM) disturbance is the suspected reason. This investigation tries to establish the connection to EMI and concentrates on the low frequency band.

Location of the Study

The site selected for this study is a station named Oxmyran, located on the main railway line in northern Sweden, see Figure 1. The closest bigger station is Vännäs and the closest town or city is the city of Umeå.

According to Banverket's failure database, "0felia", an RC-circuit in the signal box at Oxmyran has, compared to other similar circuits, failed remarkably often (32 times) during the past 6 years. This circuit failure has created large unnecessary costs for replacement of the circuit and a number of train delays. The cause of the failures is suspected to be electromagnetic interference.

Only 5 km north of Oxmyran, at the Öre Älv Station, a similar signal box is located. The same type of RC-circuit at Öre Älv has no reported faults during the same period, even though the traffic is identical. In this study, Öre Älv is used as a reference station for the measurements at Oxmyran.

Figure 1. The location of Oxmyran, pointed out on a map of Sweden with some of the railway lines and towns.

Both the Oxmyran signal box and the Öre Älv signal box were built in 1995. Before 1995 the old railway line made a big turn from Öre Älv to Nyåker and then to Oxmyran. In 1995 Banverket built a new main line with a tunnel through the mountain called Glödberget, running directly from Öre Älv to Oxmyran. The distance between the stations at Öre Älv and Oxmyran along the new route is 5 km. The old line was maintained, effectively resulting in a double track, see Figure 2.

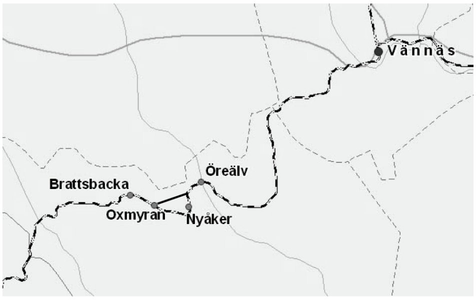

Figure 2. The main railway line from Vännäs to Oxmyran via Öre Älv and over Nyåker, and further south to Brattsbacka. The new track between Öre Älv and Oxmyran was built in 1995 and is marked as a straight black line.

For Banverket it is vital to understand the causes of the recurring faults at Oxmyran and explain why an identical signal box at Öre Älv has no similar problems at all. Is the problem related to the design, construction, operation or any external influences?

System description

When a train comes into the station at Oxmyran or Öre Älv (the two systems work identically), a relay, called RS1, pulls and gives power to the relays in a chain after the RS1 relay, indicating that there is a train at the station. When the train leaves the station, the RS1 relay cuts the power to the chain of relays. When RS1 cuts the power, the other relays in the chain will also switch and stop their signals. However, since the power from the RS1 relay to all these relays disappears, they cannot switch back. Instead the power that is needed is supplied by the RC circuit, which can hold the power within a few milliseconds. This time is enough for the rest of the relays in the chain to switch back. If the RC circuit is out of order, there will be no power to be supplied to the relays after RS1 in the chain, these relays cannot pull back, and consequently the system indicates that a train is remaining at the station. The track is then blocked for other traffic, although the train has left the station. An alarm is sent out and the maintenance support has to handle the alarm. The RC circuit investigated in this paper is shown in Figure 3, and has this sole function of supplying power to the relays.

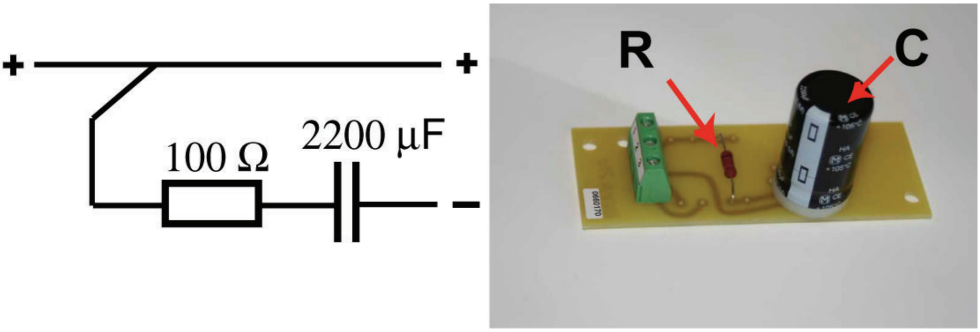

Figure 3. The investigated circuit is an RC circuit, consisting of a resistor of 100 Ω, marked R in the figure and photo, and connected in series with a capacitor of 2200 µF, marked C in the figure and photo.

The power to this subsystem comes from a rectifier that supplies the system with 27 V. Before the rectifier there is an uninterruptible power supply (UPS), to stabilize the power. Inside the UPS there are a transformer and batteries that keep the power for a specific time. If both the voltage and the ground are connected to the UPS, the voltages have a low level of noise. In the railway system the ground has to be the S-rail and therefore the ground is not connected via the UPS. Static converters supply the power to the trains over the distance between Oxmyran and Öre Älv. They are placed at Mellansel, south of Oxmyran, and at Bastuträsk, north of Oxmyran.

Method

The railway power system in Sweden works at 16 2/3 Hz, and the big currents from the trains will have this frequency. It was therefore interesting to perform measurements and analyses to determine whether this frequency was represented or dominated in the systems. The results of the measurements had to show clearly the extent to which the frequency of 16 2/3 Hz occurred, and therefore a sampling rate of 10 kHz and 60 000 samples were selected for the measurements. A frequency sample rate of 1 MHz was also used to record if any fast transient was present. Every measurement was saved in its own separate file and named after the time of the event, which provides traceability to when the measurement was carried out. To analyse and clarify the specific frequencies that were measured, a fast Fourier transform (FFT) algorithm in MatLab was used.

Measurements

A laptop computer and an NI USB-6251 DAQ (data acquisition) unit from National Instruments were used, see Figure 4. To control the measurements and collect the data from the DAQ, the software LabView from National Instruments was used. The probe measured voltages over the RC circuit. The DAQ unit has an input span of -10 V to +10 V and could not measure the 27 V DC that is supplied by the rectifier to power the RC circuit. Therefore, a probe that damped the signal by 10:1 was used to facilitate measurements with voltages up to 100 V. All the data presented in Figures 5-12 have been multiplied by 10 to restore the correct voltages. To start the measurement, the trigger level was set to 3 V, thus starting the recording every time 30 V was reached over the RC circuit. Levels below 30 V are common voltages for the system and do not cause any damages to the RC circuit, as the resistor and capacitor follow a similar specification based on 64 V.

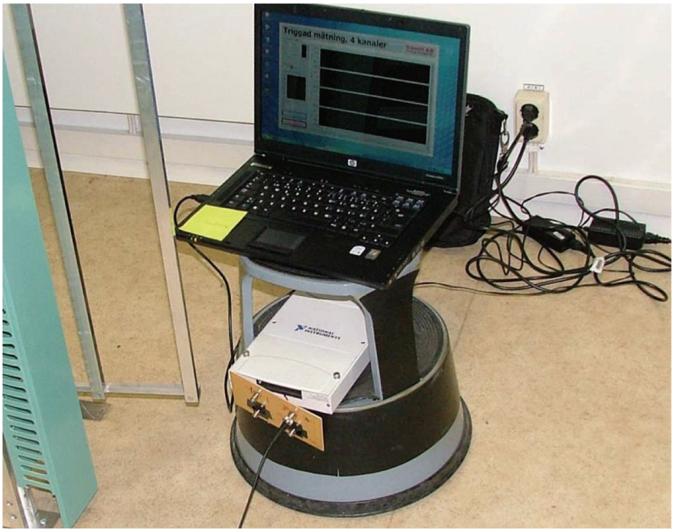

Figure 4. The set-up during the measurements at both Oxmyran and Öre Älv.

Two DAQ units and computers were used, with one set of equipment located at Oxmyran and the other one at Öre Älv, see Figure 2. Both the units were tested in the laboratory before the site test, to verify that they showed the same values from the same source and behaved in a similar way. They were checked with a Kiethley 2400 SourceMeter. To verify the function of the measurement programme on site, it was periodically tested by a measure every time the computer clock changed over to a new date. No train was passing at this time.

Reference measurements

Initial reference measurements were performed at both Oxmyran and Öre Älv to determine if there were any natural differences between the two sites. The measurements were made in both signal boxes, at Oxmyran and Öre Älv, at the same time. Figure 5 and 6 show examples of measurements for Öre Älv and Oxmyran respectively.

The measurements of 1/9/2007 from Öre Älv, Figure 5, show very low voltages. Furthermore, after two weeks of measurements at Öre Älv, the trigger level of 30 V had never been reached and only the curves from the forced midnight action had been registered.

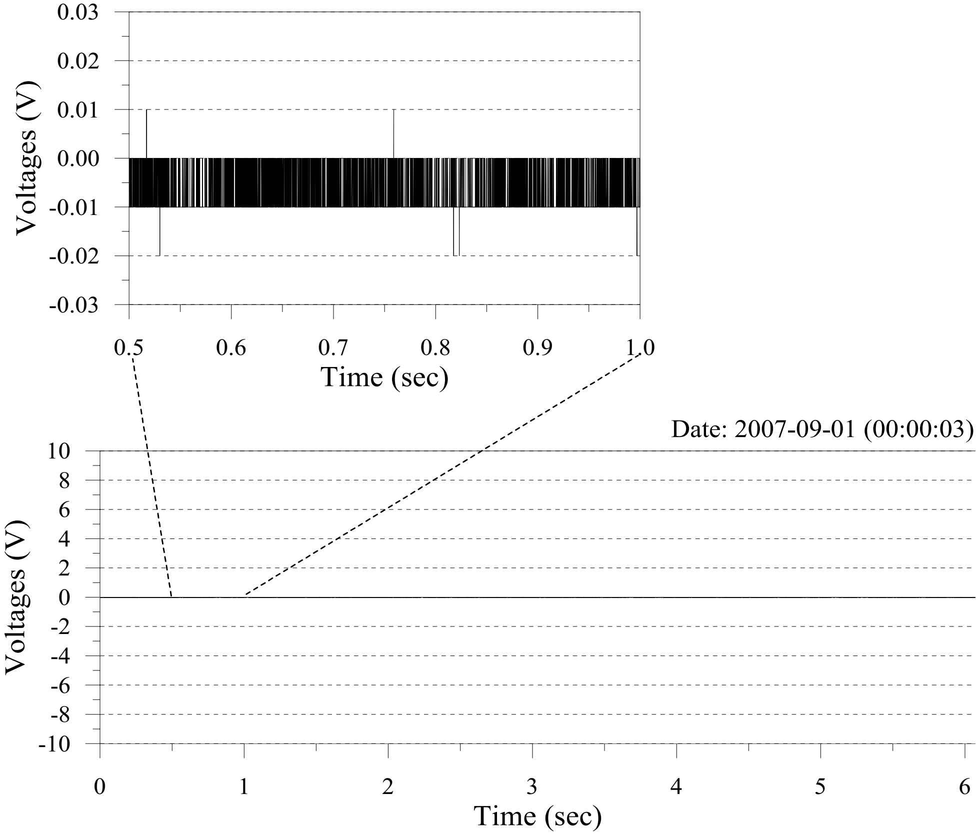

Figure 5. The voltage curve from Öre Älv.

In Figure 6, a similar curve is shown for Oxmyran. The curve from Oxmyran shows a much wider spectrum of noise, up to 80 times higher than that for Öre Älv. The levels are not high enough to cause any problem for train indication, but the figure clearly shows that Oxmyran is not as stable as Öre Älv. During the first 12 hours of measurements at Oxmyran, there were 18 triggering events of the system, indicating voltage levels above 30 V.

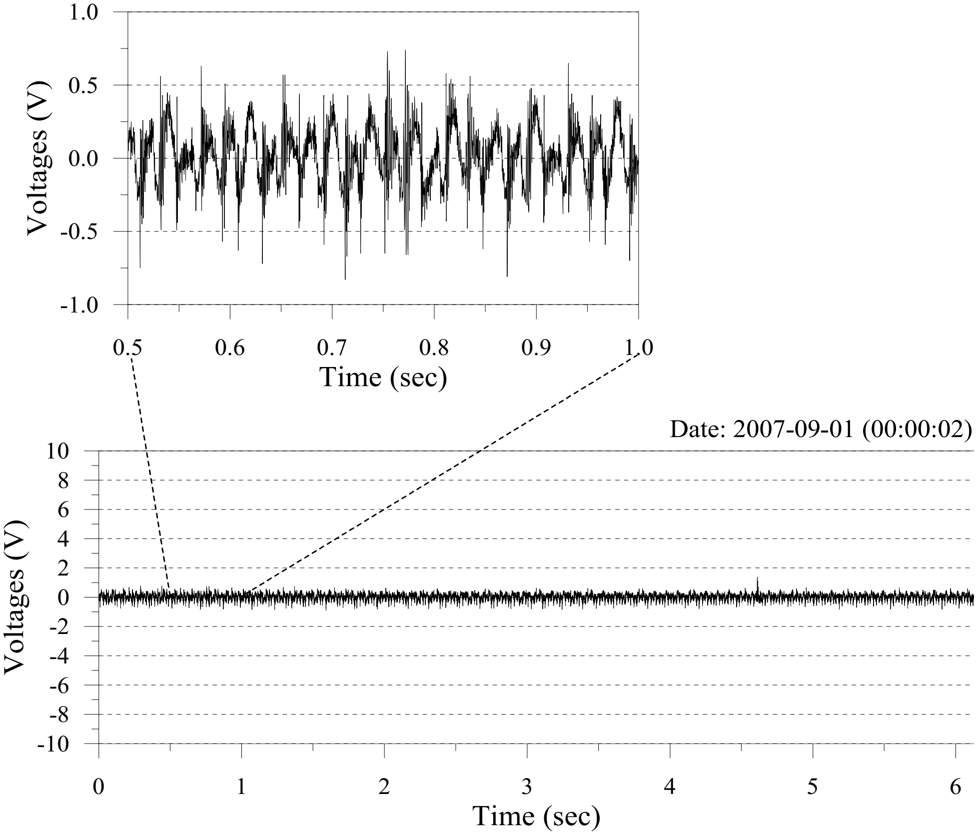

Figure 6. A voltage curve from Oxmyran.

The results from Figure 5 and 6 clearly show a significant difference between Öre Älv and Oxmyran. The background levels are much higher at Oxmyran, even when no train is passing the station.

Measurement with 10 kHz

Triggers

Every time the trigger was activated, the measurement system recorded data and saved it as a file, named after the time (year, month, day, hour, minute, second) when it was saved. Table 1 shows the number of triggering events (i.e. voltages above 30 V) that occurred each day of the measurement period. The table shows the variation in activity from no triggering event (the forced triggering event is not included) up to 689 triggering events in a single day. During the measurement period (21/9/2007 – 18/1/2008), there were 4 alarms showing that the RC circuit was out of order. The days when this happened are highlighted in the table, namely 30/9/2007 at 23.13 (11.13 pm), 1/10/2007 at 07.46 (7.46 am), 1/11/2007 at 15.12 (3.12 pm) and 8/11/2007 at 00.14 (12.14 am). In the table there are two big outliers, 1/11/2007 with 224 triggering events and 8/11/2007 with 689 triggering events. On both these two days the RC circuit was out of order. On 30/9/2007 the third highest number of triggering events occurred. On the evening of 30/9/2007, thunder occurred in the area. On the following day, 1/10/2007, an alarm was generated and the RC circuit was out of order, even though no triggering event had occurred.

Table 1. *Numbers of triggering events day and night every day during the period 20070921 to 20080118, except a small period of time between 20071204 and 20071218.*

Date	***Number of triggering events***
20070921	3
20070922	7
20070923	0
20070924	0
20070925	12
20070926	0
20070927	5
20070928	7
20070929	2
20070930	58
20071001	0
20071002	0
20071003	0
20071004	8
20071005	14
20071006	2
20071007	0
20071008	3
20071009	1
20071010	1
20071011	1
20071012	9
20071013	0
20071014	2
20071015	0
20071016	0
20071017	0
20071018	2
20071019	10
20071020	0
20071021	0
20071022	2
20071023	2
20071024	0
20071025	7
20071026	2
20071027	0
20071028	0
20071029	1
20071030	2
20071031	1
20071101	224
20071102	1
20071103	1
20071104	1
20071105	1
20071106	1
20071107	42
20071108	689
20071109	29
20071110	4
20071111	3
20071112	0
20071113	12
20071114	0
20071115	0
20071116	14
20071117	1
20071118	6
20071119	0
20071120	15
20071121	19
20071122	7
20071123	0
20071124	18
20071125	0
20071126	0
20071127	1
20071128	0
20071129	1
20071130	16
20071201	5
20071202	2
20071203	2
20071204	3
20071218	1
20071219	0
20071220	2
20071221	2
20071222	1
20071223	0
20071224	0
20071225	0
20071226	0
20071227	0
20071228	6
20071229	5
20071230	0
20071231	0
20080101	0
20080102	2
20080103	2
20080104	13
20080105	6
20080106	4
20080107	1
20080108	1
20080109	0
20080110	1
20080111	6
20080112	2
20080113	0
20080114	1
20080115	10
20080116	12
20080117	8
20080118	6

The results clearly indicate a correlation between the activity in the system and RC circuit faults, even though one fault occurred on a day when no activity at all was registered.

One explanation can be that the trigger was set to 30 V and not -30 V. Therefore, a drop of the potential in the system could not been seen in this measurement. Another explanation can be that, after a replacement of the RC circuit on 30/9/2007, the probe was not put back in the right way by the maintenance support personnel. After this replacement, data were collected and the system was checked on 4/10/2007. On this date there were no obvious faults registered for the connection to the RC circuit, but no check of the real connection was made. On 8/10/2007 the alarm was registered in the Centralized Train Traffic Control (CTTC) office at 00.14 (12.14 am), and still there were 689 recorded triggers during that day after the alarm had been registered. This alarm was not forwarded to the maintenance support personnel until 06.52 in the morning. The maintenance support personnel did not switch and repair the RC circuit until late that day, because the only spare system had been used a week before. On the day before, 7/10/2007, with 42 recorded triggers, 41 of these were recorded after 23.36, which can possibly explain the fault after midnight.

Results

During the first period of measurements, the reference measurements, analysis shows that 8 1/3 Hz is the dominant frequency in the system. This is half of the frequency that Banverket employs in their power system, 16 2/3 Hz. See Figure 7.

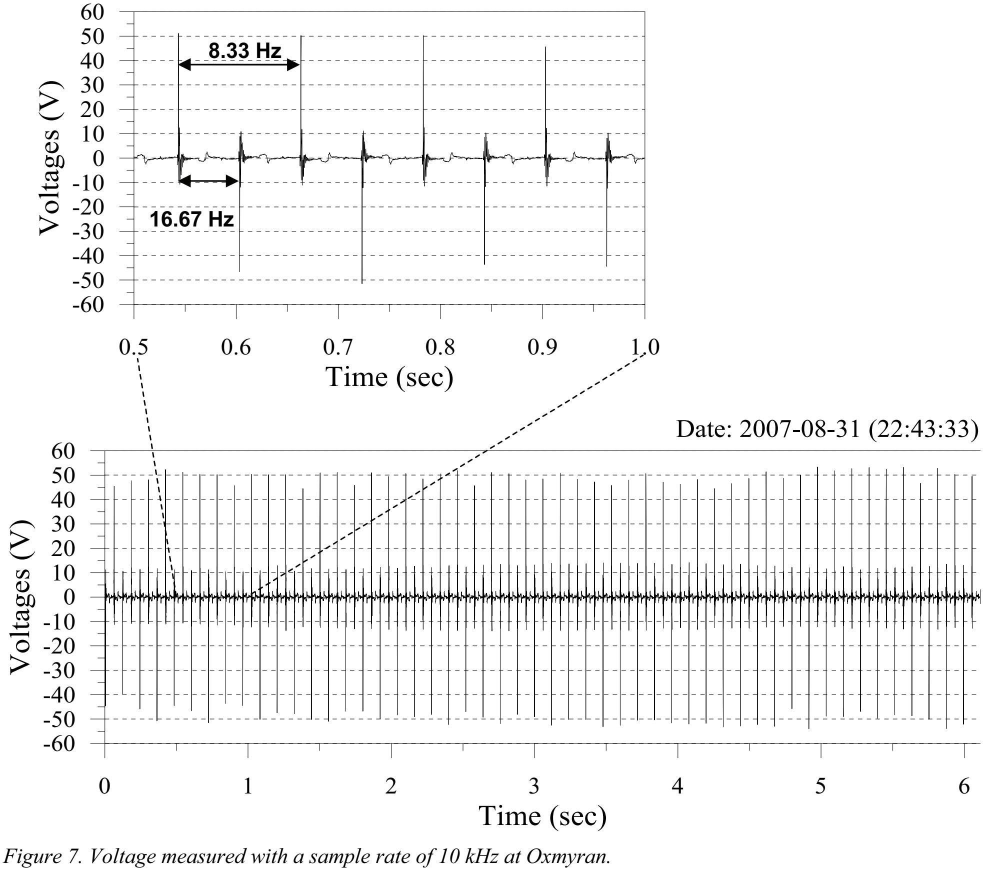

Figure 7. Voltage measured with a sample rate of 10 kHz at Oxmyran.

Many measured curves during this period are similar. On 25/9/2007 there were 12 triggers and no alarm showing that the RC circuit went out of order, In Figure 8 the transients are barely above the trigger value of 30 V. Here is a noise of several volts, but the figure shows clearly that the power is centred on zero, which means that the rectifier is not supplying power and no train is present at the station. The curve in Figure 8 can be compared to the curve in Figure 7, where the noise between the high transients is higher, but the tail dies out quicker. The transients on both these days, 31/8/2007 and 25/9/2007, have less power than what is required to break the RC circuit.

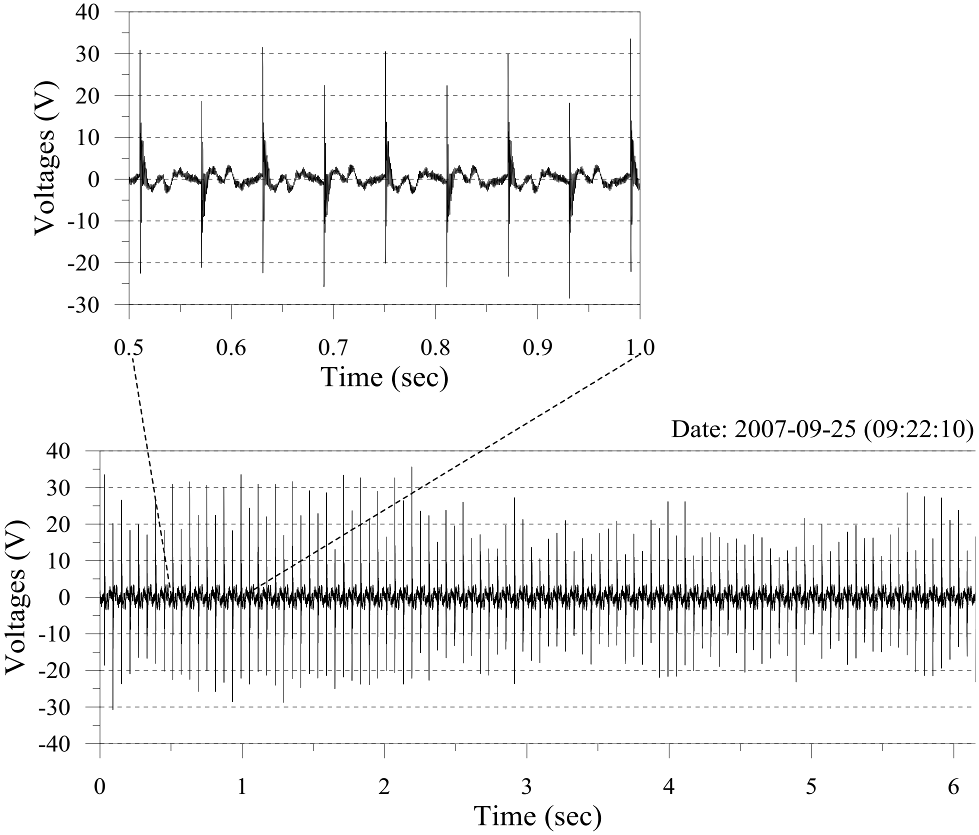

Figure 8. Voltage measured on 20070925; there were 12 triggers that day and night.

One of the times when the RC circuit was out of order was in the evening of 30/9/2007. The alarm was registered at the CTTC office at 23.13. According to the maintenance support personnel, there was a thunderstorm this evening. There were 58 triggers during that twenty-four-hour period, see Table 1, and 56 of these triggers occurred between 19.43 and 20.46 (7.43 and 8.46 pm). There were no triggers at all when the fault occurred and the last trigger was recorded at 20.46 (8.46 pm). Analysis of the last recorded curves before the alarm shows some interesting features. The curve, Figure 9, is saturated at the beginning and has a short tail.

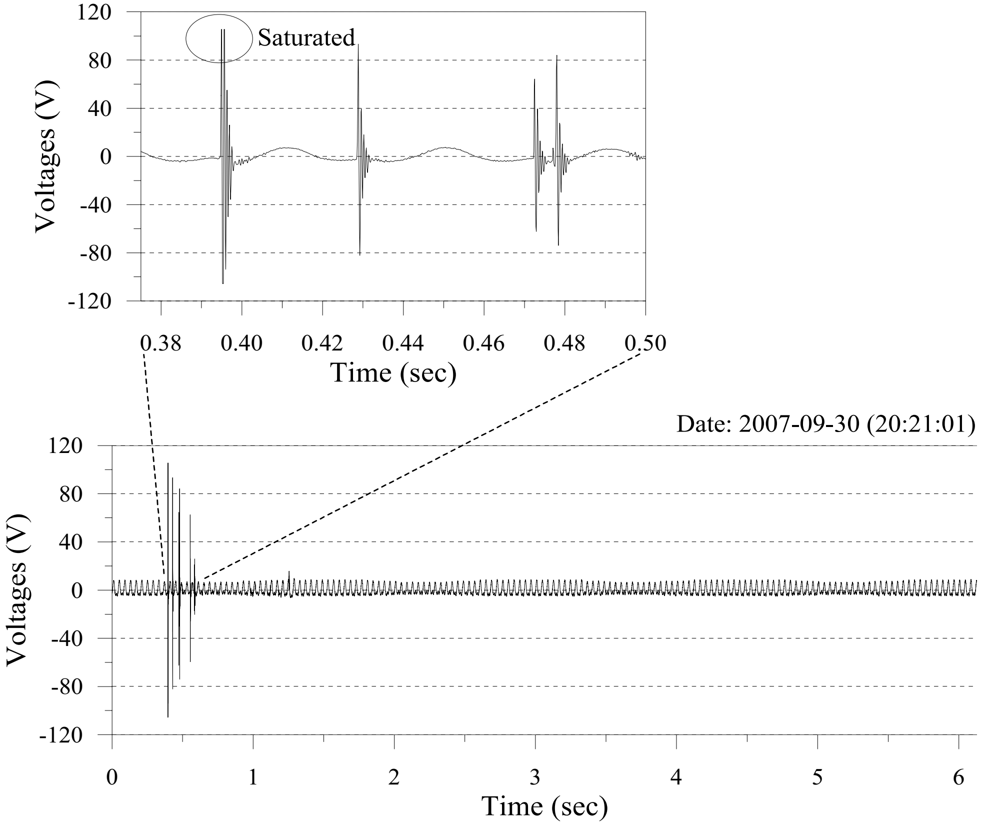

Figure 9. Measured voltages where the first transients are saturated.

The last two curves that day, 30/9/2007, were recorded at 20.41.47 (8.41 and 47 seconds pm) and at 20.46.04 (8.46 and 4 seconds pm). The voltages dropped, or the whole system's potential was raised, see Figure 10. There is no evidence that the potential between these two measurements was saturated, but it is likely that it was saturated the whole time, approximately 5 minutes.

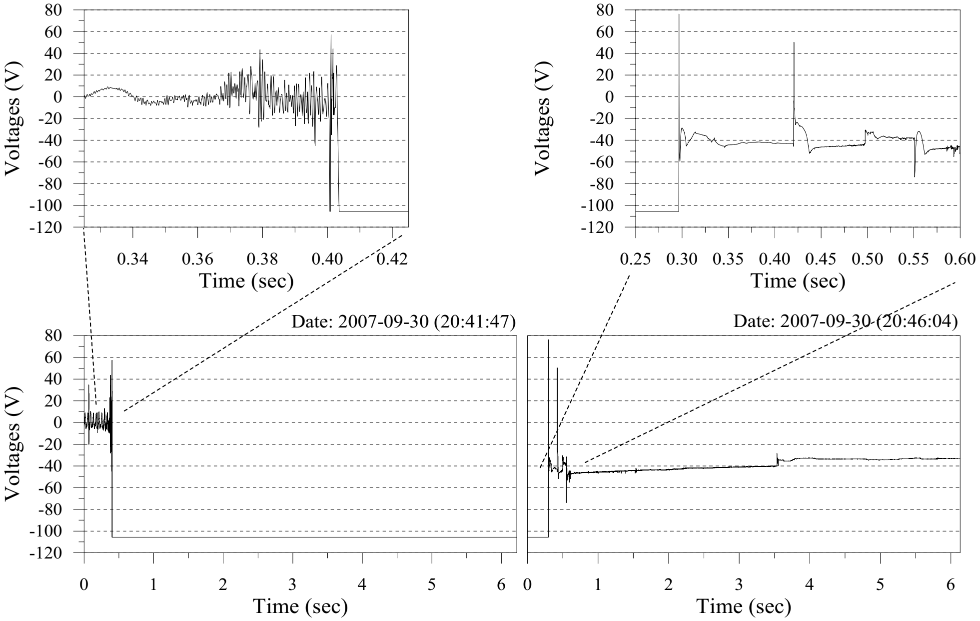

Figure 10. Measured voltages where the potential has dropped and the measurement system has been saturated. There are approximately 5 minutes between the two measurements.

The next day (1/10/2007) there was a new alarm to the CTTC office at 7.46 (am), showing that the RC circuit was out of order. During this day there were no triggers at all registered, except the forced trigger in the middle of the night. However, as explained before, the measurement system may have been malfunctioning because the probe was incorrectly connected.

The other two days when a fault was registered for the RC circuit were 1/11/2007, with 225 triggers, and 8/11/2007, with 690 triggers, see Table 1. The curves for these two days when the RC circuit went out of order are slightly different compared to the curves for other days, and contain more energy in the transients, see Figure 11.

The curve in Figure 11 was triggered at 15.04. The next curve was triggered at 15.13 and looks similar to the curve triggered at 15.04. The alarm was detected at 15.10.

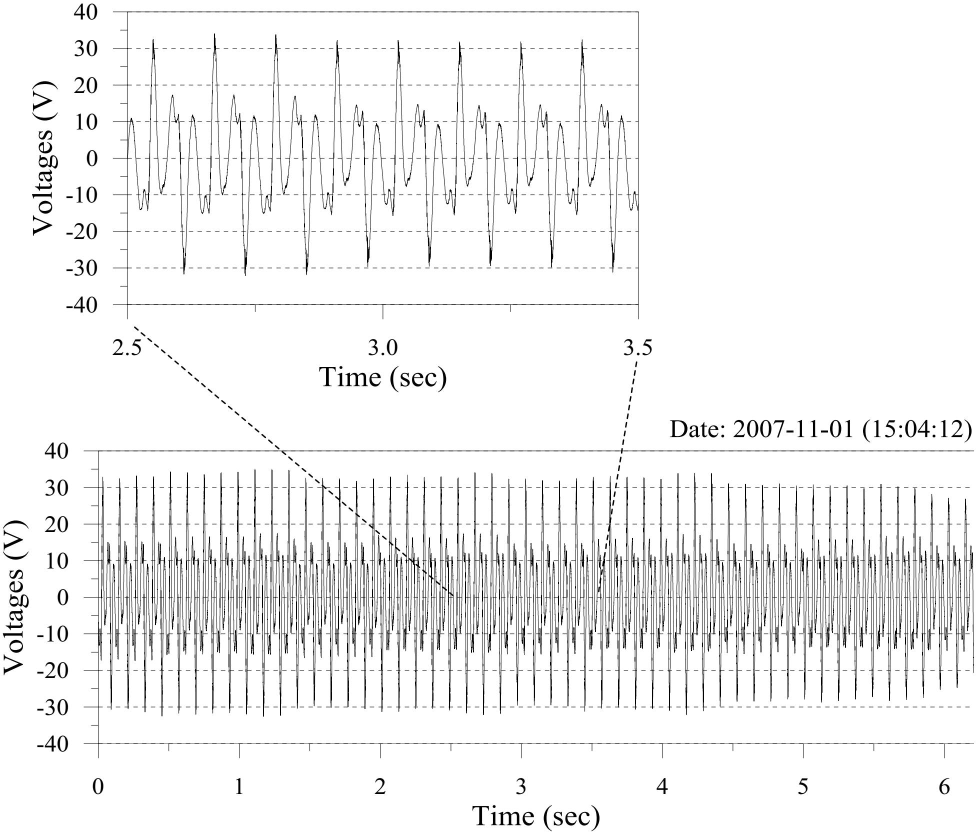

Figure 11. Voltage curve 20071101 1504.

Measurement with 1 MHz

Triggers

The number of triggering events per day is presented in Table 2. The large variation that was shown in Table 1 is also present in Table 2. On average the numbers of triggering events are higher for this sample rate. This is a consequence of the faster sample rate, 1 MHz, which catches every transient that is above 30 V. The days with outliers, concerning the numbers of triggering events per day, are 9/12/2007, 10/12/2007 and 11/12/2007. During the period no alarm was reported for the RC circuit to the CTTC office, not even on the three days that have the outliers for the triggering events.

Table 2. The number of triggering events per day.

Date	***Numbers of triggering events***	***Number of triggering events per hour***
20071116	53	2.208
20071117	67	2.792
20071118	21	0.875
20071119	20	0.833
20071120	20	0.833
20071121	1	0.042
20071122	13	0.542
20071123	5	0.208
20071124	3	0.125
20071125	50	2.083
20071126	1	0.042
20071127	63	2.625
20071128	2	0.083
20071129 - 1206	1	0.042
20071207	37	1.542
20071208	36	1.500
20071209	281	11.708
20071210	680	28.333
20071211	724	30.167
20071212 Only AM.	61	
Sum	2140	

Results

In comparison with Figure 7 and 8, Figure 12 shows, due to the faster sampling rate, only a single transient. All the curves during this measurement period show a similar behaviour. The first transient in all the curves has the same value, - 56.25 V, as seen in Figure 12. The figure shows that the transient is very fast on the flanks in the middle. The tail seen in Figure 7 and 8 is not seen in Figure 12. The transient is very fast and the voltage drops immediately after the last high transient.

The equipment was checked after the measurement and it behaved correctly in the laboratory environment.

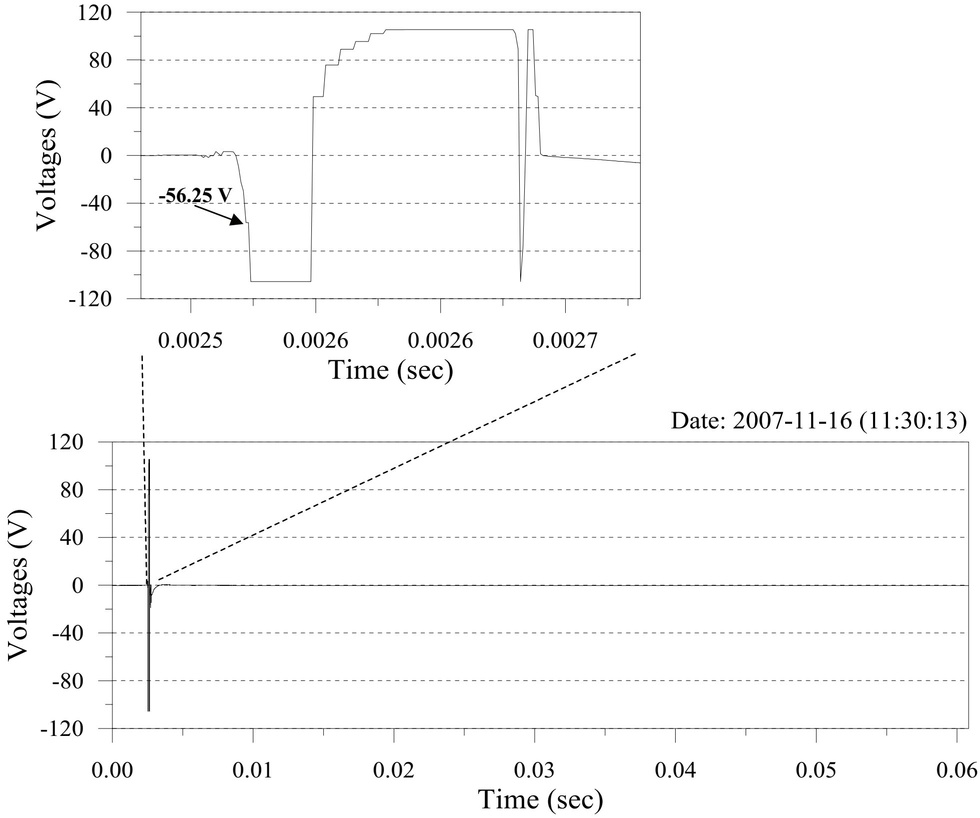

Figure 12. Voltage curve where the first transients are saturated. The sampling rate was 1 MHz.

Frequency analysis

To determine the specific frequencies that dominated the measurements, the data were analysed with an FFT (Fast Fourier Transform). The FFT was performed in MatLab. Table 3 summarises the dominant frequencies in each curve. The most recurrent frequency is 25 Hz, followed by other frequencies that can be divided by 8 1/3 Hz, which is half the frequency that Banverket employs in their power system, 16 2/3 Hz. The most dominant frequencies overall are 25 and 50 Hz.

Table 3. The dominant frequencies for specific curves as obtained through FFT analysis.

Curves	***Frequency (Hz)***														
	8⅓	***11***	***14***	***25***	***41⅔***	***50***	***58⅓***	***61***	***64***	***75***	***91⅔***	***100***	***108⅓***	***125***	***141⅔***
2007-09-01		X	X	X		X		X	X			X	X	X	
2007-08 13	X	X	X	X			X	X	X	X	X		X	X	X
2007-09-25	X	X	X	X	X		X			X	X		X	X	X
2007-09-30				X		X						X		X	
2007-11-01	X			X	X	X	X			X	X		X		

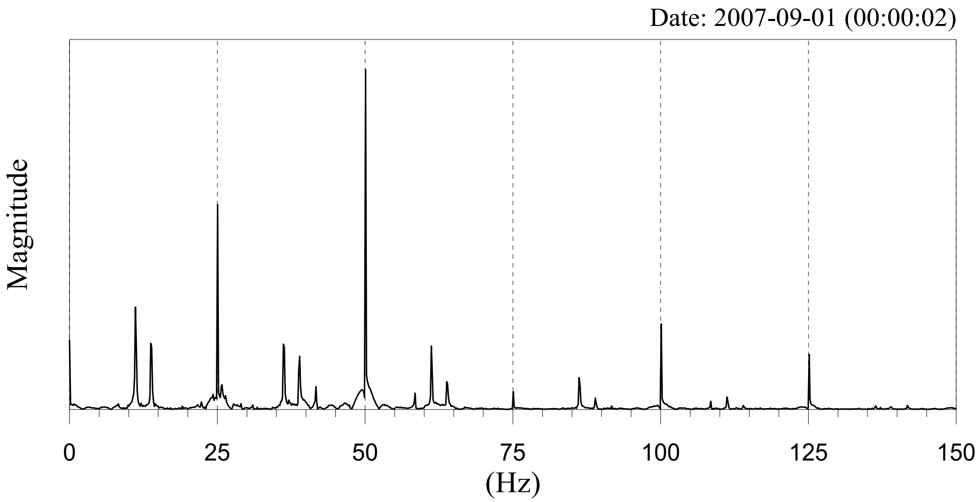

Figure 13. The frequencies from Oxmyran during the forced night trigger.

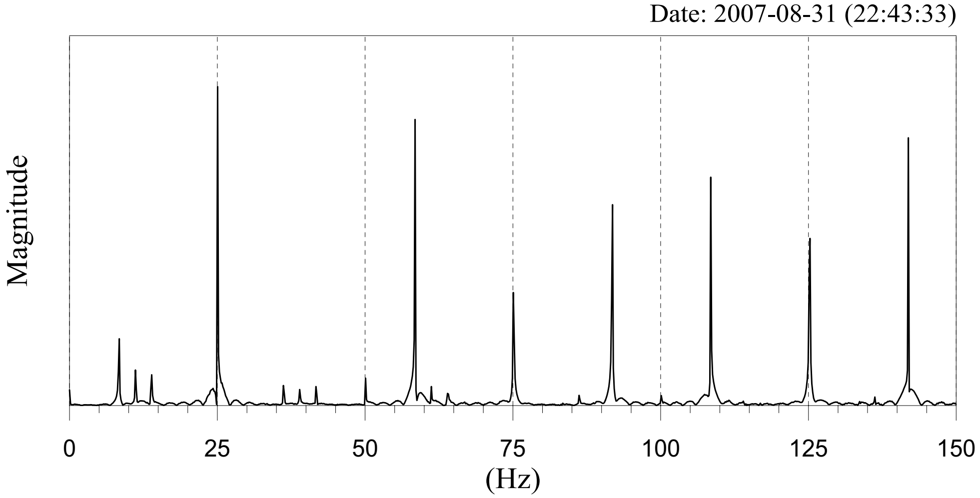

Figure 14. An FFT on the curve from the date 2007-08-31, the time 22:43:13.

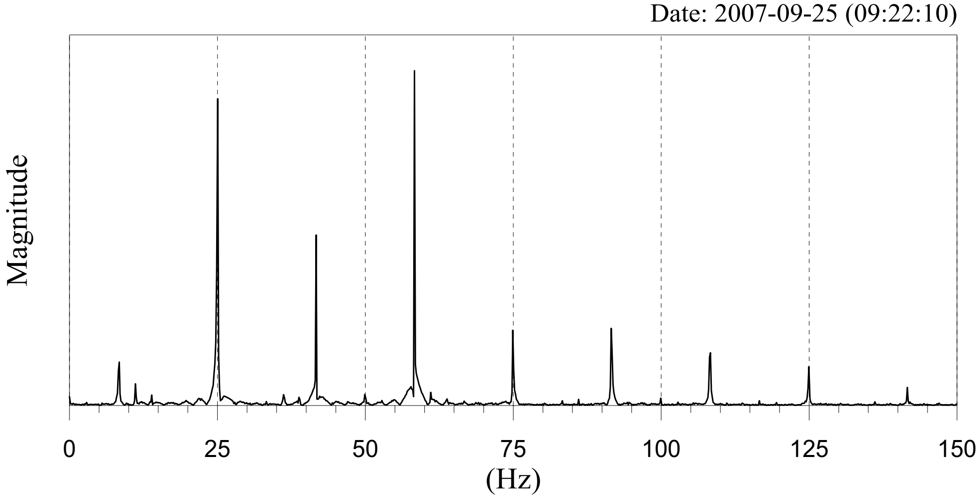

Figure 15. The FFT from the date of 2007-09-25, the time 09:22:10.

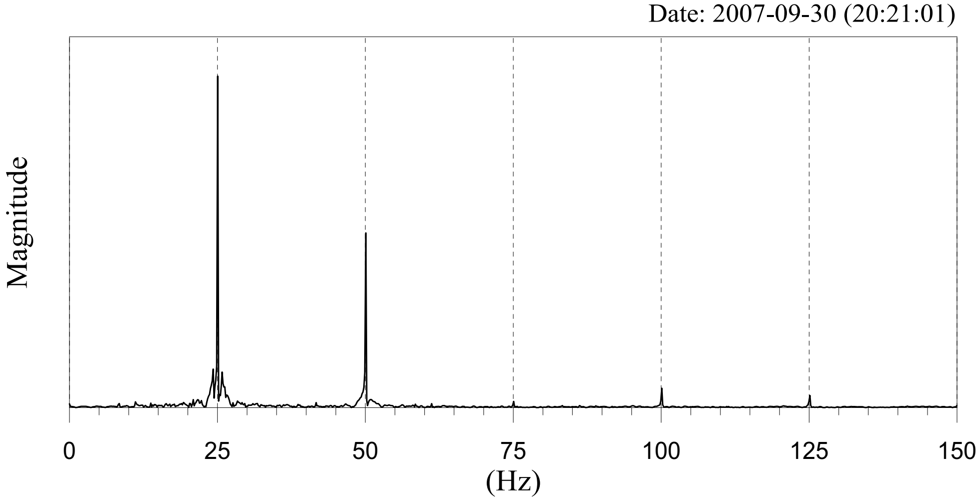

Figure 16. The FFT from the date of 2007-09-30, the time 20:21:01.

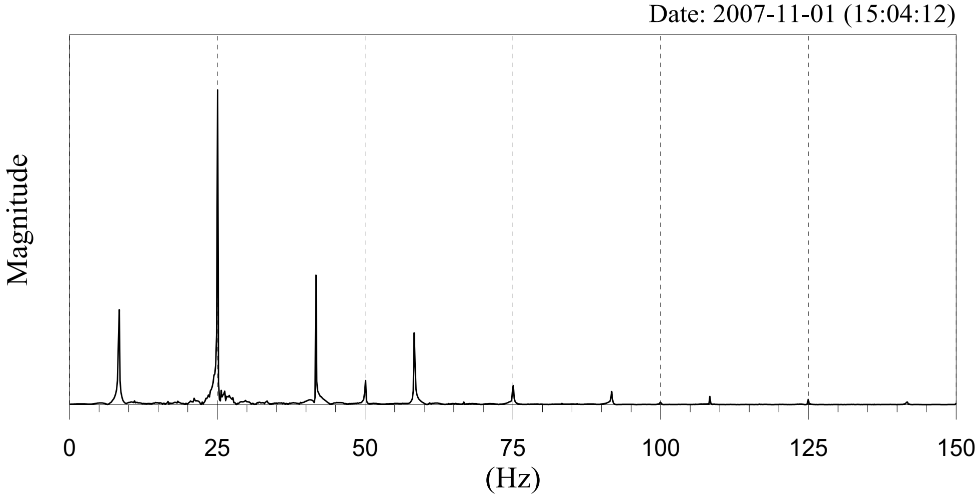

Figure 17. The FFT from the date of 2007-11-01, the time 15:04:12.

Discussion

During the measuring period at Oxmyran the RC circuit failed several times, resulting in alarms sent to the CTTC office. However, not on a single occasion was the measurement system triggered in direct connection to a failure. On the other hand, higher activity levels (numbers of triggering events) have been seen close to the time of many failures. High voltage levels were recorded during the period and some were so high that they saturated the measurement system used. However, in most cases the high transients were also very short, see for example Figure 9. This means that the transients probably did not contain enough power to make the RC circuit go out of order.

During the measurement period the trigger level was set to 30 V and not -30 V. In Figure 10 both curves dropped below -30 V and were also saturated. The reason why these two curves were monitored was a short positive transient over 30 V before and after they were saturated. In this case it can be argued that the specific voltage levels and time would contain enough power to make the RC circuit go out of order. However, again the RC circuit was not out of order until much later that day, and no specific curve was recorded that could be the primary reason for the failure of the RC circuit.

Regarding the detailed analysis of the transients, see Figure 12, the supplier of the rectifiers controls and checks every delivered rectifier according to specific instructions. The supplier also states that there is not any internal or external source that could generate the voltage -56.25 V that is seen in Figure 12. It is not a normal behaviour that a high transient should drop that fast. A more normal behaviour is seen in Figure 7 and Figure 8, and resembles more what has been seen in measurements and simulations of pantographs [17, 18, 19]. To exclude faults or mistakes during the measurement, the measurement system was checked afterwards, and it was working correctly, even if there is no guarantee that the measurement is correct.

If the rectifier had been active and delivered the power, the level should have been around 26 to 27 V, which is what the rectifier delivers to its subsystem when it is active. This gives a clear indication that it was not a train or locomotive that was the primary cause of the interference. All the measurement curves are also centred on zero, which indicates that there were no trains located at the station.

The measurements clearly show that a better filter over the specific RC circuit at the station at Oxmyran would reduce the problems, even if the source of the problems still is unknown. Today there is a UPS installed, but it is not installed like a filter, but instead as a back-up if the system should lack power for a short while.

In the analysis of the specific frequencies in the monitored data, it was surprising that the lowest frequency was 8 1/3 Hz and not 16 2/3 Hz, which is the frequency that Banverket employs in their power system. The converters used north and south of Oxmyran are both static and deliver 16 2/3 Hz in one phase. In Table 3 and Figures 13-17 the frequencies 25 Hz and 50 Hz are dominant. One theory proposing that the 50 Hz system that is used in other systems at the station might influence the DC system after the rectifier is not that plausible, in spite of the fact that every system uses the same ground. However, both the frequencies 25 Hz and 50 Hz are multiples of 8 1/3 Hz, as are 41 2/3 Hz and 58 1/3 Hz, which are dominant in several of the curves.

Conclusions

The conclusions drawn from the study are;

- The presented results clearly show that the new method used to measure EMI, has been useful and have performed well for this application.
- Demonstrably high transients occur in the system and can provide enough energy to interfere with the functionality of subsystems and hence the reliability of the system.
- The recorded ground frequency in the measurements is 8 1/3 Hz, which is half the frequency that is used in the railway, 16 2/3 Hz and has no relationship to any other systems in the railway

References

[1] ERRAC (European Rail Research Advisory Council), Strategic rail research agenda 2020. (November 2008) [Online]. Available: http://www.errac.org

[2] Karlsson V.: ‘An overall view of maintenance’, *European Railway Review*, 2005, **11**, (3), pp. 11 – 17

[3] Cella, R. *et al.*: ‘Measurement of AT electric railway system currents at power-supply frequency and validation of a multiconductor transmission-line model’, *IEEE Transactions on Power Delivery*, 2006, **21**, (3), pp. 1721- 1726

[4] Bourne, A. *et al.*: ‘Managing electromagnetic compatibility on the London underground system, EMC assurance in a railway environment’, *IEE*, 2003, **8**, pp. 1 – 11

[5] Midya, S., and Thottappillil, R.: ‘An overview of electromagnetic compatibility challenges in European rail traffic management system’, *Transportation Research Part C: Emerging Technologies*, 2008, **16**, (5), pp. 515-534

[6] McCormack, L.M. *et al.*: ‘Railway electrical systems integration – practical application of the ‘V’ Cycle for electromagnetic compatibility (EMC)’. Proc. The Institution of Engineering and Technology Seminar on EMC in Railways, pp. 119-126, Sept. 2006

[7] White, R.: ‘Electrification traction and signalling compatibility’. The 11th IET Professional Development Course on Railway Signalling and Control Systems, pp. 132-164, June 2006

[8] Ogunsola, A., and Pomeroy, S.: ‘EMC assurance and safety critical apparatus in a railway environment’. Proc. EMC '03, IEEE International Symposium on Electromagnetic Compatibility, Vol. 1, pp. 429-432, May 2003

[9] Holmes, R.: ‘Electromagnetic compatibility of electrified railways’. Proc. International Conference on Electric Railways in a United Europe, pp. 131-135, Mars 1995

[10] Ogunsola, A.: ‘EMC assurance and management, EMC Assurance in a Railway Environment’, *IEE*, 2003, **5**, pp. 1-8

[11] Allan, J. *et al*.: ‘Low frequency and radio frequency electromagnetic compatibility for rapid transit railways’. Proc. Fifth European Conference on Power Electronics and Applications, Vol. 7, pp. 106-111, Sep. 1993

[12] Mariscotti, A., and Pozzobon, P.: ‘Determination of the electrical parameters of railway traction lines: calculation, measurement, and reference data’, *IEEE Transactions on Power Delivery*, 2004, **19**, (4), pp. 1538 – 1546

[13] Hill, R.J. *et al*.: ‘Rail transit chopper traction interference modelling using the SPICE circuit simulation package’, *IEEE Transactions on Vehicular Technology*, 1989, **38**, pp. 237-246

[14] Hill, R.J.: ‘Electrical railway traction. Part 6 Electromagnetic compatibility – disturbance sources and equipment susceptibility’, *IEE Power Eng. J.*, 1997, **11**, pp. 31-39

[15] Ogasawara, S., and Akagi, H.: ‘Modeling and damping of high-frequency leakage currents in PWM inverter-fed AC motor drive systems’, *IEEE Transactions on Industry Applications*, 1996, **32**, (5), pp. 1105-1114

[16] Hill, R.J., and Cevik, I.H.: ‘On-line simulation of voltage regulation in autotransformer-fed AC electric railroad traction networks’, *IEEE Transactions on Vehicular Technology*, 1993, **42**, (3), pp. 365–372

[17] Tellini, B. *et al*.: ‘Line-pantograph EMI in railway systems’, *IEEE Instrumentation & Measurement Magazine*, 2001, **4**, (4), pp. 10-13

[18] Tellini, B. *et al*.: ‘Conducted and radiated interference measurements in the line-pantograph system’, *IEEE Transactions on Instrumentation and Measurement*, 2001, **50**, (6), pp. 1661 – 1664

[19] Tellini, B. *et al*.: ‘Conducted and radiated interference measurements in the line-pantograph system’, *IEEE Transactions on Instrumentation and Measurement*, 2001, **50**, (6), pp. 1661-1664