Dependability issues of Track Circuits - A hybrid approach

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Abstract

The study of railway electromagnetic interference (EMI) seeks to determine the source of the interference or to ensure the correct operation of the equipment within adverse conditions. The complexity of railway system increases when more electronics are used. However a simple DC track circuit is still used in train detection systems in many countries, including Sweden, our case study.

Most of the failures reported in the Swedish railway infrastructure are related to the detection system, making this research of interest to the railway community.

By searching the Swedish failures report database, 0FELIA, for the most repetitive and probable causes of failures, they were identified three worst case scenarios: low resistance between the rails, external interference as a lightning and iron-powder-bridges in the insulated joint. They were simulated using the software CST STUDIO SUITE® (Computer Simulation Technology Studio Suite), supported by real measurements on site. Measurements followed the current EMC standards and were used to tune and validate the models, resulting in simulations very close to the real measures.

Keywords: Signalling, track circuit, EMC, EMI impact, train operation, interoperability and reliability.

1 Introduction

Several European countries already have high-speed trains running across their borders, e. g. Spain, France, Italy and Germany. On certain routes, the trains can reach 350 km/h [1]. In Sweden, however, many trains run at a maximum of 200 km/h even though hundreds of kilometres of track are ready for at least 250 km/h operation [1, 2].

A system upgrade to solve the compatibility problems between new trains and old infrastructure is desperately required. For example, railway infrastructure operators suffer from railway infrastructure availability reduction caused by the rolling stock electromagnetic incompatibility with the safety critical signalling systems. But neither the signalling system, the catenary, nor the trains themselves are prepared for this updating.

In railway systems, one of the simplest but biggest problems is to identify when a rail track is occupied. Train detections systems, such as the track circuit are used to solve this problem. A track circuit is an electronic/electric device which detects whether there is a train on the track. If so, it warns the rest of the system that the track is occupied.

This simple action has a crucial responsibility for travellers' security. If a track circuit fails, a train crash could occur [3]. Although this seldom occurs, some false positives have caused injuries and fatalities; in the Cowan rail accident on 6 May 1990, 6 people died and 99 were injured. In short, a good performance of the track circuit is essential for safe transportation [4].

Unfortunately, track circuit malfunctions cause many delays. A track circuit may detect the presence of a train when the track is empty. Trains do not have access to the empty rail track, and this situation may not be detected for a long time. Even though this situation is not as much a priority as one described above, it can cause a significant loss of time and money.

In Sweden, the DC track circuit is most commonly used. Each line is divided into track circuit sections about 1 km long separated by 6 mm thick rubber insulated rail joints (Isolerade Rail, I-rail) . The principle of the DC track circuit is the connection of the two rails by the wheels and axle of the railway vehicle, also known as rolling stock, to close the open circuit [5]. The systems used to avoid failures are strengthened with backup supplies, fail-safe relays (Figure 1), opposite supplies in consecutive track circuit sections following the fail-safe principle, chokes, double relay circuits, etc.

Figure 1. Detail of the most used relay in Sweden, model JRK 10470.

In the context of failure avoidance, the FP7 project TREND (Test of Rolling Stock Electromagnetic Compatibility for cross-Domain Interoperability) designs a test setup for harmonising freight and passenger rolling stock approval tests for electromagnetic compatibility focusing not only on interferences with broadcasting services but also on railway signalling systems [6].

To identify interferences affecting the track circuit, it was performed a failure review using data from the Trafikverket's 0FELIA database. After the identification of the three most representative worst case scenarios, these are analysed. A thorough study of cross-talk causes of failure in the train detection system revealed the need for a virtual scenario; to produce a wider variety of scenarios that are difficult to measure on site, it was modelled a simulated framework in CST STUDIO SUITE®. Finally, the results were cross-referenced with the simulations to validate the virtual environment. Eventually some of the input parameters in the simulation are dependent on the measurement performed.

2 Swedish DC track circuit worst case scenarios

2.1 Introduction

In our case study, a single rail track circuit model is fed by a DC source. The chosen measurements were from a 575 m track circuit section at the Niemisel station, in the north of Sweden. With the collected data it was possible to reproduce the scenarios for the simulations, showed in the next sections.

The whole track circuit is divided in sections, each considered a unique block. Track sections are separated by an insulated joint at the rail end. In the Swedish case, a 6 mm thick rubber insulated rail (Isolerade Rail, I-rail) transports information on the track circuit status [7]. The other rail (Svetsade rail, S-rail) is welded without insulated joints and carries the return current of the railway infrastructure. Figure 2 shows the general scheme of the track circuit.

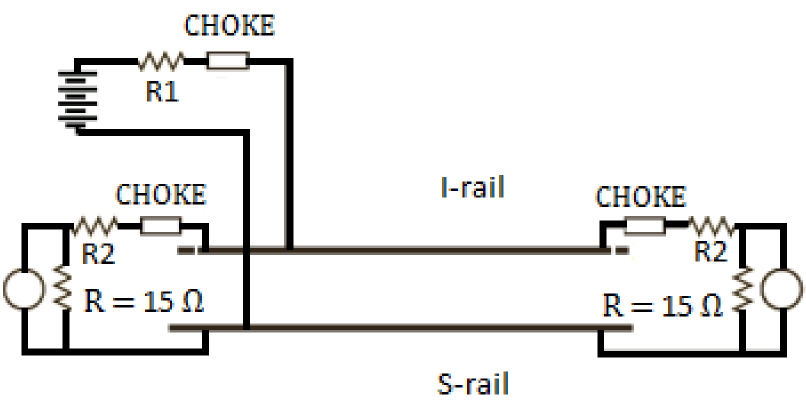

Figure 2. DC Track circuit general scheme.

Extra fail-safe actions in the Swedish track circuit include the following:

- Relay operating follows the fail-safe principle. If the current through the relay drops for any reason, the system displays an emergency signal.
- Relays and power supply are attached to opposite ends to ensure the whole track circuit section is checked; this allows the system to detect rail breaks.

- For lengths up to 1800 metres, most of the Swedish DC TCs consist of two relays placed at the ends of the track circuit section, with the power source in one end. Having two relays provides a double check against failure. If there is a contradiction between relays, a danger signal is activated and sent to the TCC (Train Control Central) to activate an emergency brake call.
- This power supply in most stations is a rectifier with a DC battery as backup. Circuits are commonly battery-powered at low voltages to protect against line power failures.
- If there is an insulation failure between track circuit sections, one circuit could falsely power the next one, reversing the electrical polarity from section to section. In the case of a short circuit of the insulated rail joint, both consecutive relays will show an obstacle on the railroad.

2.2 Features

2.2.1 Low resistance between rails

In the first case, they were considered two scenarios. As explained, the train detection system may warn that a train is occupying the track when there is no train. The opposite may occur as well, but the possibility that a train is not detected is negligible [8].

In the case of the detection of a non-existent train most failures occur at railway stations.

The Swedish DC Track circuit is limited to 1500 metres between the feeding and relay. This limit is set so that diversion and reduction in track voltage between sections should not cause faulty signalling. Some factors influence the diversion and track voltage, causing low resistance between rails and triggering a faulty signal. These influences are:

- Ballast resistance.
- Grounding of the I-rail, making the voltage drop below 1.7 V DC (voltage state change), even in the absence of a train.
- Rail structure.
- Switches and crossings (figure 3).
- Obstacles on the track.

The differences in maximum distance between the feeding and the relay in the Swedish DC track circuits occur because the resistance of the ballast varies at different climatic conditions; thus, the extent of the leakage current differs on track sections (i.e., between the I- and S-rail, over each sleeper).

The size of the diversion and track voltage are influenced by several factors:

- Material of the ballast and its consistency.
- Ballast humidity.
- Temperature.
- Type of sleeper and rail fastenings.
- Switches & crossings over the distance of the track circuit.
- Pollution in the ballast.
- Ballast going up against the rail foot or alternatively not going up.

When the track is frozen or completely dry, the dissipation is practically zero. On the other hand, in warmer autumn rain, the ballast resistance will fall to its minimum value and the diversion is therefore at its maximum.

For the purposes of our study, it was estimated the minimum resistance value of the ballast as follows:

- Ballast of gravel, 2 Ω/km track circuit.
- Ballast of macadam and wooden sleepers, 4 Ω/km track circuit.
- Ballast of macadam and concrete sleepers, > 7 Ω/km track circuit [9].

Figure 3. Switch on the track.

An obstacle across the track connecting the two rails can be caused by flooding, massive snowfalls or dropped freight, but this seldom occurs and is easily detected.

On the other hand, the undetected real train is a dangerous failure that cannot be allowed. During the last 30 years, this happened only once in Sweden. This rare and special event occurred at Boden Central Station because of massive snowfall. Even with the train occupying the track section, the automatic train detection system showed no presence of a train; the voltage did not drop below the voltage state change because all the wheels of the train were floating over a layer of snow [10].

2.2.2 External interference

The biggest natural problem that can interfere with the railway system is lightning. Cloud-to-ground lightning can cause damage in two ways: by a direct strike or by induction effects resulting from a nearby strike. Occasionally lightning can strike far from an object and still affect it. Indirect strikes can also affect the train detection system, but are not as severe as direct strikes. In this case, the wave is conducted to the object by other means, for instance, conducting systems and power lines.

The most relevant properties of the lightning that cause damage are peak current and maximum rate of current change. The largest currents are produced by return peak currents when the struck object presents a resistive load. The typical value for a peak current is about 30 kA. A current with this magnitude entering the earth with a grounding impedance of 10 Ω causes a potential rise of 300 kV and may cause surface arcing.

Another lightning property that affects the railway system is the maximum rate of change of current in objects that present inductive impedance, such as wires, earth leads etc. For instance, assuming that 10% of the peak current value with front time 0.3 μs finds its way to the wiring of an electronic device, for an inductive load of 1 mH per metre, the inductive voltage produced in a 10 cm long wire could reach 1000 V.

The safety devices used to protect against this kind of interference are the chokes (Figure 4), placed in series with relays to protect them from any disturbance.

Figure 4. Choke with possible double configuration, in series or parallel.

2.2.3 Iron-powder-bridge in the insulated joint

The insulated rail joint (Figure 5) is a simple but important component of the train detection system. It electrically insulates two consecutive rails and acts as a bond between to form a long track distance. The wheels roll over the insulated joint, milling the rail ends; the physical gap between the two rails becomes smaller each time a train passes, and may create an electrical connection. The problem is a wear out one, but the outcome is a signalling fault, as dictated by the fail-safe principle.

Conducting iron-powder-bridges might electrically connect two consecutive track sections. If this is bridged by a metal piece, the voltage in both sections could drop enough to generate an occupied track state on both sections. Magnetic fields make iron particles stick together, building conducting bridges over insulated joints, especially in areas where the traffic is heavy and the wearing of wheels is extreme. Typically this issue does not lead to problems on long distance tracks, but is reported in high volume areas. In such situations, extra maintenance is necessary, as for example, cleaning metallic particles from insulated junctions to avoid short circuits between adjacent I-rail sections.

Detectors for flat wheels or hot bearings may be considered as well; these are more insensitive to electromagnetic pulses and unaffected by the closeness of the junctions on the I-rails [11].

Figure 5. Insulated rail joint.

2.3 CST Model

2.3.1 Short circuit between rails

As all the worst case scenarios are related to the precise moment when the relay switches its state, a voltage and current sweep is done to determine when the relay switches from one state to another. The track section was measured at two different points: data on the current were collected in the source cable and data on the voltage were collected between rails. When the resistance value was modify, the limits for the sweep were from 0 Ω to 5 Ω with the smallest step of 0.1 Ω. To test the value of the resistance between rails required to switch the state from ON to OFF, it was performed a sweep from 0 Ω to 2 Ω. To check the change of status from OFF to ON, the sweep was from 5 Ω to 4 Ω.

Figure 6 shows the 3D design of two consecutive track sections with the connections to the train on the left side.

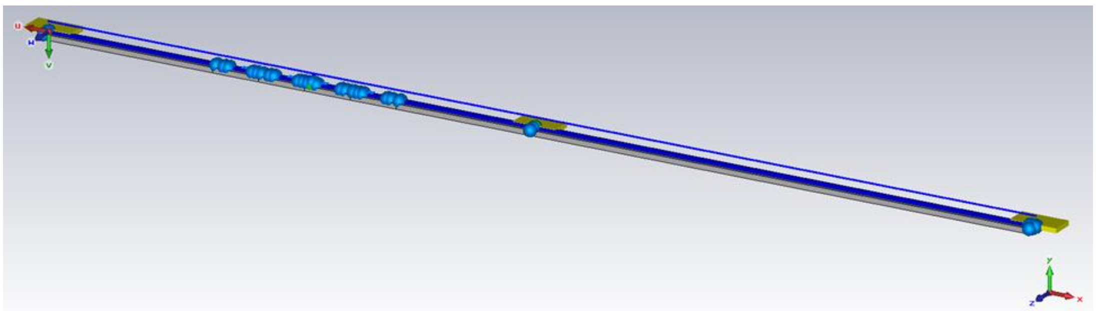

Figure 6. 3D CST model of two consecutive DC track circuit sections.

2.3.2 Lightning

To simulate external interference, for instance by lightning, the resistance between rails should be removed, since the scenario may not need the presence of a train. As electromagnetic interference, lightning can be understood as a 30 kA current entering the railway infrastructure through the grounding impedance during 300 ns. This can be performed using a CST CABLE STUDIO® task called Transient, applied to an external port connected to the rail. To be imported, the lightning characteristics can be made transient in an ASCII (American Standard Code for Information Interchange) file, as shown in Figure 7.

The 3D model of the scenario is like the previous one, but there are two modifications in the schema: R3 is removed and port 1 included.

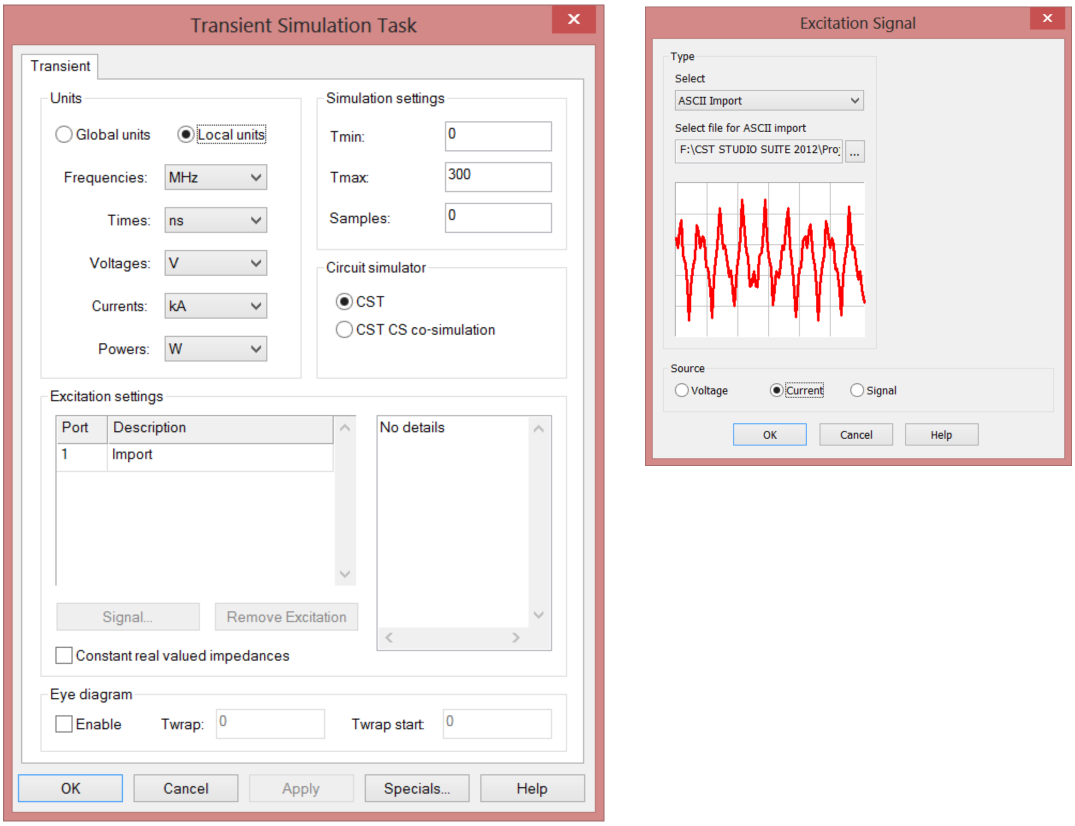

Figure 7. Introduction of lightning as transient voltage.

2.3.3 Short circuit between track circuit sections

An important point to highlight in the Swedish railway system is how to prevent one circuit from falsely powering another. This situation could occur in the event of insulation failure. When the electrical polarity from section to section (Figure 8) is reversed in a short circuit event, both consecutive relays will show an obstacle on the railroad and the system will activate an emergency brake call.

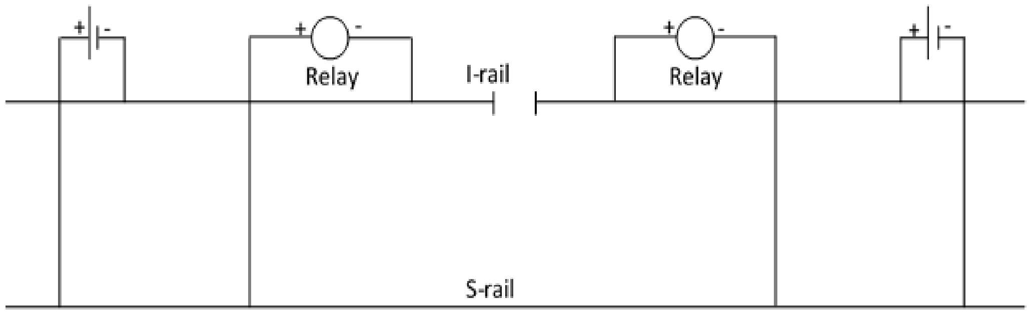

Figure 8. Layout of two consecutive track circuit sections.

To determine whether this method works, a set of tests can be performed. First, a second track circuit section must be added; at the same time, the poles of the battery and the connections of the relays must be changed (Figure 9).

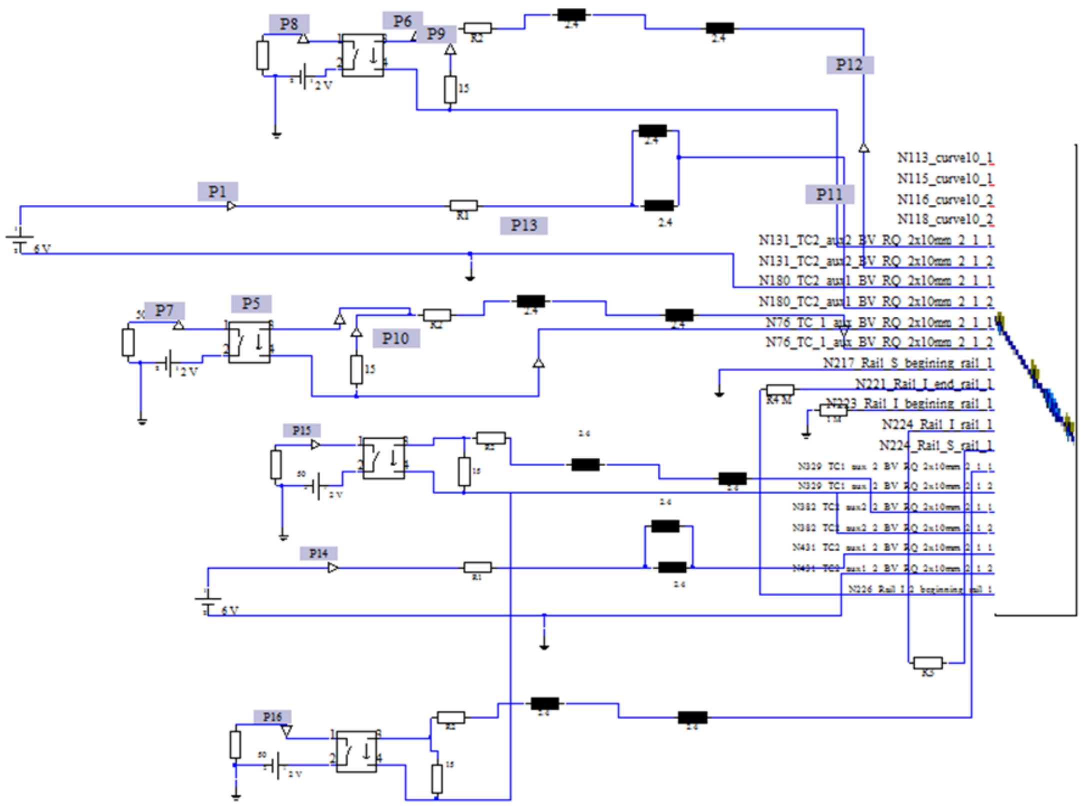

Figure 9. 2D circuit CST model of two consecutive DC track circuit sections.

To model the insulated joint, another variable resistance (R4) is added. In addition, the variable resistance R3 must be used in the first track section to simulate the presence of a train. They were performed the following tests:

First test: configuring a huge value of R4, as a good working insulated joint, and setting a value of R3 low enough to detect a train.

Second test: setting a huge value of R4 and configuring R3 high enough to not detect an obstacle on the first track section.

Third test: decreasing the value of R4 to zero to simulate a short circuit between the I-rails of two consecutive sections due to a broken insulated joint and giving R3 the same range of values as in the first test.

Fourth test: setting the same value of R4 as in the third test and the same value of R3 as in the second test.

After all these tests are performed, a minimum value of resistance can be calculated to ensure the correct insulation between rails.

2.4 Validation of the model

A measurement campaign was carried out to fine-tune and validate the model, hoping to get the same switching point in both cases.

When it was introduced a variable resistance R3 between the rails, the switching points were the next values in the relay transitions:

- OFF to ON: in the step up from 4.8 Ω to 4.9 Ω, implies 1.5 V (Von-off).
- ON to OFF: from 1.5 Ω to 1.4 Ω, implies 0.7 V (Voff-on).

However, for the new voltage values for the relay characteristics for resistance R1 = 3 Ω and R2 = 7.5 Ω in the model developed in CST, they were used three degrees of freedom to suit the simulation to the real values. This modification was done to meet the requirements imposed by the results obtained in the measurements.

3 Results

Figure 10 and Figure 11 compare the measurement values with the simulation in the virtual environment. In both transitions, from ON to OFF and from OFF to ON, the simulated values of the current are fairly close to the measured ones. It is important to note that the transitions between both states took place for the very same value of resistance between rails that was used to model the obstacle on track. This is a decisive validation of the simulation. The transitions in the simulation occur in the same situation as they do in the real case, and the simulated values follow the same trend as the real ones; thus, the scenario modelled can be considered reliable for simulations.

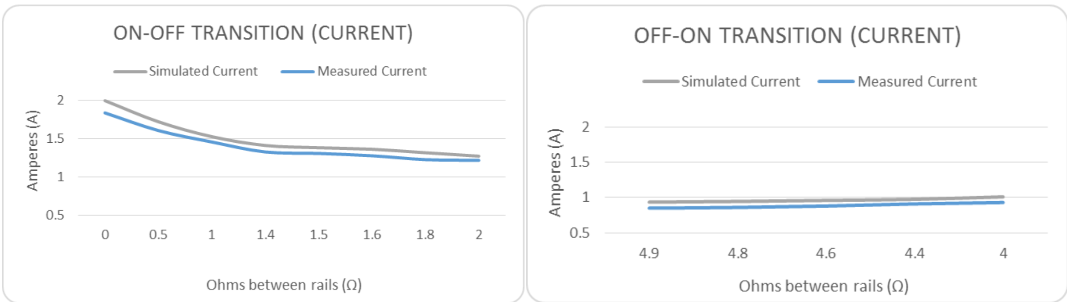

Figure 10. Comparison of simulated and measured current in the TC.

There is a greater difference in the voltages than in the currents mainly because of resistances related to imperfections not considered in this study.

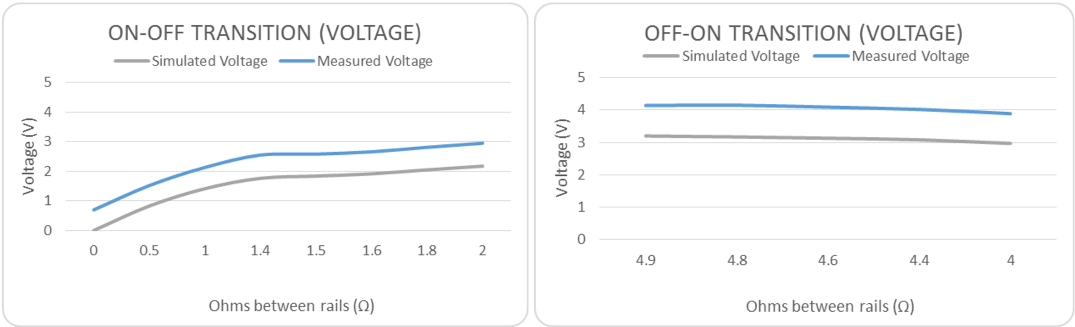

Figure 11. Comparison of simulated and measured voltage in the TC.

The study performed to simulate the lightning showed that this external force does not affect the track circuit system, contrary to what happens in other systems in the railway infrastructure [12].

STATE OF THE TRACK (Ω between the rails)	CURRENT IN PROBE P1 WITH LIGHTNING (A)
0.000	2.000
0.500	1.725
1.000	1.530
1.400	1.415
1.500	1.385
1.600	1.365
1.800	1.320
2.000	1.275

STATE OF THE TRACK (Ω between the rails)	CURRENT IN PROBE P1 WITH LIGHTNING (A)
4.900	0.935
4.800	0.945
4.600	0.960
4.400	0.975
4.000	1.010

Table 1. Current values with the influence of the lighting.

The chokes placed in series with the relays avoid the transient lightning voltage that affects the proper operation of the train detection system. In Table 1 and Table 2, the orange fields represent when the system displays a danger signal, i.e., an obstacle is on the track. Even under the effect of the lightning, the relay still switches at the same value of resistance between rails.

STATE OF THE TRACK (Ω between the rails)	VOLTAGE IN PROBE P1 WITH LIGHTNING (A)
0.000	0.005
0.500	0.830
1.000	1.415
1.400	1.765
1.500	1.840
1.600	1.915
1.800	2.05
2.000	2.175

STATE OF THE TRACK (Ω between the rails)	VOLTAGE IN PROBE P1 WITH LIGHTNING (A)
4.900	3.200
4.800	3.170
4.600	3.130
4.400	3.080
4.000	2.970

Table 2. Voltage values with the influence of lightning.

Four tests were performed to check the proper functioning of the insulated rail joint, two with proper insulation and two with a short circuit between track circuit sections.

First test: configuring a well working insulated joint and the resistance between rails for a train detecting event; as expected, the result shows that only the first section is occupied.

Second test: configuring a well working insulated joint and a non detecting train event; none of the sections detects anything.

Third test: modelling a broken insulated joint with an obstacle in one of the sections; as the Swedish DC track circuit safety configuration inverts the polarisation of two successive track circuit sections, this test ends up with both sections detecting an obstacle on the railroad.

Fourth test: configuring a broken insulated joint and no train on the track; again the opposite supply between consecutive track circuit sections safety measures results in both sections detecting an obstacle.

Finally, with our model, it was calculated the minimum resistance that ensures the correct insulation, 2 Ohms. That means that every insulation joint with a resistance over 2 Ohms will ensure the correct performance of the track circuits, in terms of insulation between track circuit sections.

4 Conclusions

From our research it was reached the following conclusions.

A reliable framework that enables the simulation of scenarios to test the operation of a track circuit was created; this can be exploited in future research.

As a train detection system, the track circuit has a simple infrastructure which is robust against most of the interferences. The weakest point of the system is its dependence on the relay. If the relay fails, the fail-safe system will show an occupied track, causing delays in the flow of traffic. The system's efficiency can be increased by improving the track circuit, but this is difficult, due to its simplicity. However, the incorporation of another subsystem, for instance, the wheel axle counter, can complement the detection mechanism.

The insulated rail joint is an important component of the infrastructure, as it is the second most likely system to fail. Good maintenance of the track and insulated rail joint is crucial to avoid situations which can lead to train delays with important economic repercussions.

These simulations suggest a typical lightning strike directly on the track will not affect the track circuit.

Although this research has focused on the track circuit, a deep understanding of the complete railway system is necessary to understand possible threats not just to the track circuit system but to railway operation in general and to be able to integrate subsystems in an infrastructure. Rolling stock is a key element in the interoperability of the railway's subsystems, strongly related to the causes of abnormal behaviour in the signalling system. Most of the EMIs on track circuits are related to transient produced by the rolling stock or external sources, which should be studied in future research.

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