IET Intelligent Transport Systems

Research Article

IET Journals
The Institution of Engineering and Technology

Test of rolling stock electromagnetic compatibility for cross-domain interoperability

ISSN 1751-956X
Received on 2nd March 2015
Revised on 17th July 2015
Accepted on 11th September 2015
doi: 10.1049/iet-its.2015.0044
www.ietdl.org

Eva Karadimou ✉, *Rob Armstrong*

York EMC Services, Market Square, University of York, Heslington, York, UK
✉ *E-mail: eva.karadimou@yorkemc.co.uk*

Abstract: This study is part of a greater body of research on the electromagnetic compatibility in the railway environment throughout Europe. In particular, this study focuses on the broadcasting services as a victim area and identifies the electromagnetic interference threats in the railway environment. After the definition of the pantograph arcing as the worst-case scenario in terms of interference to these services, a test method was carried out in a controlled environment in order to examine the characteristics of these transient arcing events. It was found out that the power radiated is a broadband signal and the high levels of the radiated emissions require further investigation and examination, including addition to the railway standards that define the cross-domain interoperability of equipment, rolling stock and fixed installations in the railway environment.

1 Introduction

The presented research forms part of the TREND (test of rolling stock electromagnetic compatibility for cross-domain interoperability) project, sponsored by the European Union under the Seventh Framework Programme. TREND deals with the electromagnetic compatibility (EMC) in the railway environment under the scope of the cross-domain interoperability and safety of the rolling stock throughout Europe. The analysis of this project focuses on the electromagnetic interference (EMI) from the rolling stock and the railway infrastructure on four different areas: the spot signalling system, the track circuits, the Global System for Mobile Communications–Railway (GSM-R) and the broadcasting services [1].

The identification of the major problems spotted in the railway environment, came from a review of the current railway standards applied. The worst-case scenarios were defined for the research areas and controlled test environments representing these conditions were designed from the members of the TREND consortium.

Table 1 describes all the TREND research areas. This table defines the EMI victims and culprits and describes the mechanisms of coupling mechanisms in the railway environment [2].

This paper focuses on the broadcasting services as a victim area in the railway environment and the study carried out to investigate a cross-acceptance EMC test for these services in regard to the worst-case scenario. The term cross-acceptance refers to the process by which approval procedures for rolling stock are simplified through the mutual recognition of approvals, certificates and test methods in several countries. This is implemented through intergovernmental agreements that recognise the approvals issued by other safety authorities.

2 Identification of the coupling mechanisms and EMI threats for the broadcasting services

There are two types of coupling mechanisms causing EMI to the broadcasting services, interference by radiation and interference by induction, capacitance or conduction. In the first case, a victim signal is affected by an interfering signal which radiates at the same frequency as the victim signal and is powerful enough to cause problems at the receiving antenna. The second, conducted, type of EMI can cause problems that affect the transmitter or the receiver.

Under the scope of the TREND project, the EMI culprits for the broadcasting services are

i. *The rolling stock:* The radiated emissions from the rolling stock in the 30–530 MHz and 900–1.8 GHz GSM bands can interfere with the broadcasting signals.
ii. *The power supply and electrification system:* Transients created due to pantograph arcing or sliding pickup shoe and breaker operations can cause disruptions to the broadcasting signals. In addition, placing the railway electrification cables in close proximity to public facilities can affect the transmission or the reception of the broadcasting services.
iii. *The infrastructure, in terms of defects and debris:* Transients due to electrical discontinuities in the track, current return paths too close to public facilities and uncontrolled ground currents either due to poor power supply return paths design or poor maintenance.
iv. *Signalling and communication systems:* The frequency allocation of the GSM-R services in the railway environment and the use of the associated equipment can cause interference problems with the GSM broadcasting zone that use adjacent frequencies. Problems can be caused by uncontrolled current return paths or poor maintenance of the signalling and communication apparatus.

3 Review of the railway standards in relation to the EMI to the broadcasting services

The current railway standards EN 50121-x [3–8] define the EMC requirements for the railway applications. An analysis was carried out under the TREND project [9] and various gaps were identified regarding the aforementioned EMI threats for the broadcasting services in Section 2. These are summarised as follows [9]:

i. EN 50121-2 [4] deals with the radiated emissions from the whole railway system to the outside world. Regarding the EMI to the broadcasting services, a lower limit for the emissions has to be defined to protect the wave propagation part of these signals. Moreover, the current standards indicate emission limits for frequency ranges 9 kHz–1 GHz. Measurement test methods and limits should be defined for frequencies in exceed of 1 GHz.
ii. As the transient events are present in the railway environment, it is of high importance to distinguish continuous emissions from

Table 1 TREND research areas

EMI culprits	EMI victims: TREND research areas			
	Spot signalling systems	GSM-R	Broadcasting services	Track circuits
rolling stock	Radiation in the 9 kHz–30 MHz frequency band. Inappropriate antennas positioning.	Radiation in the 876–925 MHz frequency band. Inappropriate antenna positioning.	Radiation in the 30–530 MHz frequency band and the 900 MHz and 1.8 GHz GSM spectrums.	Conducted from 20 Hz to 20 kHz. Radiation in 9 kHz–30 MHz frequency band.
power supply and electrification system	Transients due to pantograph arcing or sliding pickup shoe and breaker operations. Continuous high frequency return currents generated by power systems on-board the rolling stock itself or another in the same section.	Transients due to pantograph arcing or sliding pickup shoe and breaker operations.	Transients due to pantograph arcing or sliding pickup shoe and breaker operations. Electrification cables too close to public facilities.	Transients due to pantograph arcing or sliding pickup shoe and breaker operations. Transients due to locomotives starting at stations. Continuous high frequency returns currents generated by power systems on-board the rolling stock itself or another in the same section.
infrastructure defects and debris	Transients due to return current discontinuities Reflections due to debris.	No problems detected here	Transients electrical discontinuity of the track. Return paths too close to public facilities. Uncontrolled ground currents due to poor design of power supply return paths, or poor maintenance.	Uncontrolled ground currents due to poor design of power supply return paths or poor maintenance.
signalling and communication systems	CB networks affecting the 27 MHz frequency band of the BTM. Harmonics of 13.5 MHz at manufacturing plants adjacent to the railway (e.g. RF woodglueing).	GSM services allocated in adjacent channels to GSM-R services. Masts sharing GSM and GSM-R communication transceiver.	GSM services allocated in adjacent channels to GSM-R services. Overpopulation of GSM handheld equipment in stations. BTM 27 MHz tone affects CB networks. Uncontrolled ground currents due to poor design of power supply return paths or poor maintenance.	No problems detected here

transient events. Measurement techniques should be defined in that direction. The limits given in the current standards are derived from measurements that include both continuous and transient emissions. Consequently, that sets high limits for continuous emissions. This means that the emissions from the rolling stock could be under the limit, but high enough to cause severe problems to broadcasting services. In EN 50121-2:2006 [4] the use of quasi-peak measurement was introduced. This went some way to solving the problem for stationary tests, but is not possible to be used for the moving vehicle tests.

iii. Detailed limits regarding the installation of equipment closer than 3 m from the running rails should be addressed in the railway standards.

4 Immunity limits for the broadcasting services

For the TREND project, the broadcasting services that might be used by the passengers in the railway environment are FM radio, AM radio, digital audio broadcasting (DAB) radio, radio frequency identification (RFID), the GSM 900 and GSM 1800 bands, the analogue and digital TV and the WiFi. The approximate frequencies of operation for these services are shown in Table 2.

The main cause of interference to the broadcasting services is due to the fact that these services operate in the same frequency ranges as the radiated emissions from the railway environment. An assessment of the immunity levels of these services require the definition of the overlapping of these frequencies. This is shown in Table 3.

Apart from frequency overlapping, the power, or strength, of the interfering signal in conjunction with the tolerable levels of interference of the victim signal are important factors for the levels of EMI experienced. Table 4 identifies the tolerable levels of interference for the broadcasting services.

The second column of Table 4 indicates the minimum signal strength required for a desired reception. The protection ratio, in combination with the tolerable level of interference, defines the

Table 2 Broadcasting services

Broadcasting services	Frequency range
AM radio	500 kHz–1.6 MHz
FM radio	88–108 MHz
DAB	217–230 MHz: band III/1.452–1.492 GHz: band L
GSM 900	854–960 MHz
GSM 1800	1.71–2.7 GHz
broadcasting TV	470–590 MHz/598–854 MHz
GPS	1.53–1.66 GHz
WiFi	2.4 GHz
RFID	2.450–5.800 GHz

Table 3 Frequency overlapping [10]

Broadcasting services	Radiated emissions from rolling stock	Overlapping between broadcasting services operating frequency and TREND designated range
500 kHz–1.6 MHz (AM radio)	TREND designated range 30–530 MHz/ 900 MHz/1.8 GHz [2]	no overlapping
88–108 MHz (FM radio)		overlapping
217–230 MHz: band III/1.452–1.492 GHz: band L (DAB)		overlapping in band III: 217–230 MHz
854–960 MHz (GSM 900)		overlapping
1.71–2.7 GHz (GSM 1800)		overlapping
470–590 MHz/598–854 MHz (broadcasting TV)		partly overlapping
1.53–1.66 GHz(GPS)		no overlapping
2.4 GHz (WiFi)		no overlapping
2.450–5.800 GHz (RFID)		no overlapping

Table 4 Minimal signal strength, protection ratio and tolerable levels of interference for broadcasting services [11]

Broadcasting services	Minimal signal strength, dB μVm^{-1}	Protection ratio, dB	Tolerable level of interference, dB
88–108 MHz (FM radio)	60	45	15
217–230 MHz: band III (DAB)	35	6.5	28.5
RFID	38	9	29
854–960 MHz (GSM 900)	38	9	29
1.71–2.7 GHz (GSM 1800)	38	9	29
470–590 MHz/598–854 MHz (broadcasting TV)	56	4	52

immunity of the broadcasting services. In particular, the protection ratio defines the requested difference in power between the desired signal (broadcasting services) and any other interfering signal in order to achieve a good reception. The tolerable level of interference is the maximum level of power of an interfering signal that will not affect the desired signal. This table illustrates that even if there is frequency overlapping between a wanted and an interfering signal, it is not certain that EMI problems will arise. For example, for an RFID signal, if an interfering signal transmits at the same frequency range, and the power is lower than 29 dB, this will not cause EMI problems with the RFID signal.

It is important to mention that there are different tolerable levels of interference for different areas, i.e. urban or rural areas. This is correlated to the different distances and obstacles of the wave propagation. The information in Table 4 is for rural areas, where the tolerance levels are lower.

5 Worst-case scenario for broadcasting services

From the research carried out under the TREND project, it was concluded that as far as the emissions from the rolling stock are considered, a single transient event that is short in time is not likely to cause severe problems to the broadcasting services. On the other hand, even if it is not the most likely case, severe problems can be caused by continuous radiated emissions from the rolling stock at the limit given by EN 50121-3-1 [5].

From an infrastructure emissions point of view, the transient events from pantograph arcing can upset the broadcasting services. A single transient event would not consist a major issue, but the extensive presence of pantograph arcing that has been observed in countries like Sweden, where icing problems exist, can be considered as the worst-case scenario.

6 Cross acceptance EMC test for broadcasting services

6.1 Introduction

The identification of pantograph arcing as the worst-case scenario for the broadcasting services required further investigation on the influence of the phenomenon to the broadcasting signals. For this reason, a replication of the pantograph arcing was carried out in a laboratory environment to study the characteristics of the arc event [12–14].

6.2 Test environment

An investigation on the suitable environment for the pantograph arc test was carried out. Initially the real railway environment was examined. This scenario would involve several difficulties and the presence of the ambient signal and others would make difficult to determine the radiated signal from pantograph arcing. Even repeatability of the measurements would not have been a solution for this problem. In addition, an open area test site could also cause interference problems with adjacent electrical devices, for example if testing a piece of equipment that is above emissions levels, or investigating a known interference source such as the arcing test rig. For this reason, the use of a screened room and particularly of a reverberation chamber was suggested, to assure accuracy and repeatability of the experiment.

The reverberation chamber is a controllable environment used for emissions and immunity measurements. It is a controllable environment and as a closed cavity there are not ambient signals. It has reflective metallic walls and a rotating metallic non-symmetric paddle, called a ‘stirrer’. This chamber is a resonant multimode cavity and due to the metallic walls a multipath electromagnetic environment is created. The stirring paddle plays an important role in this chamber. As it rotates, the geometry (and therefore the electrical size) of the chamber changes and so do the natural resonances of the cavity. In this way, the maxima and the minima of the electromagnetic field are moving in the chamber.

There are two different uses of the stirrer. In mode stirring, the paddle rotates continuously and in mode tuning the paddles stops at different positions to take measurements. In the pantograph arcing experiment, mode tuning has been used so that the boundary conditions of the room are the same during measurements.

Averaging a sufficient number of measurements for different stirrer positions and for a full stirrer revolution provides a value of the average received power for the frequency of operation. Under these circumstances, the electromagnetic field in the reverberation chamber can be seen as statistically uniform, isotopically distributed and uniformly polarised. Practically, this means that any device radiating in this chamber has no directional properties and the total averaged radiated power can be measured.

For the experiment of pantograph arcing, the reverberation chamber at the University of York was used. The dimensions of this chamber are 4.7 m × 3 m × 2.37 m. This cavity is suitable for measurements over 300 MHz.

6.3 Laboratory setup

As aforementioned, the pantograph arcing occurs between the contact wire and the pantograph. For the replication of the contact wire a 700c (622 mm diameter) bicycle wheel was used, rotated by a DC motor. The pantograph was represented by a 1 m brass rod installed at right angles to the surface of the wheel. For the arc generation, an automotive ignition coil that could produce arcs at around 20 kV was used. The full system was supported on an alloy frame which was earthed to the chamber floor.

The representation of the pantograph arcing was achieved with the use of two separate circuits. The first one was the one to control the rotation of the wheel and the second one to generate the arcs.

A DC motor was used for the rotation of the wheel. As this was a DC brushed motor with intrinsic arcing occurring within the commutator, the radiated emissions from this part of the setup were measured before the actual pantograph arcing experiment. With the motor alone in the reverberation chamber the radiated emissions measured were at the level of the noise floor so it was confirmed that the emissions from the motor were too low to be taken into consideration. A 12 V DC battery was used to power the motor and the speed of the wheel was adjusted with the use of a rheostat. Changing the length of the rheostat and consequently the resistance in the circuit, it was possible to alter the current flowing in the motor and to change its speed.

The arc generation was controlled by a completely independent circuit. The automotive ignition coil was powered by a 12 V DC battery and it was connected to a 555 timer able to switch at a rate of 100 Hz. In this way, the automotive coil was allowed to create 100 electric arcs every second. This rate is representative of the arcing generation in the real 25 kV 50 Hz railway environment with an arc established every half cycle. The arcs were generated in a small gap between the pantograph itself and the wheel. This is presented in Fig. 1 for two different gap lengths.

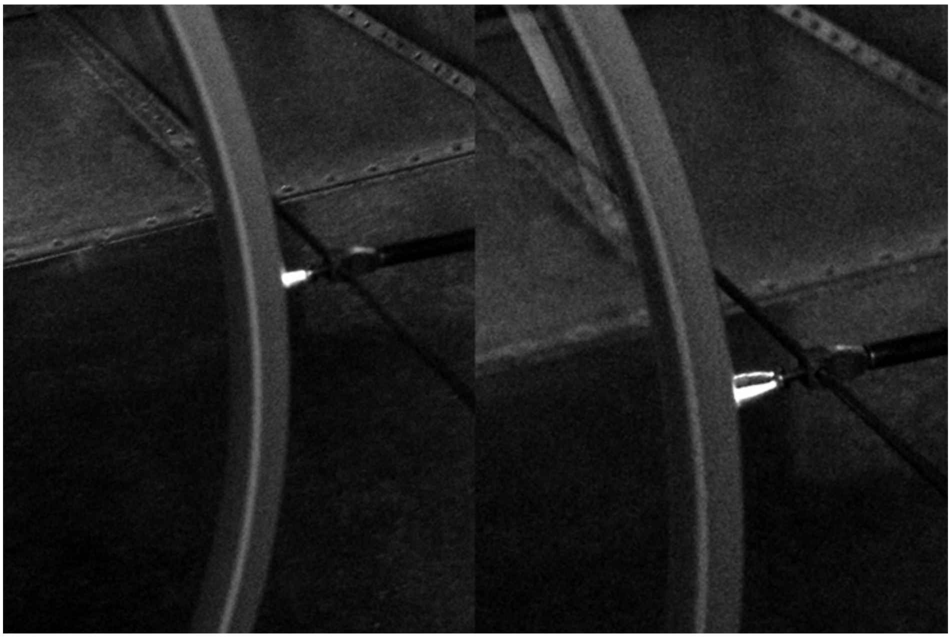

Fig. 1 *Electric arc created between the pantograph and the wheel. At the left the gap is 5 mm and at the right 10 mm*

The necessary fuses were included in both circuits to prevent any damage to the system. It was possible to control the operation of the two circuits with switches connected outside the room.

The full laboratory setup is shown in Fig. 2.

6.4 Measurement setup

The measurement setup used for the pantograph arcing experiment is represented in Fig. 3.

The achievement of accurate measurements from the pantograph arcing experiment is correlated with the compliance with IEC 61000-4-21 [15]. According to this, it is important to define the insertion loss of the chamber with a validation procedure before any radiated emission measurements. After this procedure, a factor of loss for this chamber was estimated which was taken into consideration in addition to the measurements in order to calculate the real radiated emissions from the pantograph arcing setup.

As it is shown in Fig. 3 for the measurement of the radiated emissions an Agilent spectrum analyser with frequency range 9 kHz–6.7 GHz is used and the results are recorded by running software on a PC that controls the stirrer. This moves the stirrer to a position and then triggers the spectrum analyser that measures the total energy radiated in the chamber through an antenna over a selected frequency range. Then the stirrer is moving to the next position. The same procedure is repeated for a full stirrer revolution. Hundred stirrer positions were used for this experiment. The results are averaged for all the stirrer positions and recorded by the PC. The final results are calculated by taking into account the loss factor of the chamber.

For the investigation of the characteristics of the electric arcing different parameters were examined. These were the speed of the

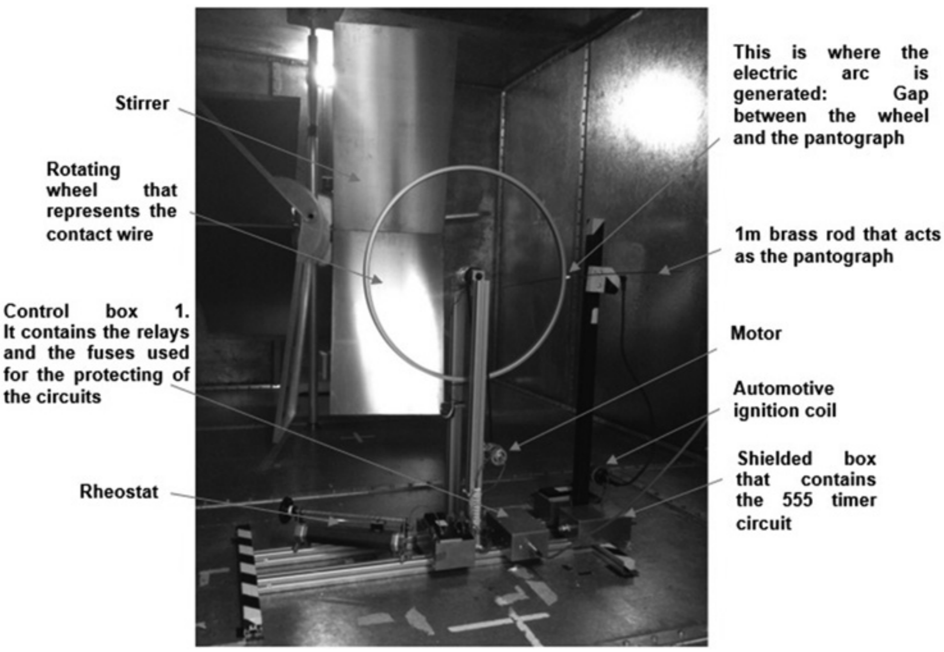

Fig. 2 *Laboratory setup in the reverberation chamber with the wheel rotating and the arcing active*

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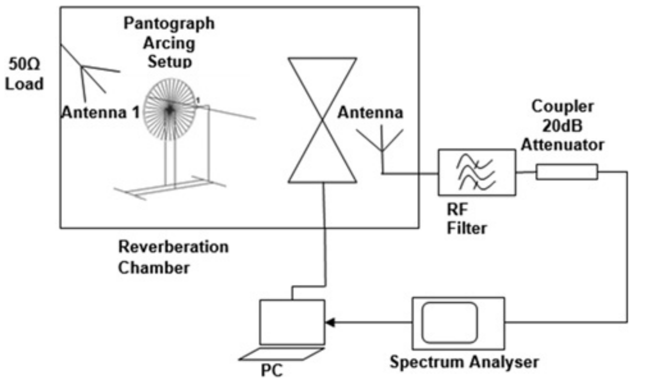

Fig. 3 *Measurement setup for the pantograph arcing experiment*

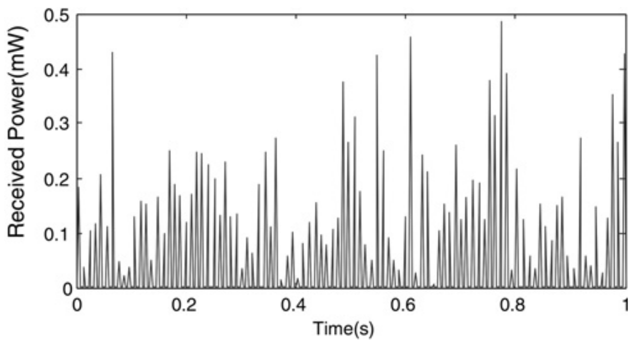

Fig. 4 *Trace from the spectrum analyser at one stirrer position*

wheel, the length of the gap between the pantograph and the wheel and the resolution bandwidth (RBW) of the received signal.

A radio frequency (RF) filter with 20 MHz bandwidth set at the frequency under examination and a coupler with 20 dB attenuation were used during the experiment to protect the spectrum analyser.

6.5 Results

In regard to the broadcasting services, the pantograph arcing test was performed at 900 MHz GSM band and at 1.5 GHz, to cover the frequency that DAB networks use mainly in Europe.

The trace from the spectrum analyser at one stirrer revolution depicted in time domain is shown in Fig. 4.

Fig. 5 compares the levels of the total energy radiated from the pantograph arcing setup at 900 MHz when the wheel is not rotating and when the speed of the wheel is 30 km/h for various gap lengths between the pantograph and the wheel.

Fig. 6 compares the radiated emissions from the arcing at 900 and 1500 MHz when the speed of the wheel is 30 km/h for various gap lengths.

Fig. 7 compares the radiated power at 900 and 1500 MHz when the speed of the wheel varies.

From Fig. 5, it is shown that the levels of the measured power radiated from the stationary wheel are higher than these when the wheel is moving with 30 km/h. This fact can be explained by considering the mechanism of the electric arc. An electric arc is essentially a plasma discharge between two electrodes. The current jumps the air gap which becomes conductive as it gets ionised because of the high voltage between the electrodes. The source of the energy radiated by the electric arc is this arc current.

When the speed of the wheel is high, then the arc moves while it is attached to the surface of the wheel and follows its movement. In this way, the arc length gets longer when the speed increases. At the same time, the moving wheel moves the air at the gap between the electrodes so the ionised air is continuously replaced with non-ionised and this fact increases the air impedance.

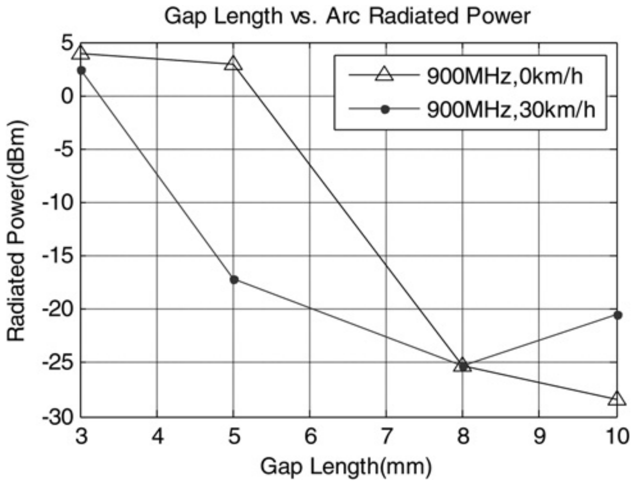

Fig. 5 *Total radiated power for 0 and 30 km/h at 900 MHz for various gap lengths*

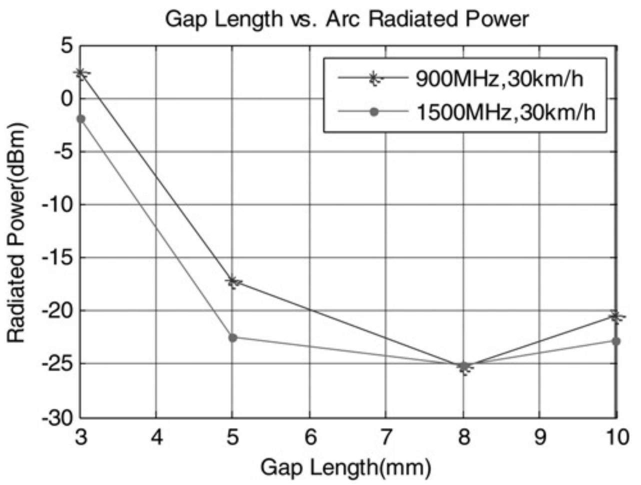

Fig. 6 *Total radiated power for 30 km/h at 900 and 1500 MHz for various gap lengths*

Regarding the distance between the electrodes, when it is long then the amount that has to be ionised to generate an electric arc is more so the impedance of the air is higher and the arc current lower. Provided that there is a finite amount of energy from the

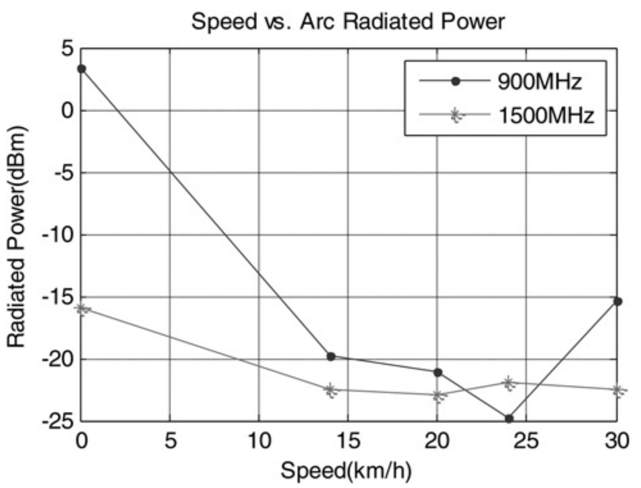

Fig. 7 *Total radiated power at 900 and 1500 MHz for various speed values*

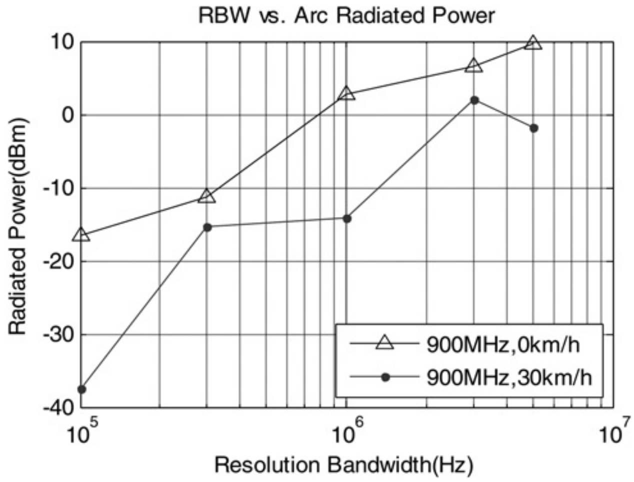

Fig. 8 *Radiated power for 0 and 30 km/h at 900 MHz for various RBW. Gap length is 5 mm*

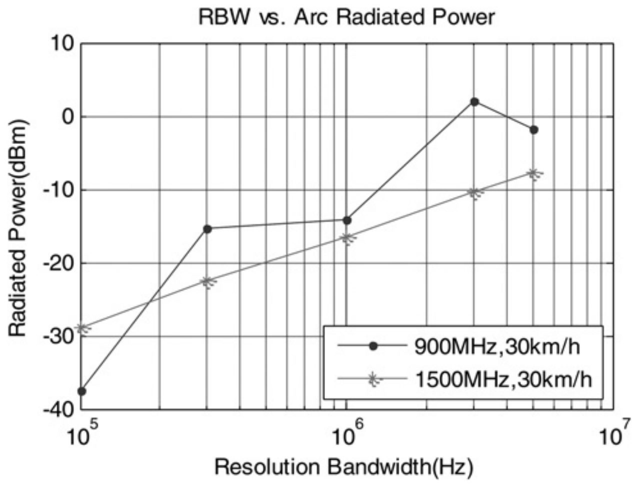

Fig. 9 *Radiated power from pantograph arc at 900 and 1500 MHz for speed 30 km/h for various RBW. Gap length is 5 mm*

coil, the radiated energy is lower for greater distances between the pantograph and the wheel.

Another parameter under investigation during the pantograph arcing experiment was the resolution bandwidth of the received signal as a reference to characterise it either broadband or narrowband. It is suggested that if the amplitude of the received signal is the same when varying the resolution bandwidth of the instrument that indicates a narrowband signal [16].

Figs. 8 and 9 show the total radiated power from pantograph arcing for various values of the resolution bandwidth. At these cases the frequency was set at 900 MHz and the speed of the wheel was 0 and 30 km/h. It is obvious that the power radiated from the pantograph arcing is a broadband signal.

7 Conclusions from pantograph arcing experiment in relation with the broadcasting services

It was shown that the laboratory setup used in the reverberation chamber provided a good approximation to study the characteristics of the real pantograph arcing of the railway environment. The main use of this aspect is to provide a level of the radiated power against which on-board equipment can be compared to. The source could therefore be used to excite different pantograph configurations.

The aspect of the moving wheel in the chamber does have the effect of stretching the arc as would be occurring in the real railway environment. The maximum speed of the surface of the wheel used in this experiment was 30 km/h for safety reasons, but does mirror low speed 25 kV operation, along with allowing the effect of moving catenary to be investigated. In general, this effect on a real train is only observed during the moving EN 50121-2 [4] tests. From the diagrams presented, it can be seen that the difference in the chamber between the stationary and the moving catenary is around 3 dB higher at smaller arc lengths. As the arc increases the stationary wheel radiated power increases compared to the moving wheel. From this it was concluded that the stationary test of a sustained arc (i.e. around a second) would represent the worst-case scenario.

Regarding the GSM 900 MHz signal, the tolerable level is 29 dBμV/m. From the pantograph arcing experiment, it was shown that the minimum radiated power from the pantograph arcing is around −25 dBm which is enough to interfere with the signal. On the other hand, the levels of tolerable interference suggest that the arc present in the chamber will not influence digital audio broadcasting systems. However, it is of high importance to mention that the radiation mechanism used in the reverberation chamber is of much lower power that the mechanism on the top of a train.

The 50121-3-2 [6] limit on radio frequency immunity is 10 V/m, which equates to −35 dBm/m^2 immunity level. For uniform illumination in the chamber (volume 33 m^2), this equates to a level in the chamber of around −1dBm. Therefore, approximately speaking, any radio frequency power generated in the chamber higher than −1dBm is likely to breach the immunity levels. It can be seen that this occurs for the situation of the smaller gap lengths.

7.1 Considerations on the pantograph arcing experiment in the reverberation chamber

It should be noted that the variation of the parameters used for the presented research was limited by the complexity of the experiment. The results of this experiment refer to the 25 kV 50 Hz railway traction system and does not directly apply to the other European railway traction systems. Moreover, it should be highlighted that for safety reasons the speed of the wheel used and the power used for the generation of the electric arcs in the reverberation chamber is not as high as can be seen in the real railway environment. The arc power being lower is mitigated by the efficient environment in which these experiments were carried out.

8 Overall conclusions from the TREND project

During the research carried out under the TREND project, it was detected that the most severe source of interference originated from the rail infrastructure for the broadcasting services is related to the pantograph arcing. The loss of contact between the pantograph and the contact wire causes transient events that generate high levels of radiated emissions. While a single transient is not considered to be an issue for broadcast services, continuous transients can cause severe issues of interference. The present paper focused on the replication of the pantograph arcing in a laboratory environment and the investigation of its effect on the broadcasting services.

The broadband nature of the phenomenon of pantograph arcing was highlighted and investigation of its effect on indicative broadcasting frequencies showed radiated emissions at high levels that are comparable to the signal tolerable levels of interference.

The other TREND research areas have been also examined by other members of the TREND project consortium focusing on the Balise Transmission Module [17], the GSM-R [12] and the track circuits system [18] used in the railway environment. The immunity levels and the worst-case scenarios were identified for these systems and associated cross-acceptance tests were suggested. Outputs from all these EMC tests suggest that a review of the current railway standards that define the cross-domain interoperability of the rolling stock around Europe is carried out.

9 Acknowledgments

The authors are grateful for the support of Professor Andy Marvin and the PhD student Lan Ma at the University of York who contributed in carrying out the presented research.

The authors thank the other members of the TREND project consortium, from CEIT (Spain), IFFSTAR (France), CAF-ID (Spain), Luleå University of Technology (Sweden), TRAFIKVERKET (Sweden), CEDEX (Spain) and colleagues within York EMC Services (UK). Further information can be found on the project website (http://www.trend-eu.org/). The TREND Project was sponsored by the 7th EU framework programme. Project reference: FP7-Transport-285259.

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