Rail Accident Investigation Branch

Rail Accident Report

Overhead line failure, St Pancras International 23 September 2009

Department for Transport

Report 12/2010
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This investigation was carried out in accordance with:

- the Railway Safety Directive 2004/49/EC;
- the Railways and Transport Safety Act 2003; and
- the Railways (Accident Investigation and Reporting) Regulations 2005.

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Contents

Preface

1 The sole purpose of a Rail Accident Investigation Branch (RAIB) investigation is to prevent future accidents and incidents and improve railway safety.

2 The RAIB does not establish blame, liability or carry out prosecutions.

Key Definitions

3 The report contains abbreviations and technical terms (shown in *italics* the first time they appear in the report). These are explained in appendices A and B.

Summary of the Report

Key facts about the incident

4 At approximately 18:35 hrs on 23 September 2009, the overhead wire supplying electric power to trains parted and fell onto the platform where passengers were leaving a Eurostar train which had just arrived at platform 9 of London St Pancras International station.

5 The supply system circuit breaker opened automatically to de-energise the wire, but the electrical controller made two attempts to re-energise the wire manually, in addition to the automatic reclosure of the supply system circuit breaker shortly after each automatic opening.

Figure 1: Photograph of displaced wire on platform (courtesy of Network Rail)

Immediate cause, causal, contributory, and underlying factors

6 The immediate cause was the parting of the overhead wire because of local overheating caused by the high electric current flowing from the wire to one of the train's *pantographs*.

7 A causal factor was the reduced distance between the electrodes of the lightning arrester together with a transient voltage induced by the closure of the vacuum circuit breaker on the train causing a flashover at the lightning arrester.

8 Probable causal factors were:

- the incorrect connection of cables in the protection equipment monitoring the flow of current to the overhead wire, allowing the excessive current to flow for longer than the specified time;
- the absence of testing during the commissioning of the protection equipment, so that the incorrect connection of the cables was not detected; and
- the margin between the specified performance of the protection equipment together with the declared performance of the overhead wire and the conditions that actually occurred was small.

9 Contributory factors were:

- the absence of a restraint on the wire allowing it to fall onto the platform;
- the automatic reclosure of the supply system circuit breaker allowing the wire to become momentarily live after each time it was automatically de-energised; and
- the electrical controller not following the instructions to contact the signaller before attempting to reclose the supply system circuit breaker.

10 Underlying factors were:

- the loose specification of the training given to electrical controllers;
- the descriptive nature of the instructions for the periodic re-assessment of the electrical controllers; and
- the emphasis in the training of the shift manager on duty on signalling and the limited coverage of the duties and responsibilities of the electrical controller.

Severity of consequences

11 There were no injuries to staff or passengers, though there was potential for injury to people on the platform from the initial movement of the wire and the subsequent attempts to re-energise it.

12 The train sustained minor damage to pantographs and supporting insulators.

13 The platforms at St Pancras International station serving HS1 were closed until 20:17 hrs when platforms 8–13 were re-opened. Platforms 5–7 were re-opened at 01:52 hrs the following morning.

Recommendations

14 Recommendations can be found in paragraph 179. They relate to the following areas:

- the maintenance of the correct spark gap between the electrodes of the lightning arrester;
- the management of the installation, testing and commissioning of safety related railway equipment;
- the risk in station areas arising from broken wires from overhead line equipment of the type in use at St Pancras;

- the coherence between performance specifications for different components of the same system;
- the need to remind electrical controllers of the need to follow a safety procedure before closing a circuit that has opened in response to a sustained fault;
- the awareness of control room shift managers of power supply control procedures; and
- the safety of persons at St Pancras in the event of damage to the overhead wire in the station.

The Incident

Summary of the incident

15 At approximately 18:35 hrs on 23 September 2009, shortly after the arrival of the 17:13 hrs train from Paris Nord at platform 9 of St Pancras International station, London, the overhead wire supplying electric power to the train, which was live at 25kV, parted and fell to the ground. This occurred during the preparation of the train for its next journey, while many passengers who had left the train were walking along the platform.

16 At approximately the same time as the wire parted, the electrical supply was de-energised automatically. Over the next two and a half minutes, there were two manual and three automatic attempts to re-energise the wire, each of which was followed by immediate automatic de-energisation.

17 There were no injuries to staff or passengers. The train sustained minor damage to pantographs and supporting *insulators*. There was potential for injury to people on the platform from the initial movement and intermittent energisation of the damaged wire.

18 Platforms 8 - 13 at St Pancras International station were closed for 1¾ hours while the damaged wire was made safe.

Organisations involved

19 The overall management of St Pancras station is the responsibility of Network Rail. Eurostar (UK) Ltd (EUKL) owns, maintains and operates the train involved. It also operates the international part of the station and is the employer of the station staff as well as the train crew. From 1 January 2010, EUKL has become part of Eurostar International Ltd.

20 EDF Energy Services Limited (EDF) owns and maintains the power supply network feeding electricity to the *overhead line equipment* (OHLE).

21 Network Rail (CTRL) Ltd (NR (CTRL)), maintains the OHLE, which is owned by HS1, and controls the power supply to the OHLE through the control room at Ashford and employs the staff controlling the OHLE under contract to HS1 Ltd, the owner of the rail link to the Channel Tunnel.

22 The French National Railways, Société Nationale des Chemins de Fer Français (SNCF), employs both train drivers.

23 ABB Power installed and commissioned the power supply equipment at St Pancras *feeder station*.

24 ABB Power, EDF Energy Services Limited, Eurostar (UK) Ltd, Network Rail (CTRL) Ltd and SNCF freely co-operated with the investigation.

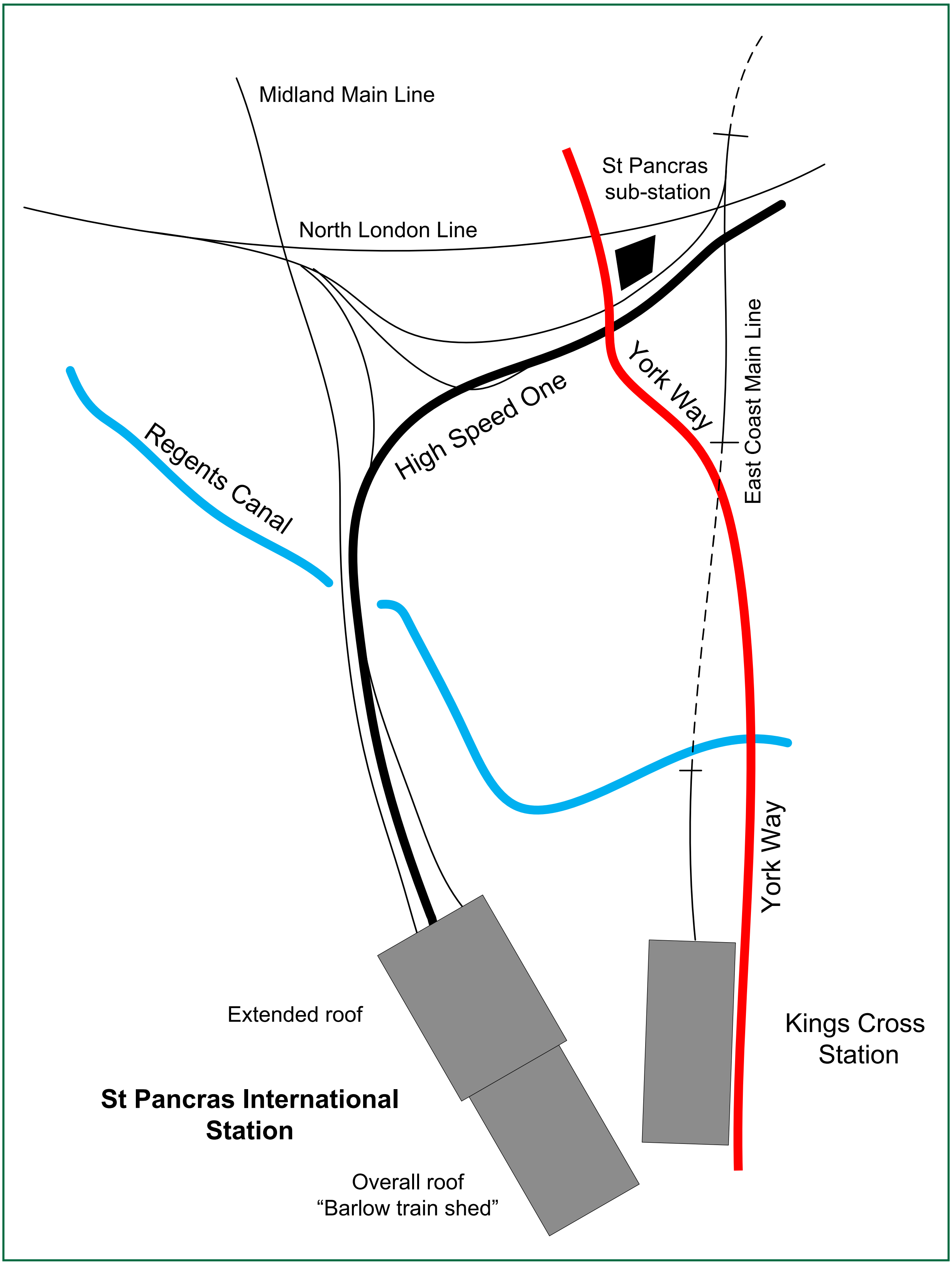

Figure 2: Location of St Pancras International station and St Pancras substation in relation to other railway routes

Location

25 HS1 is the high speed railway, formerly known as the Channel Tunnel Rail Link (CTRL), which connects London with the Channel Tunnel at Folkestone. Its London terminal is St Pancras where, while the overall management is the responsibility of Network Rail, platforms 5 to 10 are managed and used exclusively by Eurostar.

26 These platforms extend beyond the new roof under the original overall roof of the station, known as the Barlow trainshed.

27 Passengers leave these platforms by escalators at the terminal end and a travelator some 50 metres further back along the platform (figure 3).

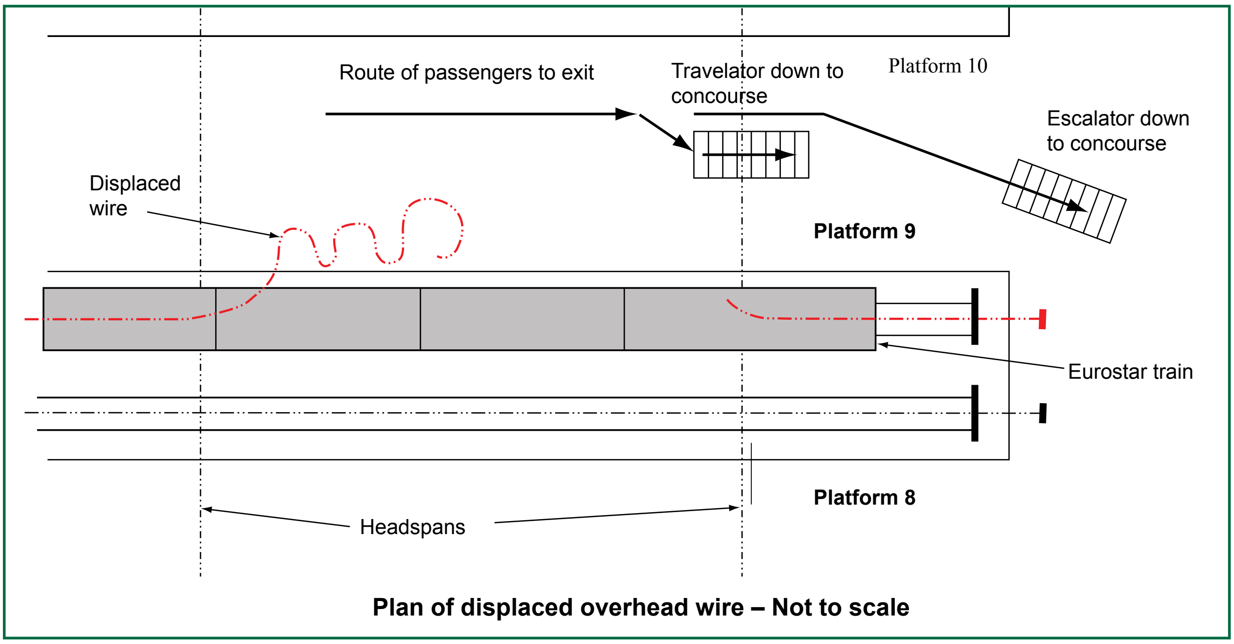

Figure 3: The route taken by passengers to leave the platform past the displaced overhead wire

Train involved

28 The train involved was the 17:13 hrs from Paris Nord to St Pancras, train number 9O47.

29 It was made up of two class 373 Eurostar electric half sets, with power car 373016 at the London end and power car 373999 at the Paris end. Each half set comprises a single power car and nine passenger coaches. A Eurostar train is made up of two half sets coupled together so that there is a power car at each outer end. The power car from which the train is driven controls both power cars.

30 The power car carries the pantographs, motors to drive the train, equipment to control the electric power passed to the motors and a cab from which the train is driven.

31 The pantograph collects the current from the OHLE. The current then passes along a *busbar*, through the voltage detector and through the vacuum circuit breaker (VCB), before entering the equipment inside the power car. All these items are mounted on the roof of the power car (figure 4).

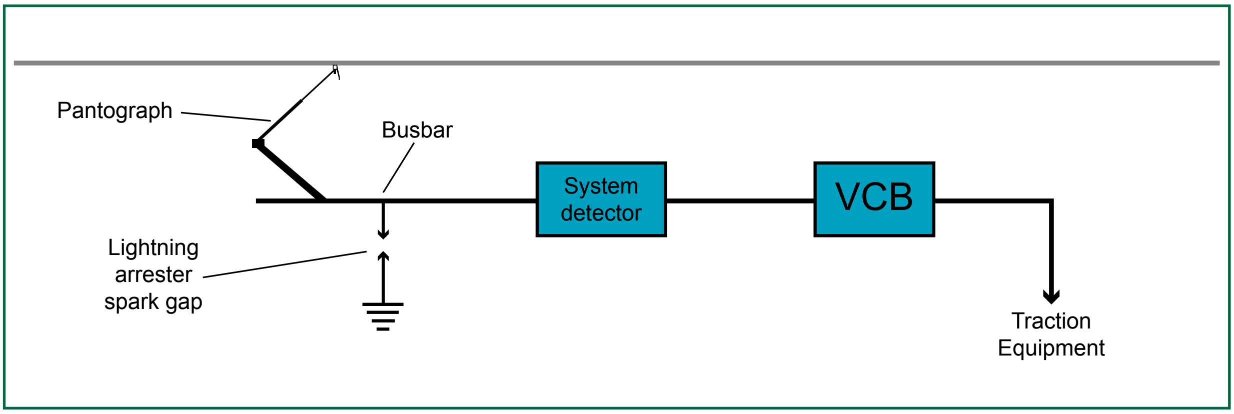

Figure 4: Diagram of roof equipment

32 Because the Eurostar trains can operate on both 3kV dc and 25kV ac systems, a voltage detector is fitted to establish whether or not the voltage present in the OHLE corresponds with that selected by the driver.

33 The vacuum circuit breaker isolates the electrical equipment from the power supply. It is controlled by the driver and also interrupts the flow of electricity automatically should an excessive current pass through it.

34 A *lightning arrester* is attached to the busbar. It consists of two steel rods, known as *electrodes*, aligned on the same vertical axis opposite to each other, but not touching. The upper electrode is mounted on the busbar connecting the pantograph to the power car's VCB and the lower is connected to the earthed body of the power car. The tips of the electrodes taper to a point. Should a voltage significantly higher than the normal line voltage of 25 kV, and sufficient to damage the train, occur in the OHLE, it is dissipated to earth by an arc striking across the gap between the electrodes.

Rail equipment involved

35 *Tramway OHLE* is installed at St Pancras and under the Barlow trainshed it is supported by transverse *headspans*. This system and the differences between it and the type of OHLE used on the rest of HS1 are described in paragraphs 116 – 118.

36 The power supply to the OHLE is fed with alternating current at 25kV 50Hz through *circuit breakers* located in a feeder station outside St Pancras International. These are controlled from the Control Room at Ashford and open automatically in the event of a fault in the overhead line (figure 5).

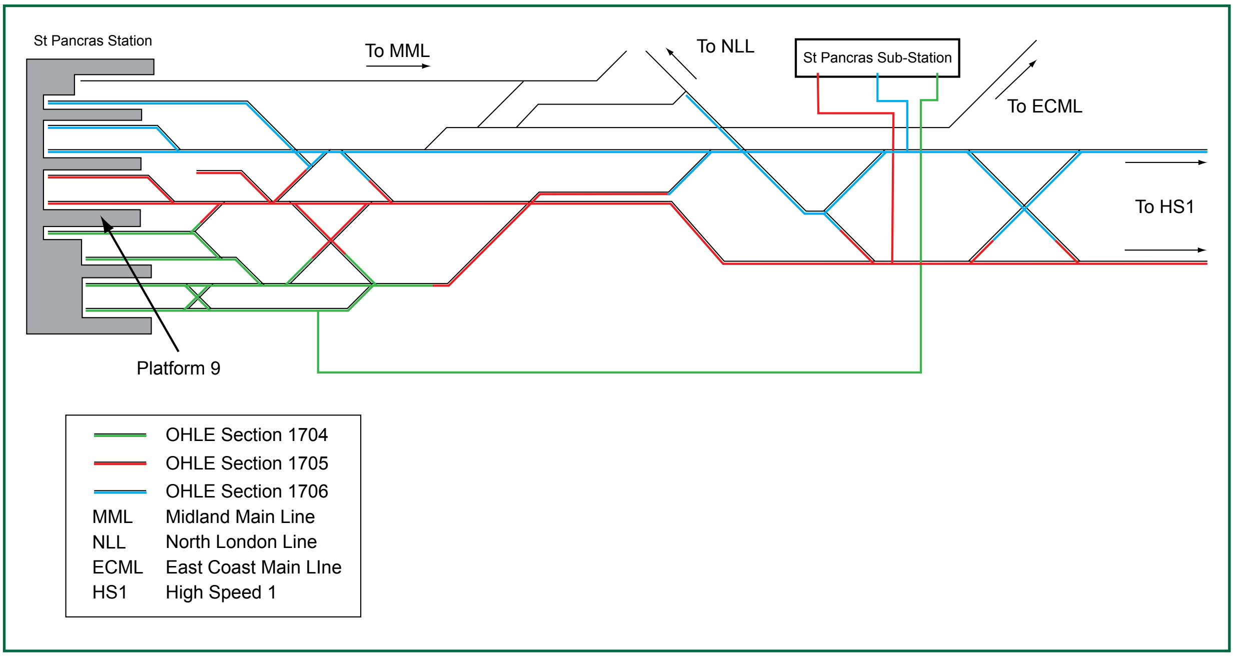

Figure 5: Diagram of the feeding arrangements

Staff involved

37 The *Electrical and Mechanical Management and Information System (EMMIS)* controller at Ashford Control Centre controlled the operation of the circuit breakers and carried out the procedures to isolate the OHLE after the incident.

38 Eurostar drivers were operating the train and Eurostar station staff at St Pancras were involved in directing the movement of passengers away from the damaged overhead line.

Events preceding the incident

39 The 17:13 hrs train from Paris Nord arrived punctually at St Pancras with 554 passengers on board, who began to leave the train normally.

40 The driver put the train into *'service retention'* condition and prepared to leave the cab at the London end of the train. When a Eurostar train is in 'service retention' condition neither cab is in service and the train power systems only supply the power car auxiliaries and trailer car hotel services such as lighting and air conditioning.

41 The driver who was to take the train back to Paris entered the cab at the Paris end of the train to prepare it for its scheduled departure at 19.34 hrs.

Events during the incident

42 The driver at the Paris end began to go through the normal procedure to prepare the train. His first action was to lower both pantographs and set the *system selector* to *'High Speed AC'*. He then raised both 25kV pantographs.

43 When both pantographs were in contact with the OHLE, and the detection equipment on the train confirmed that the selected overhead line voltage had been detected, the driver closed the VCB.

44 When the VCB on the power car at the London end of the train closed, a *flashover* occurred between the electrodes of the lightning arrester on that power car, passing a current of 5200 amps for 370 milliseconds, registered by the data recording equipment monitoring the power supply network.

45 The circuit breaker in the feeder station feeding that section of the OHLE opened automatically when a current high enough to indicate the presence of a fault was detected flowing through it.

46 The overhead wire parted where it had been in contact with the pantograph, some 10 metres on the Paris side of the headspan closest to the *buffer stops*. It fell onto the roof of the train and on to the platform where passengers were leaving the train. The wire remained in contact with the train throughout the incident.

47 After 6 seconds the feeder station circuit breaker reclosed automatically, as it was designed to do, and then opened owing to the passage of an excessive current to earth through the wire resting on the train.

48 The driver at the London end of the train was still in the cab and realised that an incident had occurred when he heard the loud bang and noticed the movement of the overhead wire when the initial flashover took place. He used the train telephone to speak to the driver at the Paris end, who was preparing the train for departure, and asked him to lower the pantographs.

49 The Paris end driver followed this request.

50 The EMMIS controller observed the operation of the feeder station circuit breaker on the screen at his workstation and used the workstation to command it to close, thirty four seconds after it had opened. Because the wire was still in contact with the train, this closure caused an excessive current to pass through the circuit breaker again, causing it to open. After a delay of 6 seconds, it automatically closed and immediately opened once more.

51 Sparks were produced where the wire was in contact with the train each time the circuit breaker closed and the wire was energised. Passengers who had already left the train moved towards the further side of the platform. There was no apparent panic, though some passengers were clearly alarmed by the event.

52 When a feeder station circuit breaker is closed and opens again immediately because of a fault condition, the EMMIS controller's display screen may show the circuit being supplied as momentarily live. The reason for this is explained in paragraph 137. Although the controller was monitoring the operation of the circuit breaker on his display screen, he did not observe any indication that it had actually closed during this sequence.

53 He was aware that EDF staff had been working in the feeder station earlier that day and contacted the EDF duty control engineer to establish whether they were still present. The EDF engineer confirmed that staff had left the feeder station and agreed that the controller should attempt to close the circuit breaker again.

54 When the controller commanded the circuit breaker to close again, one minute and forty six seconds after his previous attempt, it opened immediately. Once again the circuit breaker automatically closed 6 seconds later and reopened upon the detection of excessive current flowing.

55 While the controller was attempting this second manual closure, the control room manager received an emergency telephone call from a member of a contractor's staff working at St Pancras, who had seen the OHLE fall onto the platform, requesting that it be isolated.

56 The controller then de-energised the OHLE between the feeder station and St Pancras International, five minutes after the start of the incident.

57 Towards the end of these events, the Eurostar platform controller at St Pancras received a message from one of his staff that the OHLE had fallen onto the platform. He also made an emergency telephone call to the signaller at Ashford to request an isolation of the OHLE. This was granted immediately as the EMMIS controller had already isolated the OHLE.

58 The sequence of events is summarised in table 1.

Time (hr:min:ss)	Event
18:33:45	Train 9O47 stops at platform 9
18:33:59	Train doors open
18:34:05	London end driver starts to put the train into service retention condition
18:34:07	London end cab closed down with train in service retention condition
18:34:49	Driver in Paris end cab starts to activate that cab. This action correctly causes the VCBs to open and pantographs to lower
18:35:01	Driver in Paris end cab commands pantographs to be raised
18:35:05	Driver in Paris end cab commands VCB to close, the system detection equipment having confirmed that 25kV has been detected in the overhead wire
18:35:11	VCBs close Flash occurs on top of train and supply circuit breaker opens Train loses detection of 25kV
18:35:17	Automatic closure of supply circuit breaker followed by immediate opening
18:35:35	Paris end driver commands VCB to open and pantographs to lower
18:35:37	Pantographs lowered
18:35:52	Closure of supply circuit breaker following command from EMMIS controller followed by immediate opening
18:35:58	Automatic closure of supply circuit breaker followed by immediate opening
18:37:40	Closure of supply circuit breaker following command from EMMIS controller followed by immediate opening
18:37:46	Automatic closure of supply circuit breaker followed by immediate opening EMMIS controller initiates isolation of OHLE at St Pancras
18:39	Eurostar platform controller makes request for an emergency isolation

Table 1: Sequence of events during the incident

Events following the incident

59 The Eurostar platform controller arranged for security staff on the platform to direct passengers away from the damaged wire.

60 A Eurostar technician examined the power car internally and confirmed that no fire had started. On the instructions of the platform controller, he arranged for the incident train in platform 9 and the train standing in platform 6 to be shut down.

61 The Eurostar terminal controller closed the access doors to platform 6, where a train was being boarded, and arranged with the platform supervisor for those passengers who had already boarded to remain on the train. As soon as she was aware that the OHLE had been isolated, she arranged for those on the train to be escorted back to the departure lounge.

Consequences of the incident

62 Platforms 8- 13 in the Eurostar and South Eastern sections of St Pancras International remained closed until 20:17 hrs. They re-opened when the extent of the isolation was reduced after Network Rail OHLE staff had applied earths to make the damaged wire safe. Platforms 5 - 7 remained closed until the end of services that night, re-opening at 01:52 hrs on 24 September.

63 Normal working was resumed at the start of the service the following morning.

64 The power car sustained damage to one pantograph, the lightning arrester electrodes and adjacent insulators.

65 The overhead wire was broken between adjacent headspans.

66 There were no injuries, but during the incident there was potential for injury to people on the platform from the movement and intermittent energisation of the wire.

The Investigation

Sources of evidence

67 The following sources of evidence were used:

- witness statements;
- recorded data from the train and the EMMIS control system;
- CCTV recordings taken from St Pancras International station;
- site photographs and visits to the train, Ashford control room and St Pancras feeder station; and
- discussions with equipment suppliers and technical specialists.

Key facts and analysis

Identification of the immediate cause[1]

68 **The immediate cause of the incident was that the overhead line failed mechanically because of local overheating caused by high current flow.**

69 Data recordings of the supply system show that a current of 5200 amps had passed for 370 milliseconds. The voltage drop between the pantograph head and the wire is likely to have been of the order of 20 volts; this will produce 19.25 kilojoules of energy at each of the two contact points[2] between the pantograph and the wire, 38.5 kilojoules in total. This energy could only have passed as heat into the wire and the pantograph head. Since the train was stationary, the heat was concentrated at one point in the wire. This overheated the wire, caused it to start to melt and reduced its strength sufficiently for it to break.

70 Laboratory analysis of changes in the grain structure of the copper wire adjacent to the break shows that a temperature high enough to cause the underside of the wire to melt had been achieved. The melting of the wire reduced its effective cross section and the heating reduced the strength of the remaining section.

71 There was no indication of any other defect in the contact wire at that point which could have caused the wire to part as a result of a mechanical failure. This has enabled any possibility of a purely mechanical failure to be discounted.

72 CCTV recordings show a white flash at the first instance of high current flow, indicating that this current flowed to earth across the lightning arrester electrodes rather than through a displaced overhead wire. Had the *inrush current* and the hotel load current been high enough to overheat the wire and cause it to part, a flashover would not have occurred at the lightning arrester. This eliminates the possibility of the normal inrush current or the hotel load current causing the overhead wire to part.

73 The pantograph was tested following the incident and the forces and rising and lowering times were found to be correct, enabling a pantograph defect to be discounted.

Identification of causal[3] factors and contributory[4] factors

74 The RAIB identified six causal and contributory factors. These relate to:

- a combination of the reduced distance between the electrodes on the lightning arrester and the likelihood of a high transient voltage being induced in the overhead wire;

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[1] The condition, event or behaviour that directly resulted in the occurrence.

[2] The head of the pantograph which slides along the underside of the overhead wire consists of two separate carbon strips each in contact with the wire.

[3] Any condition, event or behaviour that was necessary for the occurrence. Avoiding or eliminating any one of these factors would have prevented it happening.

[4] Any condition, event or behaviour that affected or sustained the occurrence, or exacerbated the outcome. Eliminating one or more of these factors would not have prevented the occurrence but their presence made it more likely, or changed the outcome.

- incorrect installation of the protection equipment in the feeder station;
- lack of continuity testing during commissioning of the supply system;
- the design of overhead wire system not providing restraint following a break in the contact wire;
- the closure of the circuit breaker by the EMMIS controller; and
- the automatic closure of the feeder station circuit breaker following an opening under fault conditions.

The combination of the reduced distance between the electrodes and the induced transient voltage

75 **An incorrect distance between the points of the electrodes on the lightning arrester, and the induced transient voltage resulting from the vacuum circuit breaker closing, caused a flashover at the lightning arrester. This combination of factors was causal to the incident.**

The reduced distance between the electrodes of the lightning arrester

76 As described in paragraph 34, the lightning arrester dissipates a high voltage by an arc which is struck between the electrodes. When such an arc is created, the tips of the electrodes are eroded and the length of the spark gap is increased. To enable the correct gap to be restored, the upper electrode is adjustable: it is mounted on a screw thread and locked in position by a *lock-nut* which is tightened against the busbar.

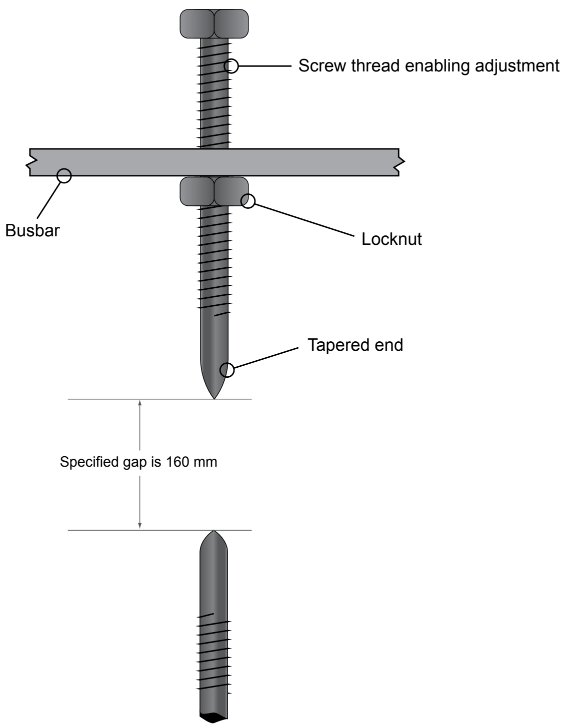

Figure 6: Arrangement for locating the upper electrode in the busbar

77 When the lightning arrester was examined after the incident there was erosion present, the lock-nut had fully wound down and the upper electrode was loose. If the electrodes had been in as-new condition, this position of the upper electrode would have produced a spark gap of 122 mm. The gap is specified to be 160 mm.

78 The electrode and busbar were subjected to vibration tests by mounting them firmly on equipment used to calibrate accelerometers. Vibrations were induced at varying frequencies to establish any conditions under which the electrode would move. Movement occurred when vibration between 180 and 250 Hz was applied and both the lock nut and the electrode would rotate and move downwards when a maximum acceleration of 0.2g was applied. This showed that, when the lock-nut was not correctly tightened, the electrode could rotate and move freely downwards.

79 The maintenance instructions specifically state that the spark gap is to be checked as being 160mm +/- 2mm, and adjusted as necessary, every six months. Its last scheduled examination before the incident was in April 2009, but the records of that examination have not been found. If the electrode had been adjusted and the lock-nut had not been tightened adequately, sufficient time would have elapsed to permit the nut to loosen and the electrode to move downwards.

80 One pantograph on power car 373016 had been changed on 12 March 2009. The pantographs are close to the section of the busbar where the lightning arrester is mounted. It is possible that that section of the busbar was disturbed during the pantograph change, the lock-nut was loosened very slightly and that at the examination in April the looseness was not found.

81 Eurostar initiated a special examination of the lightning arresters on all power cars, whether based in the UK, France or Belgium, to ensure that they are locked tightly at the correct separation. No other loose lock-nuts were found during this examination.

The condition of the Vacuum Circuit Breaker

82 The manufacturers, Alstom, examined the VCB at their works in Preston and found it to be in good order.

83 The normal gap of 8 mm between the contact surfaces in the vacuum chamber did not break down when a voltage of 60 kV was applied, indicating that a satisfactory vacuum had been maintained.

The induction of a high transient voltage in the overhead line

84 The flow of current across the lightning arrester spark gap can be initiated by several factors:

- the presence of a foreign body – no debris was found at the time of the incident;
- water spray or rain – the incident took place under cover on a dry day;
- *ionised gas* – while such gas would be developed when the pantograph came into contact with the overhead line, the amount of gas produced would be significantly dispersed and would have cooled after travelling the distance to the spark gap from the overhead line;
- steady state *over voltage* – any sustained over voltage would have been detected by the supply system monitoring equipment and no such detection was recorded.

All of these factors have been eliminated for the reasons given.

- Transient over voltage – the operation of a VCB can initiate very high transient voltages making this the most likely explanation of the event.

85 Transient voltages are more usually associated with the opening rather than the closure of circuit breakers. However, VCBs can cause voltages several times the magnitude of the supply voltage to be induced in supply circuits when they close.

86 The reasons for this are outlined in appendix C.

Transient voltage required to initiate a flashover across the lightning arrester

87 An analysis by specialist engineers has estimated that a gap between the electrodes of 122 mm might be expected to experience a flashover when a voltage slightly higher than 55 kV is applied to it.

88 This is approximately twice the value of the supply circuit voltage and therefore within the range of the voltage which can be induced during the closure of a VCB.

89 It is therefore likely that a combination of a large induced voltage and a reduced length of spark gap caused the flashover to occur.

The incorrect installation of the protection equipment

90 **Cables in the circuit detecting the flow of excessive current to the OHLE were incorrectly connected, allowing the current to flow for longer than specified. This factor was probably causal.**

91 Protection equipment is installed in the feeder station to monitor the electricity supplied to the OHLE. Conditions monitored at each circuit breaker include the voltage in the OHLE, the magnitude of the current flowing and the relationship between the two.

92 The equipment causes the circuit breaker to open automatically, or '*trip*', when it detects an unsafe condition, such as the flow of an excessively high current.

93 The specification of the protection equipment required the current flowing as a result of a fault of this nature, which would have caused a reduction in the supply system voltage at the circuit breaker, to be interrupted within 200 ms. Had the current been interrupted in 200 ms rather than 370 ms, it is probable that the wire would not have broken.

94 An inspection of the installation after the incident found that two wires had been transposed. This prevented the protection equipment detecting a relationship between the line voltage and current flowing which indicated that a fault had occurred. Consequently, it did not initiate the tripping of the circuit breaker despite detecting a reduction in the voltage in the OHLE. This wiring error has now been rectified.

95 EDF has examined all other similar equipment on the CTRL and found that it was installed correctly.

96 Secondary detection equipment, providing additional protection in the event of excessive current alone, operated to trip the circuit breaker and isolate the OHLE. The operation of this secondary protection is deliberately delayed to avoid conflict between the relays in the feeder station. This also provides discrimination between the VCB on the train and the feeder station circuit breaker so that the VCB isolates a fault on the train before the feeder station circuit breaker trips. This prevents the OHLE being de-energised due to a fault on the train which can be isolated by the train's VCB. The effect of this is discussed in paragraphs 106 - 114.

97 When the initial fault occurred the current flowed for 370 ms. The maximum time permitted by the performance specification to which the equipment was designed for any type of fault is 300 ms.

The commissioning procedure

98 **The absence of continuity testing during commissioning of the supply system protection equipment meant that the transposition of the wires was not detected. This was a probable causal factor.**

99 The testing procedure simulated a fault condition by injecting a current at the terminals of the equipment which operated the circuit breaker. This tested the correct operation of the equipment itself, but not the connections to it from the transformer installed to detect the current flowing to the OHLE.

100 ABB Power, who supplied the equipment, carried out the tests during the commissioning of the installation on 25 January 2007 in accordance with their testing procedure.

101 No tests were carried out to verify that the connections between the transformer and the operating equipment were correct.

102 Had the testing current been applied at the terminals of the transformer, rather than the terminals of the operating equipment, the error would have become apparent.

103 The commissioning programme for the CTRL had included short circuit tests to verify the correct operation of the electrical protection equipment at feeder stations. Some testing of this type was carried out in the St Pancras area but it did not result in the identification of the installation error.

104 The incident exposed shortcomings in the quality management of the installation, testing and commissioning processes of safety related equipment, since an installation error was not detected.

The overhead line design specification

105 **The margin between the specified performance of the protection equipment and OHLE, and the conditions that caused the OHLE to fail was small. Had the specification provided a greater margin, it is more likely that the OHLE would have survived intact. It is therefore probable that this limited margin was causal.**

106 The type of fault which occurred should have been interrupted within 200 ms (paragraph 93). However, the protection system did not operate as designed (paragraph 94).

107 The secondary system was designed to detect excessive current and specified to operate within 300 ms (paragraph 97) but it allowed the excessive current to pass for 370 ms[5].

108 The duration of the excessive current flow (i.e. the time before the current was interrupted) was 23% longer than the maximum of 300 ms specified. The specified performance was not achieved because the secondary protection relay had been set with a time delay to ensure that it did not operate before the primary protection.

[5] This data was obtained from the equipment recording the operation of the power supply network.

109 The specification for the OHLE requires it to sustain a current of 6000 amps for 3 seconds[6]. The specification for the contact wire alone requires it to sustain the same current flowing longitudinally, but the current flow will effectively be limited to a duration of 300 ms as this is the maximum specified time for fault clearance.

110 The actual current passed was 5200 amps for 370 ms.[7]

111 When a current of this magnitude flows between the copper overhead wire and the carbon strip forming the top surface of the pantograph, a voltage of approximately 20 volts is produced between the wire and the carbon strip[8]. The current flow across the voltage releases energy in the form of heat at the interface.

112 If the voltage across the interface is 20 volts, a current of 5200 amps flowing for 370 ms across the wire to pantograph interface would release 38.5 kilojoules of energy.

113 The flow of 6000 amps across the wire to pantograph interface for 300 ms – the maximum specified time in which a fault is to be isolated – would release 36 kilojoules of energy. This is 7% less than the amount derived in paragraph 112. It is not certain whether the lesser input of heat over that period of time would be sufficient to cause the wire to part, but it is probable.

114 Taking into account either the length of time before the fault was isolated or the amount of heat produced, the margin between the actual circumstances and those specified to be sustainable is small, even though less than the maximum specified current was passing.

The use of 'tramway' OHLE

115 **The 'tramway' OHLE provided no restraint to prevent the contact wire falling onto the platform once it had parted. This exacerbated the consequences of the failure and is therefore contributory.**

116 On HS1, OHLE installed above tracks other than at terminal platforms comprises a catenary wire and a contact wire. The catenary wire is supported at intervals and carries the weight of the assembly.

117 The contact wire is suspended from the catenary wire by vertical 'dropper' wires. It provides an approximately horizontal surface which the pantograph contacts to collect electric current. If the contact wire itself should part, then the length which falls is limited by the distance between adjacent dropper wires, which is not usually more than 10 metres.

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[6] This is to allow excessive current to flow as a result of a fault without causing additional damage to the OHLE other than at the immediate location of the fault.

[7] This data was obtained from the equipment recording the operation of the power supply network.

[8] This normally arises from the nature of the copper-carbon interface causing the production of ionised gas which, together with the magnetic effect of the current, forces the pantograph head a very small distance away from the contact wire. The value of 20V is derived from 'Study of the electrode gap influence on electrode erosion under the action of an electric arc', European Physical Journal, 2000, pp 111-122.

118 In terminal platforms on Network Rail infrastructure the catenary wire is not generally used, the OHLE comprising a single contact wire directly supported at intervals. This arrangement is known as ‘tramway’ OHLE and is cheaper to install where the strength and stability of the combined catenary and contact wires is not required due to lower train speeds. It may be suspended either from arms attached to a fixed structure or from wire headspans, with a fixed structure anchoring it at the buffer stops. Headspans are used at St Pancras International station (figure 7).

119 The contact wire is 107 mm^2 in cross sectional area and weighs 0.95 kg/metre.

120 Because ‘tramway’ OHLE comprises only a single wire suspended at intervals from headspans, should the wire part a length at least equal to half the distance between headspans will be able to fall. It is very likely that this wire will not remain on top of a train below it, but will fall onto the area adjacent to the train. This could include a station platform.

121 The distance between headspans varies. At St Pancras International the headspans are 40 metres apart, though the distance between the anchor at the buffer stops and the first headspan is 33 metres. (At other London terminals the distance between the supports of tramway OHLE varies from 16 metres to 20 metres.)

122 Should the wire at St Pancras part, sections of wire between 18 metres and 38 metres long may fall to a position within touching distance of people on the platforms or in nearby parts of the station.

123 If OHLE comprising catenary and contact wire had been installed, then the length of unrestrained wire between droppers would be 10 metres. This would limit the length of wire within touching distance to 8 metres, even if it parted adjacent to a headspan.

124 If twin contact wires, connected to each other and each of the same cross section as the contact wire actually used, had been installed, the current density at the points of contact with the pantograph would have been halved. The heat input to each wire would also have been halved and it is possible that it would not have been sufficient to cause the wire to weaken and part.

125 As the wire fell onto the platform it would have remained electrically energised until it came into contact with a sufficiently earthed item. The wire would also tend to return to the coiled state it would have been in when stored on the cable drum prior to installation. This would cause it to whip quickly away from the point where it parted. Both these phenomena, the wire being electrically live and moving rapidly, presented a hazard to anyone present on the platform.

126 The area of the platform affected by the fallen wire, and therefore the hazard it presented, is related to the length of wire actually displaced. Reducing the length of wire displaced (by restraining it) would have limited the consequences caused by this contributory factor described in paragraph 125.

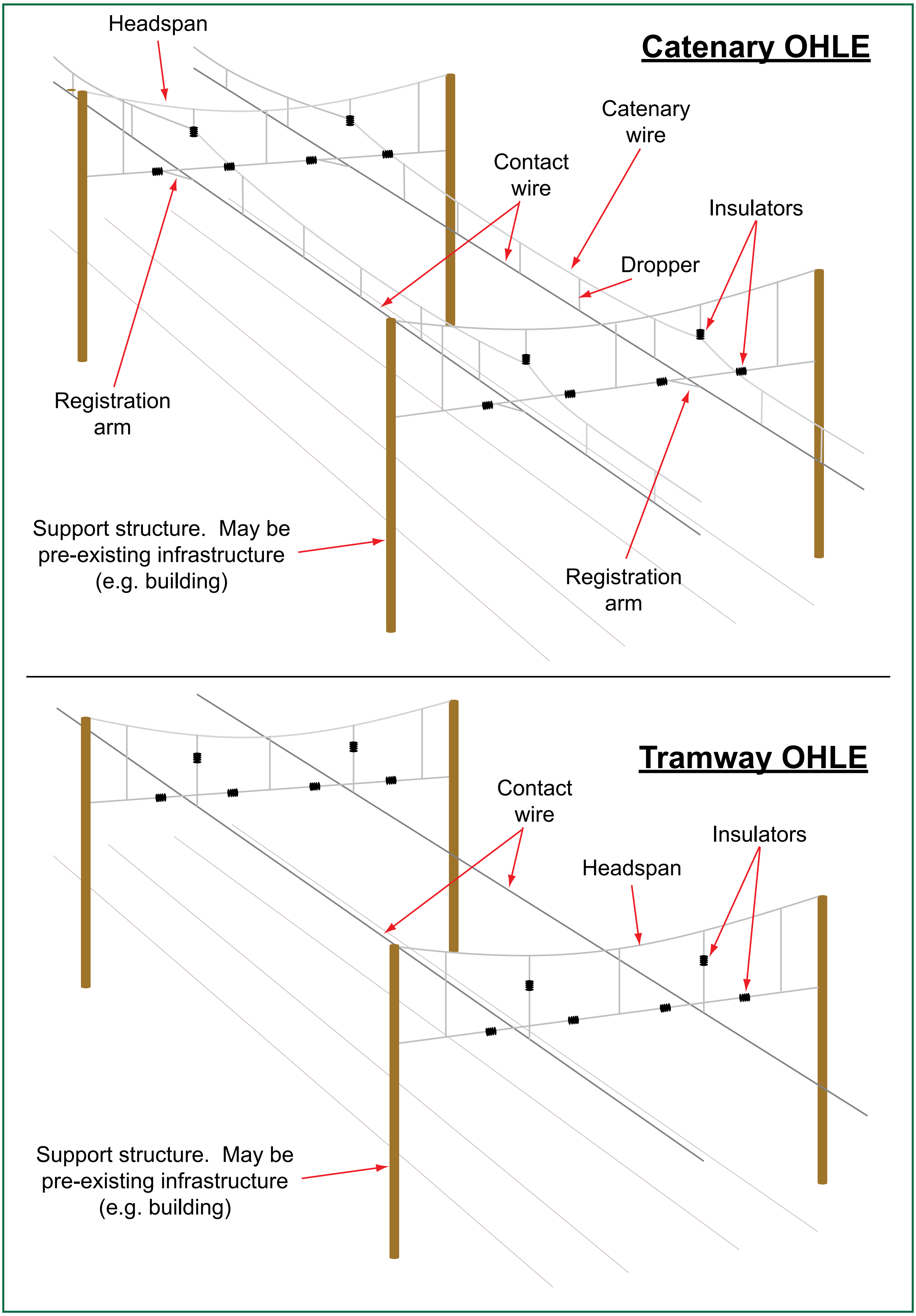

Figure 7: Diagram showing the different types of OHLE

The automatic reclosing of the supply system circuit breaker

127 **The supply system circuit breaker was designed to close automatically following an opening under fault conditions, causing the wire to become live momentarily after it had fallen onto the platform. This exacerbated the hazard to persons on the platform and is contributory.**

128 The circuit breakers are designed to re-close automatically, after a delay of six seconds, to provide a rapid recovery from transient faults (such as those caused by birds creating an electrical path to earth), with a minimum disruption to railway operation.

129 This feature caused the wire lying on the platform to become live again after the initial opening of the circuit breaker and after both attempts to close it by the EMMIS controller.

130 At stations, damaged wire may fall onto the station platform, as in this incident. It is likely that members of the public will be present and exposed to a hazard.

131 If the auto re-close function had not been fitted, then after each initial flow of excessive current the fallen wire would not have been energised again. Three of the events when the wire became live would not have occurred.

The closure of the supply system circuit breaker by the EMMIS controller

132 **The EMMIS controller did not follow the instruction to contact the signaller before attempting to close the supply system circuit breaker, causing the wire to become live on four further occasions. This exacerbated the hazard to persons on the platform and is contributory.**

133 The EMMIS controller's workstation includes a keyboard, mouse, tracker ball and flat screen. The condition of the supply network and the OHLE is displayed on the screen, which can display an overview of large sections of the route, or smaller sections in detail, according to the selection made by the controller. The controller uses the keyboard, together with the mouse and/or the tracker ball, to command the operation of circuit breakers.

134 Control room instructions[9] require that when a supply system circuit breaker opens automatically, and has automatically re-closed and re-tripped after 6 seconds, the first action of the controller is to contact the signaller to find out whether any trains are on the section of line affected. If trains are present, the signaller contacts the drivers, instructing them to lower their train's pantographs to isolate them from the OHLE. This enables the EMMIS controller to initiate a procedure to establish whether the cause lies in a train or the OHLE. Part of this procedure includes disabling the automatic re-closure equipment.

135 The controller did not follow these instructions by contacting the signaller. Had he done so, he would have been advised of the presence of both trains at St Pancras. The next step would have been for the signaller to contact the drivers of each train. The controller would then have become aware that it would be unsafe to attempt to close the circuit breaker, as the driver at the Paris end of the train at platform 9 was aware that a problem had occurred.

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[9] This is 'EMMIS Control Instructions – Module FAULT – Issue March 2009'.

136 When the initial circuit breaker opening occurred, the shift manager and the controller were in conversation. There is evidence that the controller raised the issue of the circuit breaker opening, and that the controller and manager agreed that an attempt should be made to close the circuit breaker. That decision was contrary to the control room instructions for the initial response, which require the signaller to be informed, an attempt made to establish the cause of the tripping, and disabling of the auto re-close function.

137 When a circuit breaker closure is initiated by the controller there is a short period in which the circuit breaker is actually closed, even if there is a persistent fault. During this period the OHLE momentarily becomes live. The monitoring equipment can often register this brief livening and display it on the controller's screen. Because the equipment monitoring the supply system interrogates its condition every $1/10^{th}$ second, rather than providing an absolutely continuous indication of its condition, there may be a delay of up to $1/10^{th}$ second in indicating a change of state. Therefore, when a circuit breaker is closed the display usually shows at least part of the OHLE being supplied as live, even if the circuit breaker then trips immediately.

138 When he attempted to close the circuit breaker the first time, the controller did not observe the brief livening. This may have led him to believe that the circuit breaker might not have actually closed.

139 His uncertainty was compounded by knowing that EDF staff had been working in the feeder station earlier in the day. To clarify the matter, he contacted the EDF control engineer. This call established that the staff had left the feeder station. On discussing the issue with the EDF control engineer, the controller decided to attempt to close the circuit breaker again.

140 When a controller closes a circuit breaker following a trip, he does not receive any reminder that he is closing it after fault conditions have been detected by the protection equipment. If such a warning, requiring a response, had been given on the display screen, the controller would have had to confirm that his action was intended. This might have caused him to consider whether such action was appropriate.

Identification of underlying factors[10]

141 The RAIB identified two possible underlying factors:

- the training given to the EMMIS controller; and
- the induction given to the shift managers in charge of the CTRL controllers at Ashford.

The training and induction of control room staff

142 The response of the EMMIS controller and the shift manager to the incident may have been influenced by their introduction to the function of the control room and their responsibilities.

[10] Any factors associated with the overall management systems, organisational arrangements or the regulatory structure.

The training and assessment of EMMIS controllers

143 **The training of EMMIS controllers is loosely specified and course notes are not provided. The instructions for the assessment and periodic re-assessment of EMMIS controllers are descriptive and general in nature.**

144 The controller had worked in the railway industry for 15 years. In 2003 he became a signalling and telecommunications technician employed by Carillion Rail plc on the CTRL Project, before joining the CTRL itself in late 2006.

145 The training of newly appointed EMMIS controllers is carried out by one of the controllers.

146 A syllabus, known as a 'course itinerary', developed during the implementation of the CTRL project and approved by the CTRL Head of Electrification, is provided indicating the topics to be covered each day over a period of 18 weeks. These topics include the components of railway electrification, response to faults, incident management, rules, equipment operation and the organisation of EDF. The last 6 weeks are concerned with mentoring and assessment. Training notes are not provided. The detailed content of the course is left to the discretion of the trainer.

147 Copies of the control room procedures are not issued individually to controllers, but they do have permanent access to a copy in the control room.

148 Much of the initial training is 'one to one' tutoring with the trainer in a classroom backed up by periods on a simulator. The trainee then spends time with a controller at work. Gradually the trainee is allowed to carry out some of the duties under the close supervision of the controller. These duties are increased as the trainee gains confidence and competence and as the controller becomes confident in the trainee's abilities.

149 Assessment of competence is by observation of the trainee carrying out procedures such as handing over between shifts and handling incidents. The simulator is used with increasingly complex scenarios being applied to put the trainee under increasing pressure.

150 Re-assessment of competence to respond to infrastructure failures takes place annually. Re-assessment of handing over between other staff and response to unplanned events, other than failures, takes place every 2 years.

151 The controller was initially passed out as a controller in April 2007. He was last re-assessed for his response to failures in February 2009 and passed the assessment successfully. This included the tripping of a circuit breaker in a situation broadly similar to the event at St Pancras.

152 The assessment instructions describe the type of skills required and the general circumstances likely to face the controller. The assessment method is not specified and relies on the judgement of the assessor.

153 Because neither the exact training given nor the emphasis placed on the response to tripping of circuit breakers are recorded, it is difficult to give an accurate assessment of the effect of the lack of a detailed training and assessment specification on the performance of the controller. Nevertheless, it is possible that it contributed an oversight by the controller, which resulted in him not following the instructions laid down in the control room procedures.

The induction of newly appointed shift managers is directed to the work of the signallers rather than the EMMIS controllers

154 **The training of the shift manager on duty at the time of the incident emphasised signalling and included only limited coverage of the duties and responsibilities of the EMMIS controllers.**

155 The shift manager is responsible for directing the activities of the signallers and controllers, implementing contingency plans, investigating operating incidents and maintaining a log of incidents and unusual occurrences.

156 The training of shift managers lasts up to 15 days. It covers incident management, emergency isolations of the OHLE and track possessions. It includes visits to other control centres as well as table top exercises. One half day is spent at the Electrical Control Room at Paddock Wood. Three days are devoted to man management skills.

157 The shift manager had joined the railway in 1992 as a signaller, later moving to human resources where he became involved in track safety assessment, managing a team of 22 assessors. He was appointed as a CTRL shift manager in 2007. His specific training included a course on the signalling system used on the CTRL.

158 Although the shift manager's background was in signalling and track safety, his introduction to the EMMIS controller's role was limited to gaining authorisation to carry out an emergency isolation of the OHLE.

159 This authorisation is needed because there is sometimes only one controller on duty at any time. Personal needs will necessitate the controller leaving his work station for limited periods during each shift, and an immediate response must be given to a request for an emergency isolation.

160 Operators at most other electrical control rooms work in pairs to cover this situation.

161 Witness evidence indicates that not all shift managers are confident in their competence to respond to a request for an emergency isolation. It is possible that some would consider waiting for the EMMIS controller to return, rather than immediately carrying out the procedure.

162 The emphasis on signalling, rather than electrical power supply control, in the induction of the shift manager may lead to a situation where the controller has to rely on a shift manager with limited knowledge and experience of a controller's work, together with limited confidence when an intervention is needed.

163 This limitation is not addressed in training and may have influenced the shift manager's thinking and decision to agree to the closure of the open track circuit breaker.

Observations[11]

The correct initiation of emergency calls

164 When a call is made to a control room to arrange for the power to the OHLE to be switched off in response to an emergency, the Rule Book instruction requires the opening words to be 'This is an emergency call.'

165 The emergency calls made by Eurostar staff at St Pancras to the control room at Ashford did not begin with this statement.

166 A notice reminding Eurostar staff that such calls must open with those words has been issued.

[11] An element discovered as part of the investigation that did not have a direct or indirect effect on the outcome of the incident but does deserve scrutiny.

Summary of Conclusions

Immediate cause

167 The immediate cause of the incident was that the overhead line parted because of local overheating caused by high current flow (**paragraph 68**).

Causal factors

168 The causal factor was:

- The reduced distance between the points of the electrodes on the lightning arrester, and the induced transient voltage resulting from the vacuum circuit breaker closing, caused a flashover at the lightning arrester (**paragraph 75, Recommendation 1**).

169 It is probable that the following factors were causal:

a. Cables in the circuit detecting the flow of excessive current to the OHLE were incorrectly connected, allowing the circuit breakers that were intended to open automatically to remain closed and the current to flow for longer than specified (**paragraph 90, No recommendation**).

b. The absence of continuity testing during commissioning of the supply system protection equipment meant that the transposition of the wires was not detected (**paragraph 98, Recommendation 2**).

c. The electrical protection system did not operate as specified and the margin between the specified performance of the protection equipment and of the OHLE and the conditions that caused the OHLE to fail was small. (**paragraph 105, Recommendation 4**).

Contributory factors

170 The contributory factors were:

a. The ‘tramway’ OHLE provided no restraint on the contact wire to prevent it falling onto the platform once it had parted (**paragraph 115, Recommendation 3**).

b. The supply system circuit breaker was designed to close automatically following an opening under fault conditions, causing the wire to become live momentarily after it had fallen onto the platform (**paragraph 127, Recommendation 3**).

c. The EMMIS controller did not follow the instruction to contact the signaller before attempting to reclose the supply system circuit breaker, causing the wire to become live on four further occasions (**paragraph 132, Recommendation 5**).

Underlying factors

171 The underlying factors were:

a. The training of EMMIS controllers is loosely specified and course notes are not provided (**paragraph 143, No recommendation**).

b. The instructions for the assessment and periodic re-assessment of EMMIS controllers are descriptive and general in nature (**paragraph 143, No recommendation**).

c. The training of the shift manager on duty at the time of the incident emphasised signalling and included only limited coverage of the duties and responsibilities of the EMMIS controllers (**paragraph 154, Recommendation 6**).

Actions reported as already taken or in progress relevant to this report

172 Eurostar has undertaken a special examination of the security of the lightning arrester electrodes on the Eurostar power cars, including those allocated to France and Belgium (paragraph 81).

173 Eurostar has issued a written notice to staff at St Pancras that telephone calls to the EMMIS controller requesting an emergency isolation must begin with the works 'This is an emergency call' (paragraph 166).

174 NR (CTRL) is developing a more detailed specification to define the training, assessment and re-assessment of EMMIS controllers and is examining, with a view to amendment, the competence standards for shift managers. All EMMIS Controllers have also received refresher training and assessment on responding to fault conditions (paragraph 171).

175 NR (CTRL) has issued a temporary instruction to the controllers that in the event of a circuit breaker supplying the overhead line at St Pancras opening automatically, Eurostar staff at St Pancras are to be contacted before any closure attempt is made. Compliance with this temporary instruction ensures that staff at St Pancras can advise the controller of any out of course situation affecting the OHLE. It also gives the controller a clearer indication as to whether there is a problem affecting the station platforms. Had the instruction been in place, and correctly implemented, at the time of the incident, the controller would not have made any attempts at manual closure.

176 Making the instruction permanent would establish this additional check as part of the procedure and prevent a recurrence of the events described in paragraphs 50 – 54 (**paragraph 175, Recommendation 7**).

Actions reported that address factors which otherwise would have resulted in a RAIB recommendation

177 EDF has examined installations on the CTRL similar to those in the feeder station at St Pancras, and has not found any similar defects.

178 In the light of this action, described in paragraph 95, addressing the factor identified in paragraph 90, the RAIB has decided not to issue a further recommendation.

Recommendations

179 The following recommendations are made:[12]

1 *The purpose of this recommendation is to ensure that the correct spark gap is maintained to prevent the operation of the lightning arrester at lower than intended voltages.*

Eurostar should review, and amend if appropriate, the design and/or maintenance of the lightning arrester spark gap electrodes to further reduce the risk of reduction in the length of the gap (paragraph 168).

2 *The purpose of this recommendation is to ensure that sound quality management processes are in place to monitor the suitability of the installation, testing and commissioning procedures.*

ABB Power should review its quality management processes as they relate to the installation, testing and commissioning of safety related railway equipment (paragraph 169).

3 *The intent of this recommendation is to reduce the mechanical and electrical risk from broken cables from OHLE of the type currently in use at St Pancras falling onto the public or staff, particularly where it is in proximity to public areas of the station.*

Network Rail and EDF should investigate the possibility of reducing the risk associated with damaged OHLE of the tramway type used at St Pancras International falling onto station platforms. This investigation should include, but not be limited to:

- improved electrical protection system (e.g. to deliver a more rapid response);
- improved support for the contact wire;
- enhanced resilience of the contact wire;
- avoiding the use of automatic reclosure of circuit breakers supplying the tramway OHLE above platform tracks (paragraph 170).

continued

[12] Those identified in the recommendations, have a general and ongoing obligation to comply with health and safety legislation and need to take these recommendations into account in ensuring the safety of their employees and others.

Additionally, for the purposes of regulation 12(1) of the Railways (Accident Investigation and Reporting) Regulations 2005, these recommendations are addressed to the Office of Rail Regulation to enable it to carry out its duties under regulation 12(2) to:

(a) ensure that recommendations are duly considered and where appropriate acted upon; and

(b) report back to RAIB details of any implementation measures, or the reasons why no implementation measures are being taken.

Copies of both the regulations and the accompanying guidance notes (paragraphs 167 to 171) can be found on RAIB's website www.raib.gov.uk

4 *The purpose of this recommendation is to ensure coherence between the specifications for equipment components.*

Network Rail should review, and if appropriate amend, the requirements for the performance of electrification systems being brought into use so that the electrical protection system, the OHLE and its rating provide an adequate margin of protection against all reasonably foreseeable electrical hazards (paragraph 169).

5 *The purpose of this recommendation is to remind the EMMIS controller that a safety process has to be completed before a circuit breaker that has opened owing to a sustained fault may be closed.*

Network Rail (CTRL) should investigate the possibility either of causing a suitably worded reminder, which must be responded to, to appear automatically on the EMMIS controller's screen warning of the safety process to be followed before closing a circuit breaker which has opened on automatic reclosure or of introducing other effective means of reminding the controller of the correct procedure to be followed (paragraph 170)

6 *The aim of this recommendation is to improve the awareness of new shift managers of the power supply control procedures.*

NR (CTRL) should review the induction procedures for new shift managers so that they are made aware of:

- the safety procedures to be followed in response to any matter arising from the operation of the OHLE;
- the importance of carrying out the emergency isolation procedure immediately; and
- the procedures to be followed by EMMIS controllers to recover the situation following an automatic trip while ensuring safety (paragraph 171).

7 *The purpose of this recommendation is to improve the safety of persons at St Pancras in the event of OHLE damage in the station.*

Network Rail (CTRL) should make permanent the temporary instruction to EMMIS controllers that staff at St Pancras are to be contacted to confirm that all persons are in positions of safety before attempting to reclose a circuit breaker supplying the station that has opened automatically (paragraph 176).

Appendices

Appendix A - Glossary of abbreviations and acronyms

CTRL	Channel Tunnel Rail Link
EDF	Electricité de France Energy Services Limited
EMMIS	Electrical and Mechanical Management Interface System
HS1	High Speed One
OHLE	Overhead line equipment
VCB	Vacuum circuit breaker

Appendix B - Glossary of terms

Buffer stops	Equipment installed at the end of a track, such as one in a terminal platform, to prevent a train passing beyond the end.
Busbar	A rigid electric conductor mounted on insulators connecting items of electrical equipment. One connects the pantographs to the VCB on the roof of a Eurostar power car.
Circuit breaker	A switch in an electric circuit which is usually remotely controlled and will open automatically should an excessive current pass through it.
Earth	The body of the earth to which items of electrical equipment which can be touched are connected to prevent injury by electricity. An item which is 'earthed' can be touched safely by a person in contact with the ground.
Electrode	A rod in a lightning arrester which faces another on the same axis, but is separated from it. When the lightning arrester operates an electric current flows across the gap between the electrodes.
EMMIS Controller	The member of staff controlling the power supply to the OHLE on the Channel Tunnel Rail Link. He also monitors and controls tunnel air management, tunnel water pumping and electricity supply to other services on the CTRL.
Feeder station	A building and/or compound containing electrical equipment which is part of a supply network of an ac electrified railway.
Flashover	An uncontrolled electrical discharge between two bare electrical conductors.
Headspan	A network of wires above and transverse to a railway line from which the overhead wires are suspended.
High Speed AC	One of the electrical power supply systems from which Eurostar trains take power. It is used between St Pancras and the Channel Tunnel. The system to be used has to be selected before the pantographs of a stationary train are raised.
Inrush current	The current which flows through a transformer for a very short period when it is initially energised to generate the magnetic fields inside the transformer. Typically it may be about three times the normal maximum current depending on the point in the alternating current wave form at which the transformer is energised. It normally decays to the steady state current over several cycles.
Insulator	A component which does not conduct electricity used to support live cables or busbars and to separate them from other components.

Ionised gas	A gas which has been raised to a high temperature by the passage of electricity and is in a state in which it will conduct electricity.
Lightning arrester	A device fitted to an electric circuit to dissipate the effect of a lightning strike without damaging the circuit.
Lock-nut	A nut which is tightened against another nut or item secured on the same screw thread to prevent the nut or item becoming loose and moving, usually through vibration on the thread.
Overhead line equipment	The arrangement of supports, insulators and wires above an electrified railway which carries the electric current to electric trains.
Pantograph	The folding current collector mounted on the roof of an electric train supplied through overhead wires.
Over voltage	A voltage above the specified normal operating range for an electric circuit.
System selector	The switch in a Eurostar cab which enables the driver to select the appropriate system from which the train is required to draw electric power.
Tramway OHLE	A type of OHLE which uses only a single wire which is unsupported between headspans or other suspension equipment.
Trip	The automatic opening of a circuit breaker when a fault occurs in the circuit it is supplying.
Vacuum circuit breaker	A circuit breaker in which the contact surfaces completing or interrupting the electric circuit are contained in a vacuum.

Appendix C - The induction of transient voltages by Vacuum Circuit Breakers

1 Transient voltages are more usually associated with the opening rather than the closure of circuit breakers. When the circuit breaker opens the current flow is interrupted. This causes an increased voltage to be induced across the contacts in the circuit breaker. The value of this voltage depends on the exact nature of the circuit and the rate at which the current is interrupted. The greater the rate at which the current is interrupted, the greater the magnitude of the induced voltage.

2 When a VCB closes current may start to flow between the contacts before they have come together if there is sufficient voltage to cause an electrical breakdown through the good, but nevertheless imperfect, vacuum containing the contacts of the VCB. This is called ‘pre-strike’.

3 The voltage and current in an alternating current circuit vary regularly between two maxima of opposite polarity. Between these maxima both current and voltage pass through zero.

4 The VCB can also cease conduction as the current passes through zero. If it does so, the voltage across the VCB gap will increase rapidly and may well cause a further pre-strike.

5 When a pre-strike occurs, the consequent current would include very high frequency components due the specific nature of the circuit. These high frequency currents can cause multiple, rapid zero-crossings of the current.

6 The transient voltage induced is dependent on the exact nature of the circuit and the point in the wave at which the closure of the VCB takes place. It is possible for voltages several times the supply voltage to be induced in the circuit.

7 The magnitude of the transient voltage induced can only be established if the detailed nature of the supply circuit and the exact point on the alternating wave at which closure started are known.

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