PRODUCED BY THE OPERATIONS DIRECTORATE OF ENERGY NETWORKS ASSOCIATION

Engineering Recommendation P24

Issue 2 2020

AC supplies to railway systems

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Operations Directorate
Energy Networks Association
4 More London Riverside
London
SE1 2AU

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First published, 1984.

Revised, 2020.

Amendments since publication

Issue	Date	Amendment
Issue 2	March 2020	Major technical revision of P24 Issue 1 which for the most part has consisted of re-writing larger portions of the document. The document has been imported into the latest ENA engineering document template. Any editorial changes necessary to comply with the conventions and formatting in the ENA engineering document template and Engineering Recommendation ER G0 Rules, for structure, drafting and presentation of ENA engineering documents have been carried out. Clause numbering of this EREC has changed significantly to conform to the latest ENA engineering document template. Key changes are summarised as follows: • Update terminology throughout document to align with latest. • Align the document with the latest a.c. traction technology. • Widen the scope of connections described in P24 (33 kV, 132 kV and 275/400 kV). • Update and include the latest guidance for the two connection arrangements used most widely for traction loads: EHV/25 kV transformer (1 x 25 kV) and EHV/25/25 kV transformer (2 x 25 kV). • Update the guidance on estimating traction loads • Update the guidance on disturbance limits.

		• Update guidance on earthing and equipment specification.
		• Remove reference to legacy software and methods no longer used i.e. HARP (theory is retained where appropriate).
		• Include brief description of developing connection technology i.e. SFC connection.
		Specific changes to clauses are as follows:
		• Title: Document title changed from '*AC traction supplies to British Rail'* to '*AC traction supplies to railway systems'.*
		• Foreword: new clause added to provide publishing information, the purpose of the document and who it is intended for use by.
		• Introduction: major amendment to this Clause to update the context and include reference to the '1 x 25 kV' and '2 x 25 kV' arrangements. A new flow diagram has been added which depicts the 'Traction connection development and design process'.
		• Clause 2, Normative references: new references added including BS EN 50163, BS EN 50388, BS EN 6007-5, BS EN 60076-6, ENA TS 50-19 and ENA TS 12-4Reference to '132 kV' connections throughout the document has been changed to 'EHV', thus encompassing 275 kV and 400 kV connections.
		• Clause 3, Terms and definitions: all terms have been subject to a minor amendment and new terms added including
		  o 1 x 25 kV arrangement
		  o 2 x 25 kV arrangement
		  o Transformer station
		  o Feeder Station
		  o Disconnector Compound
		• Clause 4, Railway systems: content has been updated to reflect modern traction technology. Added new clause describing regenerative braking.
		• Clause 5, Types of supply point: major update to the descriptions and guidance for the two most common arrangements for transformer supplies: '1 x 25 kV' and '2 x 25 kV'. New figures have been added to depict the typical connection arrangements. Previous guidance on auxiliary supplies has been removed (now covered by Clause 17). New clause added to explain the typical 'boundary' arrangements between parties.
		• Clause 6, Load estimating: complete re-write of guidance regarding load estimating for traction supplies.
		• Clause 7, Standards of security: minor amendments to the requirements for security.
		• Clause 8, Nature of traction current: The content from the previous issue largely been deleted. New content now reflects modern traction pulse-width modulated (PWM) drives.
		• Clause 9, Disturbance limits: major amendments to update and clarify guidance on disturbance limits, taking account of changes to ENA EREC P28, ENA ER G5, changes to grid voltage unbalance limits, and to reference ENA ER P29. New clause inserted to define harmonic aggregation.

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Clause 10, Disturbance estimation: major amendments to guidance on disturbance estimation (unbalance and harmonics). Reference to legacy software no longer in use has been removed.
Clause 11, Reduction of disturbances: the majority of the previous content has been deleted as this topic is generally covered in the new Annex A.
Clause 12, Equipment: this clause has been subject to a major amendment. All previous content has been largely deleted. The key components are still covered:

Transformers - broad requirements are now included, derived from the most recent traction supply connections.
Cables - broad requirements are now included and previous guidance from Issue 1 Clause 3 has been retained.
Overhead lines - broad requirements are now included.
Circuit-breaker, disconnector and earth switch - broad requirements are now included alongside the applicable National Standards.
Communications - previous content replaced with reference to Clause 15.
Metering - previous content deleted and replaced with new guidance

Clause 13, Earthing: complete re-write of guidance on earthing design for traction supplies. Extensive guidance now covers design requirements, criteria for segregated electrode systems, and interconnected electrode systems.
Clause 14, Protection: major amendments to guidance on protection design for traction supplies. Previous diagrams from P24 Issue 1 and ENA TS 41-15 Part 9 have been captured in new simplified, indicative diagrams.
Clause 15 System monitoring and control: major amendments to guidance on requirements for system monitoring and controls. New diagram added to indicate typical signals and monitoring interface.
Clause 16, Operational safety aspects: the previous content has been largely deleted. The pertinent points have been retained - those which are unique to traction connections (isolation of the return current conductor). Reference to ENA EREC G38 has been added.
New Clause 17, Non-traction power supplies: new clause added providing guidance on:

LV non-traction power supplies to Railway Infrastructure Manager
HV non-traction power supplies to Railway Infrastructure Manager
LV power supplies to Electricity Network Operator
Loss of return protection

Annex A: New annex added to describe options for the use of Scott transformer. Previous descriptions (P24 Issue 1, Clause

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		9.1 and Appendix C) of power electronics which could be used with transformer supplies have been retained in this annex. • Annex B: New annex added to describe the option of employing a static frequency converter (SFC). • Previous appendices (P24 Issue 1, Appendix A and B), describing use of legacy software (HARP) have been removed.

Contents

Figures

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Foreword

This Engineering Recommendation (EREC) is published by the Energy Networks Association (ENA) and comes into effect from the published date. It has been prepared under the authority of the ENA Engineering Policy and Standards Manager and has been approved for publication by the ENA Electricity Networks and Futures Group (ENFG). The approved abbreviated title of this engineering document is "EREC P24", which replaces the previously used abbreviation "ER P24".

This document supersedes ENA ER P24 Issue 1 1987.

The requirements described in ENA TS 41-15 Part 9 Issue 1 1989[1], *Standard circuit diagrams for equipment in 132 kV substations*, are considered useful for information purposes however, the guidance in this document takes precedence on such matters.

This document provides guidance on the planning, design and construction of new connections for a.c. traction loads to be supplied at 25 kV. The content of this document has been developed in conjunction with Network Rail and reflects the latest technology and arrangements in use by the rail industry.

This document should be read in close conjunction with other relevant industry Standards for network connection design and operation, namely:

- ENA ER G5 [N5];
- ENA EREC G12 [N6]
- ENA ER G38 [N7];
- ENA ER P28 [N9];
- ENA ER P29 [N10].

Where the term "shall" or "must" is used in this document it means the requirement is mandatory. The term "should" is used to express a recommendation. The term "may" is used to express permission. Where the term "shall" is used in this document it expresses a requirement. The term "may" is used to express permission.

NOTE: Commentary, explanation and general informative material is presented in smaller type, and does not constitute a normative element

[1] ENA TS 41-15 Part 9 is no longer maintained by ENA and its content considered useful for information only.

Introduction

Electric traction has been used on main line railways in Great Britain since the 1890's. Early a.c. electrification made use of frequency converters to provide a low frequency (25 Hz) supply and assist the commutation of traction motors, but from the 1950s the British Transport Commission settled on the emerging standard of 25 kV and 50 Hz for new main line electrification. Electrification of the West Coast Main Line between London Euston, Manchester and Liverpool quickly followed, together with electrification of the Great Eastern Main Line, several suburban lines around major cities, electrification of the West Coast Main Line to Glasgow, the East Coast Main Line between London King's Cross and Edinburgh and the Midland Main Line between St Pancras and Bedford.

The ‘classic’ 1 × 25 kV electrification, utilising return conductors and booster transformers to provide suppression of signalling and telecommunications interference, was maintained as a standard configuration until the late 1990s. Growth in traction capacity requirements, and improvements in analysis techniques for system design, then permitted other systems to be introduced. The ‘classic’ 1 × 25 kV arrangement is now permissible, subject to correct traction power system design, without booster transformers, and with aerial earth wires replacing the return conductor system.

Similarly, the 2 × 25 kV ‘autotransformer system’ was introduced into main line electrification in Great Britain in the mid-2000s. This was developed by Charles Scott in 1914 to reduce traction interference and improve feeding efficiency on the New York, New Haven and Hartford Railroad in the USA. This is a system which removes the need for booster transformers, and utilises autotransformers at distribution sites to provide a 25-0-25 kV system, effectively distributing power at 50 kV. This reduces losses, improves voltage regulation, and may be used for heavily loaded routes, or as a means of extending the feeding distances on lighter loaded routes. Sections of the West Coast Main Line have been converted to an autotransformer system, as necessary, since 2005, and it has been implemented as part of electrification of the Great Western Main Line.

With the continuing interest in a.c. railway electrification, it is appropriate that the experience obtained should be presented in the form of guidelines for good engineering practice. This present document can be applied to a.c. traction supplies for ‘classic’ 1 × 25 kV arrangements, with or without booster transformers, or 2 × 25 kV ‘autotransformer’ arrangements. The latest developing technology for traction connections is also described in high-level detail within the Annexes of this document.

The process of developing and designing a new 25 kV traction connection is depicted in Figure 1. The guidance in P24 will be most relevant during the feasibility study when both the Railway Infrastructure Manager and the Electricity Network Operator should work together to consider the connection options.

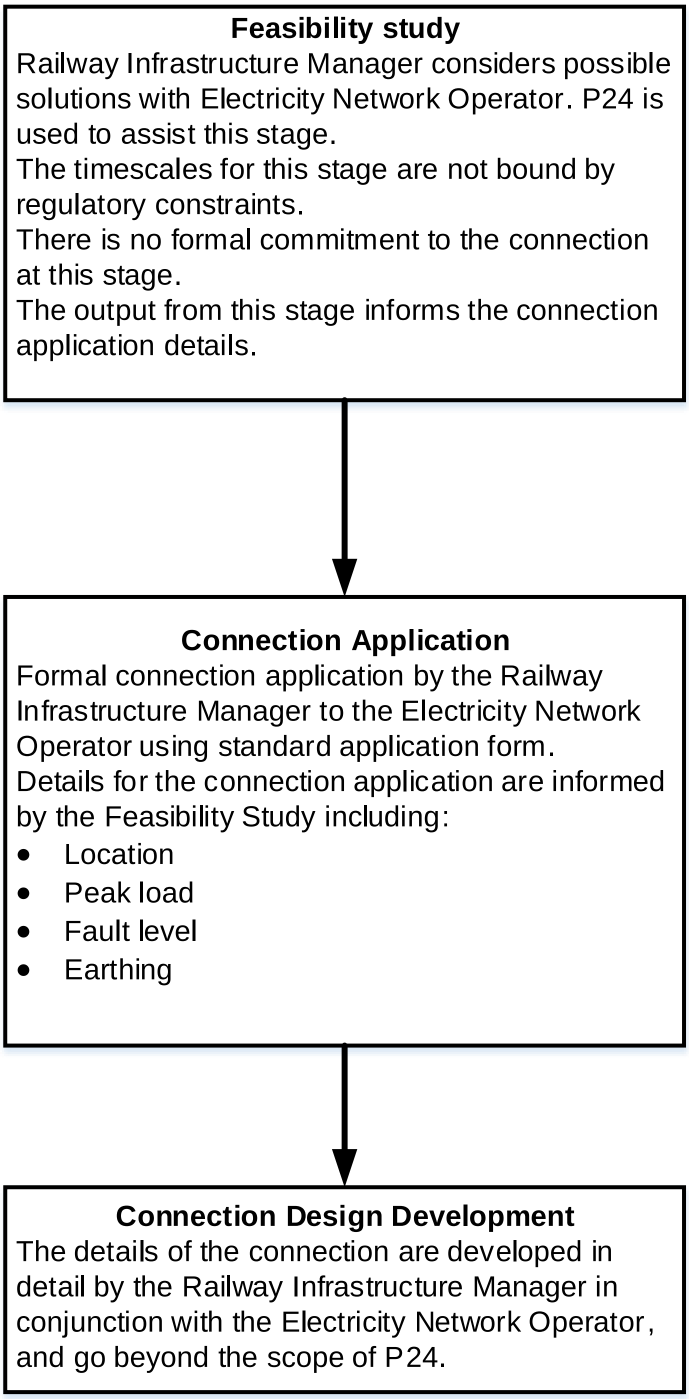


Figure 1 — Traction connection development and design process

1 Scope

EREC P24 applies to new a.c. traction connections and new a.c. auxiliary supplies to railway infrastructure.

EREC P24 also applies to the major changes to, existing a.c. traction supplies and existing auxiliary supplies, where reasonably practicable.

2 Normative references

The following referenced documents, in whole or part, are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

Standards publications

BS EN 50122-1, *Railway applications. Fixed installations. Electrical safety, earthing and the return circuit. Protective provisions against electric shock*

BS EN 50152-1, *Railway applications. Fixed installations. Particular requirements for alternating current switchgear. Circuit-breakers with nominal voltage above 1 kV*

BS EN 50152-2, *Railway applications. Fixed installations. Particular requirements for alternating current switchgear. Disconnectors, earthing switches and switches with nominal voltage above 1 kV*

BS EN 50163, *Railway applications. Supply voltages of traction systems*

BS EN 50329, *Railway applications. Fixed installations. Traction transformers*

BS EN 50388, *Railway Applications. Power supply and rolling stock. Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability*

BS EN 50341-1, *Overhead electrical lines exceeding AC 1 kV. General requirements. Common specifications*

BS EN 50522, *Earthing of power installations exceeding 1 kV a.c*

BS EN 50633, *Railway applications. Fixed installations. Protection principles for AC and DC electric traction systems*

BS EN 50641, *Railway applications. Fixed installations. Requirements for the validation of simulation tools used for the design of traction power supply systems*

BS EN 60076-1, *Power transformers. General*

BS EN 60076-5, *Power transformers. Ability to withstand short-circuit*

BS EN 60076-6, *Power transformers. Reactors*

BS EN 60214-1, *Tap-changers. Performance requirements and test methods*

BS EN 61850 (series), *Communication networks and systems for power utility automation*

Other publications

[N1] Statutory Instrument 2002 No. 2665, *The Electricity Safety, Quality and Continuity Regulations 2002 (as amended)*

[N2] Meter Operator Code of Practice Agreement, www.mocopa.org.uk

[N3] Railway Group Standard GL/RT1255

[N4] ENA EREC C55, *Insulated Sheath Power Cable Systems*

[N5] ENA ER G5, *Planning Levels for harmonic Voltage Distortion and the Connection of Non-Linear Equipment to Transmission Systems and Distribution Networks in the United Kingdom*

[N6] ENA EREC G12, *Requirements for the Application of Protective Multiple Earthing to Low Voltage Networks*

[N7] ENA ER G38, *Operational procedure associated with electricity supplies for traction purposes on AC and DC electrified lines*

[N8] ENA ER P2, *Security of Supply*

[N9] ENA ER P28, *Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the United Kingdom*

[N10] ENA ER P29, Issue 1 1990, *Planning limits for voltage unbalance in the UK for 132kV and below*

[N11] ENA TS 41-24, *Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations*

[N12] ENA TS 43-50, *Specification for Single Circuit Overhead Lines on Wood Poles for use at 132kV*

[N13] ENA TS 12-4, *Terminating equipment for pilot cables subject to induced transient voltages exceeding 650 V r.m.s.*

[N14] ENA EREC S34, *A guide for assessing the rise of earth potential at substation sites*

[N15] Network Rail NAT/TW/InfraInv/ENG/EP6248683, *Design and Installation of New, Renewed or Refurbished Distribution Electricity Network Operator's (DNO's) Intakes and Consumer Facilities*

[N16] The Grid Code, National Grid Electricity Transmission plc

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply. Terms not used in the text of this document are included to assist the reader on interpretation of rail network infrastructure.

3.1
automatic power control (APC)
means whereby

(i) the electric power circuits on the rolling stock are automatically switched OFF before a train enters a neutral section;

(ii) the rolling stock transformer connections are automatically selected according to the voltage of the overhead line equipment;

(iii) the electric power circuits on the rolling stock are automatically switched ON after a train leaves a neutral section.

3.2
APC magnet
magnet fixed on the sleeper ends before and after a neutral section Inductor which operates the **APC** system on the train.

3.3
1 × 25 kV arrangement
transformer a.c. traction supply commonly used for connections on the 132 kV network.

NOTE: 1 × 25 kV transformers consist of an EHV winding, connected between two phases on the EHV, and a 25 kV LV winding (EHV/25 kV)

3.4
2 × 25 kV arrangement
autotransformer a.c. traction supply commonly used for connections on the 275 kV and 400 kV grid.

NOTE: 2 × 25 kV transformers consist of an EHV winding, connected between two phases on the EHV, and two 25 kV windings (EHV/25-0-25 kV).

3.5
bond

3.5.1
continuity bond
electrical connection, and type of traction bond, used to connect across gaps in the traction return rails, particularly at points and crossings.

3.5.2
cross bond
electrical connection, and type of traction bond, used to provide paralleling interconnections between traction return rails

3.5.3
impedance bond
device which, whilst allowing the traction return current to flow freely, so impedes the flow of track circuit signalling current as virtually to isolate two track circuits one from another

3.5.4
signalling bond
electrical connection designed to connect train detection circuits to running rails, and not normally required to carry traction return current.

3.5.5
structure bond
bond connecting the steelwork of an overhead line equipment structure, or bridge, or other metal structure, to a traction return rail or aerial earth wire

3.5.6
traction bond
electrical connection in the return circuit, often between running rails used for traction current return, or between these rails and other parts of the return circuit

NOTE: Where these bonds form the sole connection of the return circuit path, such as between rails and a traction feeder station, they are designated as red bonds.

3.6
booster transformer
device to induce into the traction return rails, or return conductors where provided, virtually the whole of the traction return current, in order to reduce to a minimum any interference with communication circuits.

NOTE: A ‘supply booster transformer’ is a legacy item (different from the booster transformer) located at the transformer station.

3.7
contact wire
bare solid conductor being the lowermost of the wires forming the overhead line equipment.

NOTE: The pantographs of electric trains press against the underside of this wire and collect the electric current required by the trains.

3.8
EHV
voltage greater than or equal to 132 kV

3.9
EHV supply transformer
transformer providing a 25 kV supply to Railway Infrastructure Manager

3.9.1
EHV/25 kV transformer
transformer used for **1 × 25 kV arrangement**

3.9.2
EHV/25-0-25 kV transformer
transformer used for **2 × 25 kV arrangement**

3.10
electric locomotive
hauling unit (for hauling coaching or freight stock, but not carrying passengers or freight) on which the electric motors for the movement of the train, the associated switchgear and other equipment, are mounted, and having one or two cabs containing apparatus for driving.

3.11
electric multiple unit
two or more vehicles coupled together and not normally uncoupled in service, having a driving cab at each end of the multiple set, and including a motor coach.

3.12
electric multiple unit train
one multiple-unit, or two or more multiple-units coupled together to form one train, and controlled from one driving cab.

3.13
electric train
train of coaching or freight stock worked by one or more electric locomotives; single or coupled electric locomotives; or an electric multiple-unit train

3.14
isolated
appropriately disconnected from all sources of supply by which it can become live

3.15
Electricity Network Operator
company operating the electricity network to which the traction supply is connected

NOTE: Electricity Network Operator includes both transmission Electricity Network Operators and distribution Electricity Network Operators

3.16
neutral section
arrangement of wires and insulators including a length of earthed contact wire introduced into the overhead line equipment and designed to ensure that two sections, which must not be connected electrically, are kept electrically separate even during the passage of the pantographs of electric trains

3.17
overhead line equipment (OLE)
arrangement of wires, suspended over the railway line, for supplying electricity to electric trains, together with the associated fittings, insulators, and other attachments, by means of which the wires are suspended or registered in position.

NOTE: The whole of the electric track equipment with its structures, foundations, etc., may collectively be described as "overhead line equipment."

3.18
overlap
An overlapping of the ends of two lengths of overhead line equipment; arranged in such a manner that the pantographs of electric trains can pass smoothly and without break of contact from one contact wire to the next over the same line.

3.19

pantograph

retractable frame, mounted on insulators on the roof of electric multiple-unit trains and electric locomotives, which presses against the underside of the contact wire, and through which the electric current is collected from the overhead line equipment.

3.20

feeder station

railway distribution site operated by the Railway Infrastructure Manager containing electrical switchgear and equipment

NOTE: Feeder stations take 25 kV supplies from the Electricity Network Operator, and provide feeds to the railway overhead line equipment. To distinguish a 2 × 25 kV feeder station, this is normally referred to as an “autotransformer feeder station”, or ATFS.

3.21

disconnector compound

compound adjacent to the **feeder station** containing the operational boundary between the Electricity Network Operator and Railway Infrastructure Manager

3.22

return conductor (RC)

conductor attached to the overhead line equipment supporting structures, generally at the side of the track, and which carries traction return current.

NOTE 2: A return conductor should always be mounted on insulators. If not, it is an aerial earth wire.

3.23

Railway Infrastructure Manager

company operating the railway infrastructure (traction network)

3.23

section

length of overhead line equipment between two sectioning railway distribution sites

3.24

supply return conductor

conductor between the **EHV supply transforme**r and the return current busbar at the feeder station.

3.25

track circuit

electrical circuit formed partly by the running rails and employed for indicating the presence of trains and for controlling signalling.

3.26

track sectioning site

railway distribution site which contains electrical switchgear and equipment, and at which separate electrical sections of overhead line equipment are connected

NOTE: may be termed “track sectioning cabins”, or TSCs, where the site is an indoor substation. For outdoor sites, or as a generic term, they are known as “track sectioning sites”, or TSSs.

3.27
traction return rail
designated running rail, carrying traction return current and to which traction and structure bonds are connected

NOTE: It is also connected to the return current busbar at every railway distribution site.

3.28
transformer station
site containing the **EHV supply transformers** and associated switchgear.

4 Railway systems

4.1 General

Railway traction power supplies are provided at intervals along a railway, based upon required traction power demand, available capacity, resilience of railway route traction power supplies and availability of connection opportunities. Depending upon these factors, supply points to railway feed distances of between 20 km to 100 km.

In order to provide the required level of availability, it is normal for each supply point to be provided with two circuits, each of which is capable of supplying the full traction demand. Occasionally, where alternative traction power is available, the traction power system design may require only one circuit. Similarly, in areas of high capacity, resilience requirements may demand three circuits. This is undertaken by the Railway Infrastructure Manager as part of the traction power system design.

4.2 Railway 25 kV System Feeding Arrangements

4.2.1 1 × 25 kV arrangement

A typical 25 kV system outgoing circuit configuration is shown in Figure 2. 25 kV single-phase supplies are received by Railway Infrastructure Manager at the feeder station, from which connections are provided to the railway overhead line equipment. Each incoming supply has its own circuit-breaker on the feeder station 25 kV busbar, and typically two outgoing circuits breakers are aligned with a single track, each feeding in opposite directions. The two incoming circuits are generally derived from different phase pairs of the three-phase system. Even where this is not the case, supplies are not generally paralleled.

Each circuit feeds the railway to a mid-point track sectioning site (MPTSS), at which neutral sections are provided to give electrical phase separation to the next feeder section. Between the feeder station and the mid-point site, intermediate track sectioning sites (TSSs) are added to give additional sectioning. These do not always require bus section circuit breakers, and may sometimes be provided with load-breaking disconnectors instead of circuit breakers, dependent upon the design of the protection scheme. This reduction in circuit breakers permits rationalisation of the distribution sites to simpler configurations.

Where mid-point and intermediate track sectioning sites are installed with indoor switchgear, the term “cabin” is often used to clarify this, and so the terms mid-point track sectioning cabin (MPTSC) and track sectioning cabin (TSC) are often used for such sites.

Historically, the system fault level for ‘classic’ 1 x 25 kV arrangement was limited to 6 kA. However, advances in system analysis and signalling equipment design since the 1980s have permitted the more standard 12 kA fault level to be adopted in some areas. The fault level is controlled through the design of the EHV supply transformer, or through the use of additional fault limiting reactors in series with the 25 kV winding of the EHV supply transformer.

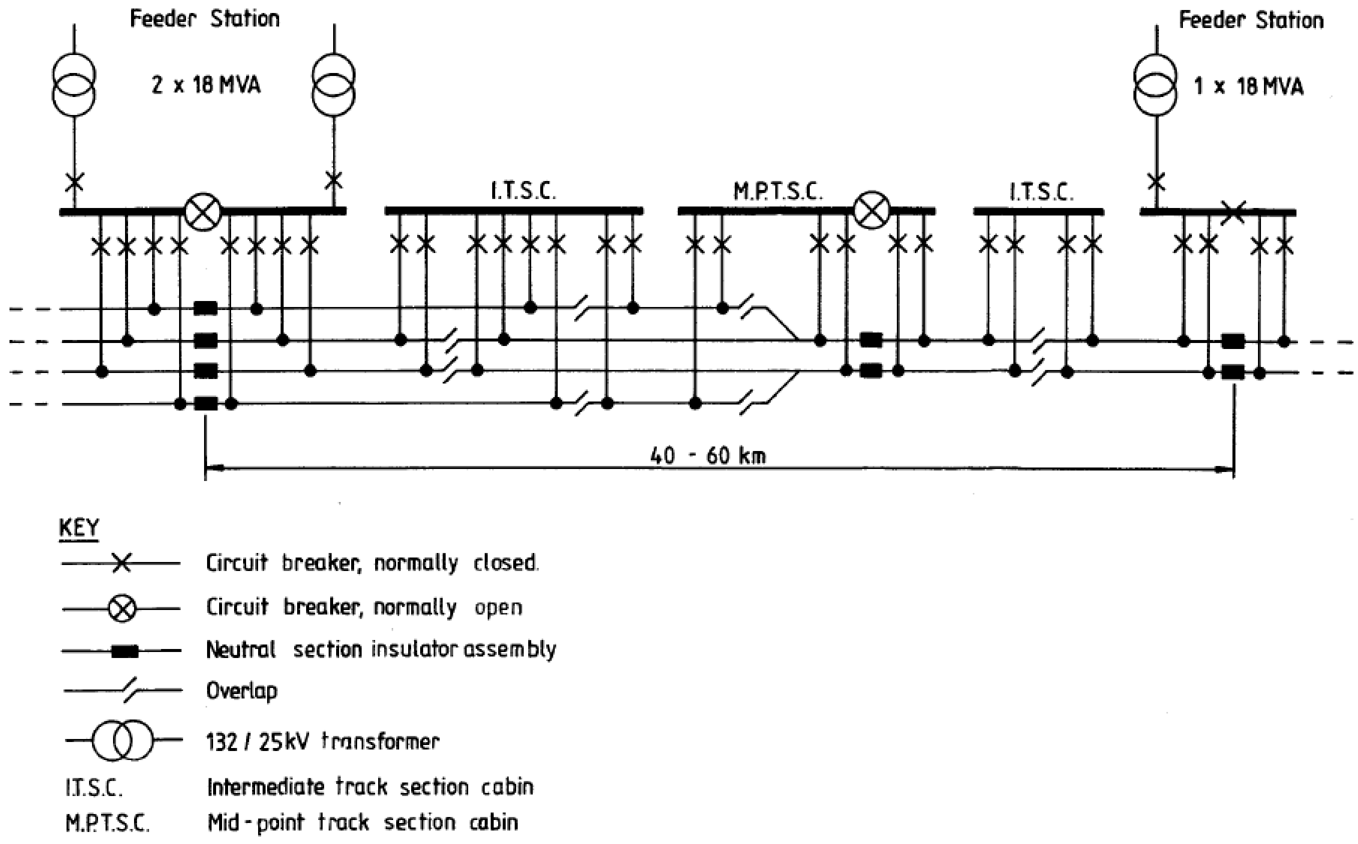


Figure 2 — Typical 25 kV traction network feeding arrangement using 1 × 25 kV transformers

4.2.2 2 × 25 kV arrangement

A typical autotransformer 25 kV system configuration is shown in Figure 5. 25 kV-0-25 kV (split-phase) supplies are provided at the feeder station, which for this configuration is normally known as an autotransformer feeder station, or ATFS. These supplies are normally derived from a purpose-designed three-winding EHV supply transformer, used to supply both 25 kV phases and control fault levels in the same way as the classic EHV supply transformer. As for the 'classic' 1 x 25 kV arrangement, the incoming circuits are normally derived from separate phase pairs of the three-phase system.

Supplies to the overhead line equipment are taken from a double-pole distribution system, with catenary and contact wire system being derived from the +25 kV, or "C" pole busbar, and the wire being derived from the −25 kV, or "A" pole busbar.

Each circuit feeds to a mid-point autotransformer site (MPATS), which provides sectioning of both the track feeders and feeder wire, and acts to separate feeding sections as for the 'classic' 1 x 25 kV arrangement. Sectioning autotransformer sites (SATS) may also be provided to give additional sectioning, replicating the action of track sectioning sites in the 'classic' 1 x 25 kV arrangement. Additionally, intermediate autotransformer sites (ATS) may be provided without sectioning, and it is possible for these to be rationalised to utilise only load-break disconnectors in the same way as the rationalisation of the 'classic' 1 x 25 kV system. This reduces the switchgear requirement which would be associated with a fully-sectioned autotransformer system.

4.2.3 Normal Operation

Under normal feeding conditions, the two incoming circuits feed the railway in opposite directions, although each is capable of feeding the full geographic area covered by the feeder station. A neutral section is provided in each overhead line at the feeder station.

4.2.4 Emergency Operation

In the event of loss of a single incoming circuit, due to fault or maintenance outages, the Railway Infrastructure Manager will close the bus section circuit breaker at the feeder station to permit the remaining circuit to feed both busbar sections. This is known as "first emergency" feeding, and the railway system is expected to operate a normal service under these N−1 outage conditions.

In the event of loss of the second incoming circuit, the Railway Infrastructure Manager will close the bus section circuit breakers at the mid-point sectioning sites and open the feeder station bus section breaker, so that each adjacent feeder station now feeds up to the feeder station under outage, and this becomes the emergency mid-point. This is known as "second emergency" feeding, and may have an impact on train performance and system capacity.

4.2.5 Electrical Control Arrangements

Railway traction system 25 kV switchgear operates under the control of an Electrical Control Operator (ECO) who is able, by means of a remote Supervisory Control and Data Acquisition (SCADA) system, to operate all the circuit-breakers, remote-controlled disconnectors and remote-controlled earth switches in the traction power system. The operation of switchgear on incoming circuits, in liaison with the Electricity Network Operator, is subject to the operational requirements described in ENA ER G38 [N7].

The operation of manual disconnectors and manual earth switches is restricted to authorised personnel working to the instruction of the ECO. The position of all circuit-breakers, remote-controlled disconnectors, and remote-controlled earth switches is indicated by the SCADA system within the Railway Infrastructure Manager Electrical Control Room (ECR).

4.3 Electric Train Characteristics

Each electric locomotive and multiple-unit collects current from the contact wire of the railway overhead line equipment by means of a pantograph which, via a circuit-breaker, is then connected to the high voltage terminal of the converter transformer primary winding. The other end of the primary winding is arranged to return the current through the wheels of the electric locomotive or multiple-unit to the traction return rail. Historically, only one of the running rails of the track concerned was used for this function, known as single-rail return, but with modern signalling systems it is now normal for both running rails to be available for traction return (double-rail return).

Electric locomotives and multiple-units introduced before the 1980s generally used d.c. traction motors. Converters for the d.c. traction supply were initially solidstate rectifiers with voltage control provided by mechanical tap-changers, but during the 1980s thyristor control, usually in a two-stage series-bridge arrangement, replaced the tap-changer. Further advancement in the late 1980s led to the use of the a.c. synchronous drive instead of the d.c. motor, in addition to the replacement of relatively slow thyristor control with fast transistor technology. Clause 8 of this document provides more detailed description of the drive technology.

4.4 Regenerative braking

Modern traction drives almost universally utilise pulse-width modulated (PWM) inverter circuits, and induction motors. Traction converters of this type are capable of operation in all four quadrants of operation, covering both directions of motor control and both motoring and generation and so are normally configured to provide a level of braking, and regeneration of kinetic energy into the traction power system.

Generally, the PWM switching strategy remains the same for all quadrants, and hence there is little change in the harmonic profile of the traction current for regenerative braking in comparison with that for motoring. Whilst modern traction drives are highly efficient, generally operating with less than 10% loss, this loss nevertheless has an impact on regenerative energy production. Due to this, the maximum regenerative braking current of a train will normally be less than the maximum tractive (motoring) current.

Regenerative braking energy is generally absorbed by other trains on the 25 kV section, but in the event that the section does not contain a motoring train, the surplus regenerated power flows back through the feeder station and grid supply point. However, this surplus power flow should not constitute a requirement for export metering.

As part of the initial introduction of regenerative braking, attention was given to regenerative under-reach, in which the regenerating current acts to reduce fault in-feed at a supply point, and therefore causes under-reach of distance protection on the traction system overhead line feeders. The effect of regeneration is to shift the locus of the fault impedance at the relay, with the risk that this shift is sufficient to move the locus outside the tripping zone. For modern protection relays or IEDs, with polygonal reach characteristics, this impedance locus shift is generally insufficient to cause an under-reach problem, but nevertheless this may be analysed. Notwithstanding this, the relevant standard for traction systems, BS EN 50388 requires a train which is regenerating into an overhead line fault to have the capability to detect a line short-circuit fault and disable regenerative braking. This is done in order to prevent regenerative under-reach.

5 Types of supply point

5.1 General

In principle it is possible to connect railway supply points at any voltage between 33 kV and 400 kV via a transformer with a 25 kV LV winding. The need to limit supply system disturbances usually requires connection at 132 kV or a higher voltage level. A feasibility study (see Figure 1) undertaken with the guidance in this document will provide determination of the availability and cost of suitable connection points and hence, dictate the connection voltage.

There are two established types of supply point arrangement, described as follows.

a) 1 x 25 kV arrangement — predominately utilised for 132 kV connections

b) 2 x 25 kV — predominately utilised for 275/400 kV connections

The above two arrangements can be used at any supply voltage and both arrangements use a single-phase transformer supply which is connected between two phases of the Electricity Network Operator three phase network. Normally, both transformers at a supply point would not be connected across the same pair of phases in order to minimise voltage unbalance. Where possible, the phase pairs used should be rotated along the route of the railway. This ensures that when a transformer is out of service, the units on either side (which are now electrically adjacent) will not be connected to the same phase pair.

Where it has been assessed that a railway transformer supply arrangement is unsuitable due to unbalance and disturbance issues, the options for phase balancing may be investigated as described in Clause 9, otherwise an alternative supply point or connection arrangement may be considered.

The alternative, to the established supply point arrangements described above, is to employ a special transformer unit or to incorporate power electronics. In these circumstances the Railway Infrastructure Manager would specify, own and operate such equipment and the Electricity Network Operator would provide a standard three-phase metering circuit breaker connection, unless otherwise agreed. Further detail of the possible options is described in Annex A and Annex B, as briefly listed below.

a) Scott transformer connection (see Annex A.1).

b) Transformer connection incorporating power electronics (see Annex A.2).

c) Static Frequency Converter (see Annex B).

5.1.1 1 × 25 kV arrangement

A typical 1 × 25 kV arrangement is described in Figure 3. On the secondary side of the EHV/25 kV transformer, one terminal (normally termed the “C” pole) is connected to the 25 kV catenary busbar from which the railway overhead line equipment (OLE) is fed. The other secondary winding terminal is connected to the return current busbar (RCBB) of the feeder station, to which the traction current is returned from those rails which carry traction return current (traction rails) and return conductors where installed.

The traction return rails are bonded to the railway overhead line support structures as well as being cross-bonded at intervals, thereby forming a distributed earthing system which combines the rail to earth leakage conductance, structure to earth conductance and the designed value of the feeder station and grid supply point earthing system. The traction return rails are directly connected to the feeder station return current busbar.

In the simplest case of a rail return system, the return current flows to the feeder station return current busbar only via the traction return rails. This not only results in voltage rise in the running rail with respect to earth, but where line-side metallic signalling and telecommunications circuits are in used this can cause induced voltages in these adjacent circuits.

In order to reduce the effects of rail current, additional return conductors may be used, and for existing electrified routes these may been supplemented with booster transformers.

Booster transformers are structure-mounted 1:1 transformers, connected so that the contact system current is balanced by current in the associated return conductor, and installed at 2 mile (3.2 km) intervals as shown in Figure 4.

The use of booster transformers with unswitched return conductors is no longer permissible for new installations, and the complexity of providing switched return conductors means that new classic systems are generally ‘boosterless’ return conductor systems, utilising return screening conductors for induction suppression.

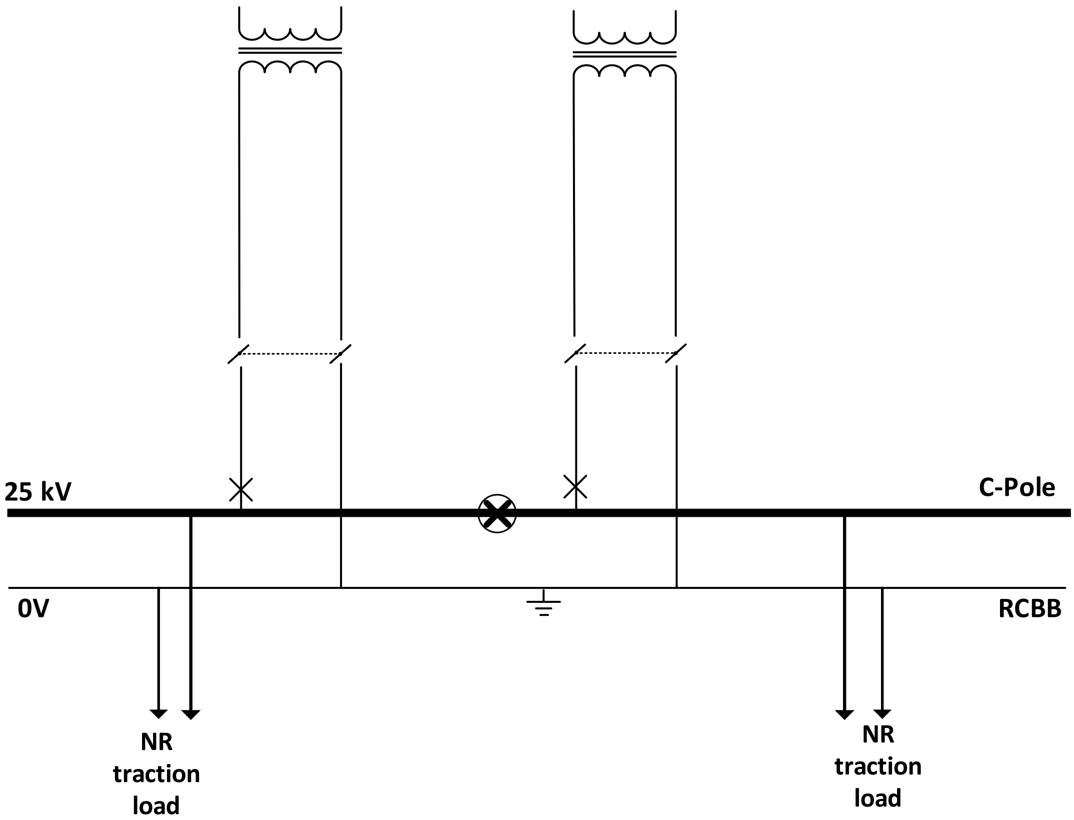


Figure 3 — 1 × 25 kV railway feeder configuration

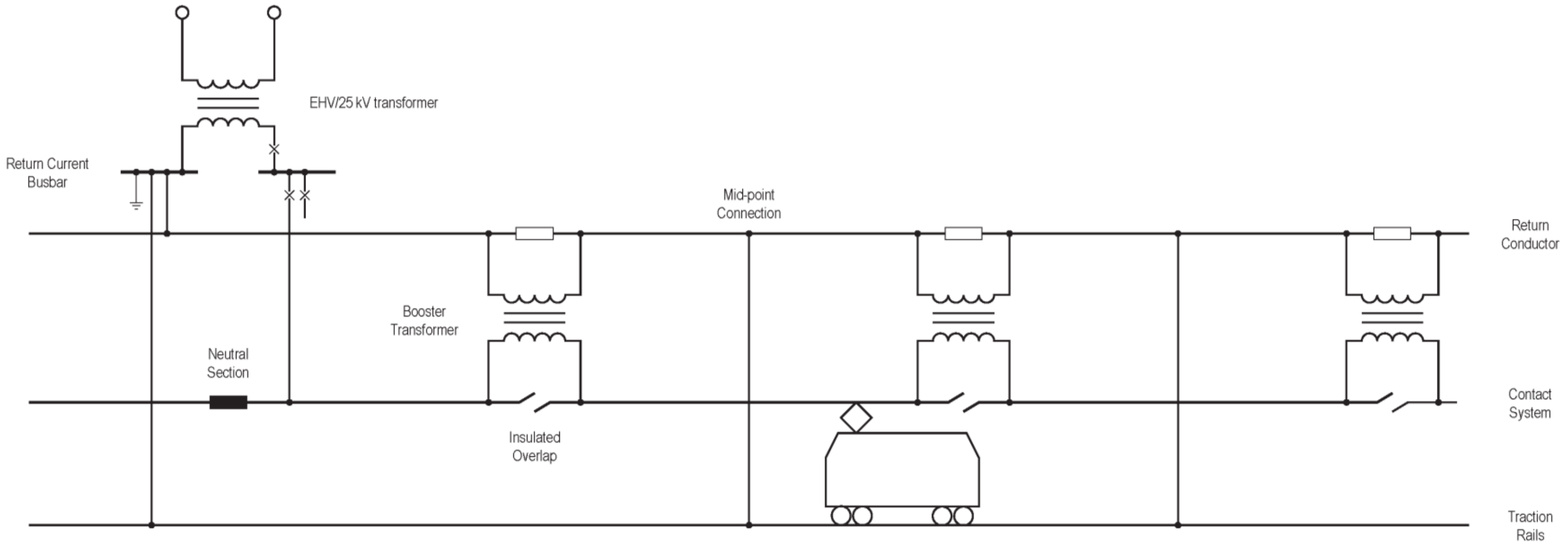


Figure 4 — Use of booster transformers on a 1 × 25 kV supply system

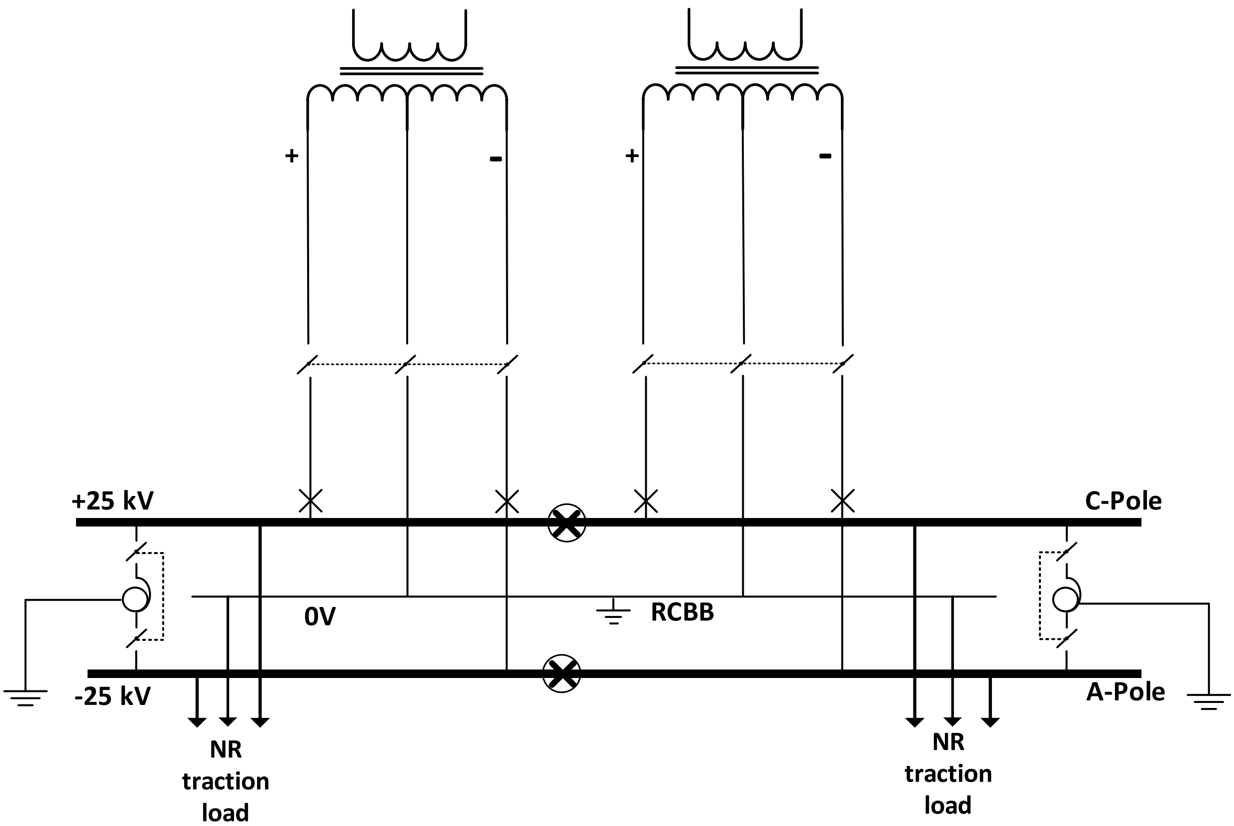
5.1.2 2 x 25 kV arrangement

A typical 2 x 25 kV autotransformer (ATFS) arrangement is depicted in Figure 5 and Figure 6. The system provides +25 kV and −25 kV terminals (normally termed the “C” pole and “A” pole respectively) as well as the neutral connection. The normal voltage across the +25 kV and −25 kV poles is 50 kV, such that the system is able to distribute traction power at 50 kV.

The ‘C’ pole is connected to the +25 kV busbar from which the railway overhead line equipment (OLE) is fed. The ‘A’ pole is connected to the -25 kV busbar to which the feeder wires are connected. The neutral is connected to the return current busbar (RCBB).

Regularly spaced autotransformers, typically located at sites 10 km apart, are used to step down the 50 kV distribution to a 25 kV supply to the trains. The advantage of using autotransformers for this purpose is that they provide no isolation between HV and LV systems, and so are able to share conductors. This provides an efficient three-conductor feeding arrangement which also acts to divert return current from the traction rail system. Further, given that the autotransformers form shunt connections to the 50 kV system, the voltage drop problem associated with booster transformers in series with the overhead line system is removed.

The neutral current connection to the feeder station is provided to carry 25 kV return current component, associated primarily with train operation in the first autotransformer section from the feeder station. For remote feeding, the system transfers load to 50 kV distribution, and so the feeder station neutral current is reduced.



NOTE: The autotransformers are normally located at feeder stations as depicted, but may also be located at intermediate track sites as depicted in Figure 6.

Figure 5 — 2 x 25 kV railway feeder configuration

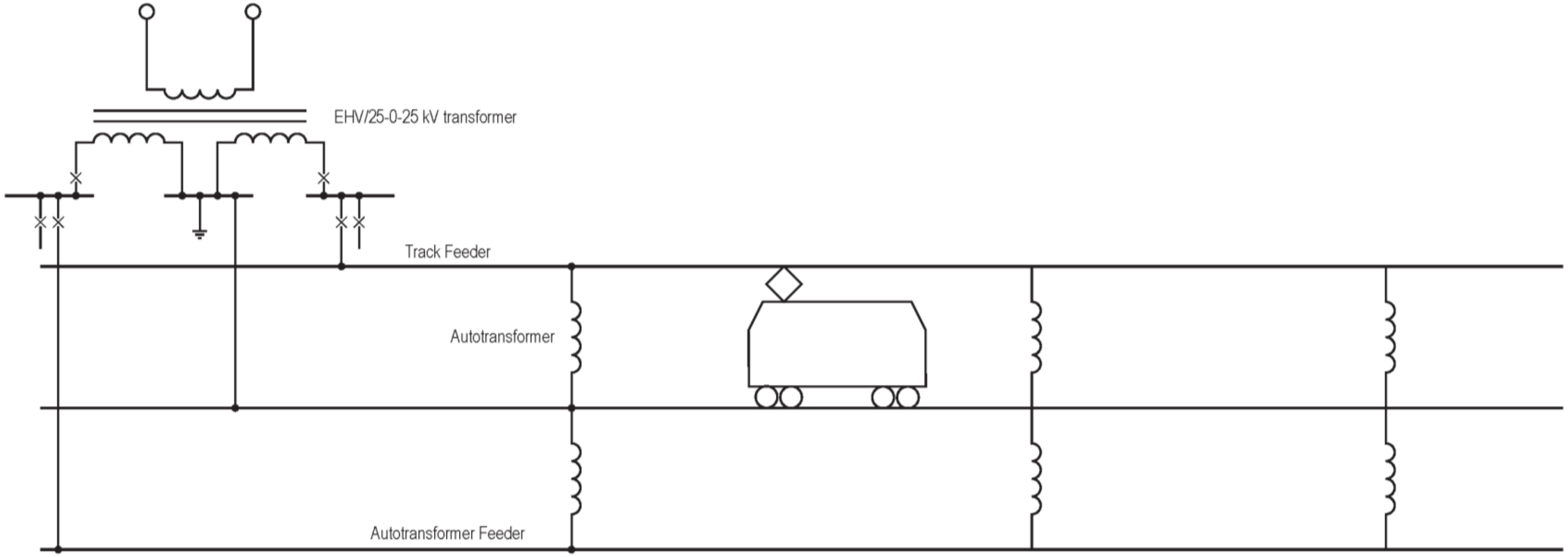


Figure 6 — Railway network for a 2 × 25 kV supply configuration

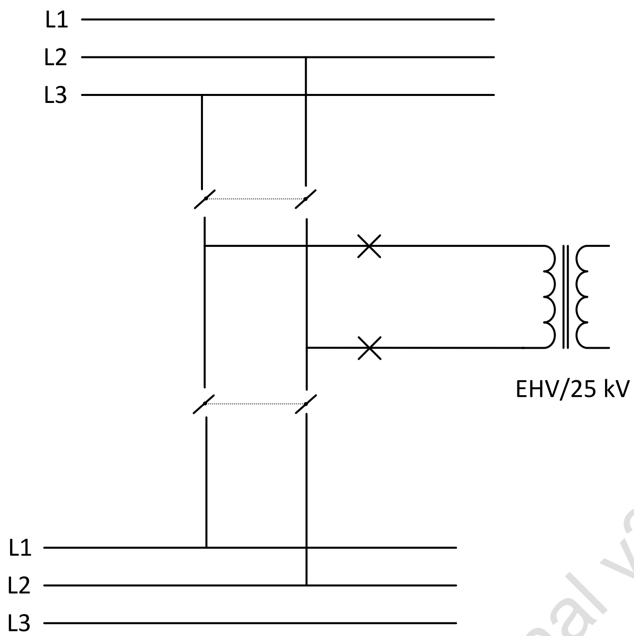
5.2 EHV connections for security of supply

The requirements for security of supply are described in Clause 7.

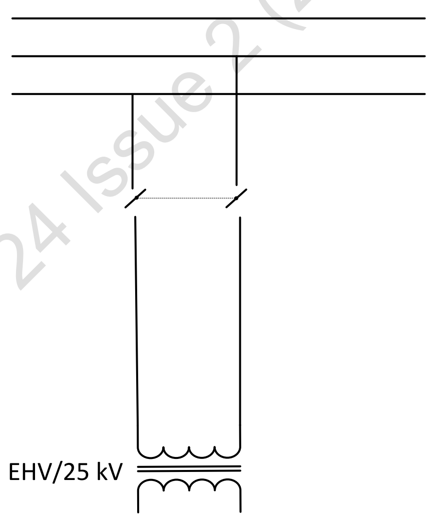
Where practicable, supplies should be derived from a source which has a level of security not less than that afforded by the provision of duplicate fully rated feeders to the railway 25 kV system. Such a level of security would be given by a sectionalised busbar fed from two circuits, or by two separate busbars each independently fed. The circuit feeding the EHV supply transformer would be connected one to each section of busbar and may be banked with other transformers feeding Electricity Network Operator 66 kV, 33 kV, 20 kV, 11 kV or 6.6 kV networks or consumers. Figures 7(c), 7(d) and 7(e) depict typical busbar connections. These arrangements may be preferred to the simple tee-connection, as shown in Figures 7(a) and 7(b), when it can be shown that the enhanced security of supply to Railway Infrastructure Manager is justified either operationally or financially

The required degree of security of supply would also be achieved by tee-connecting the EHV transformer to separate high voltage circuits, cable or overhead (including two circuits on the same tower). Typical tee-connections are depicted in Figures 7(a) and 7(b). These briefly show a transformer switched directly on a busbar, Figure 7(a), and a tee-connection to an overhead line, Figure 7(b).

The disconnectors shown in Figure 7(b) are invariably motorised so that the EHV circuit can be restored to service following a fault on the tee-connected circuit. By installing a switching disconnector instead of the conventional motorised disconnector, it may be possible to make a tee-connection which would otherwise be operationally unacceptable.

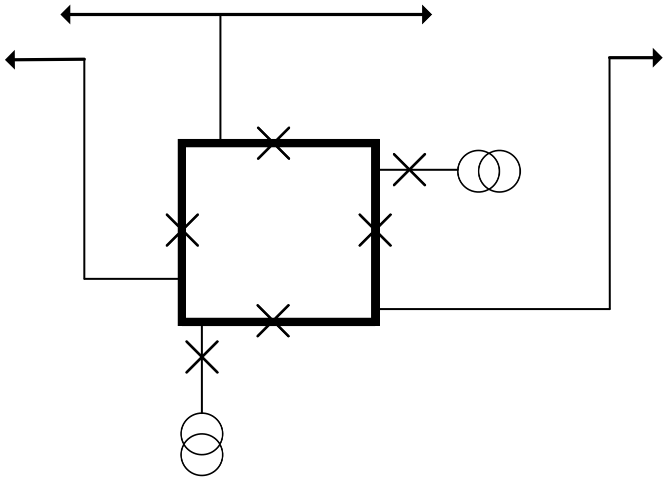


a) Transformer switched on an EHV busbar

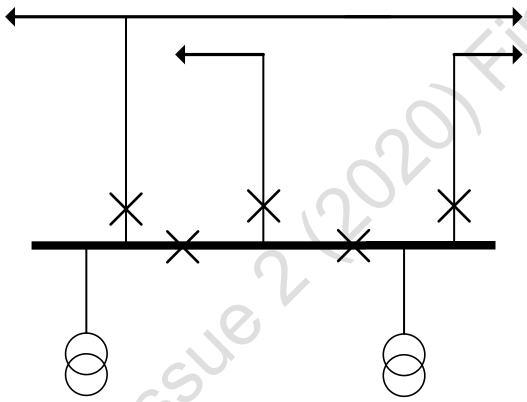


b) Transformer teed to an EHV overhead circuit

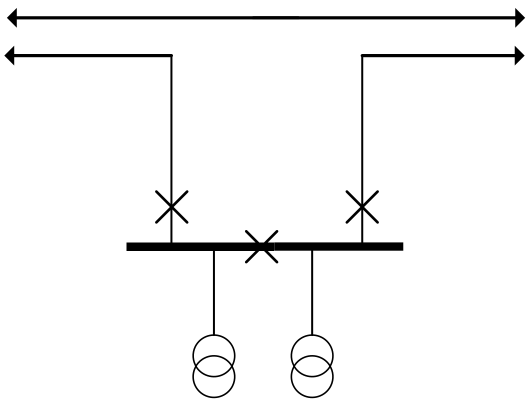
Figure 7 (a) and (b) — Typical teed connections for 25 kV supplies



c) Mesh corner connection for traction supply



d) Simplified alternative to mesh corner



e) Traction supply connected to an EHV double busbar

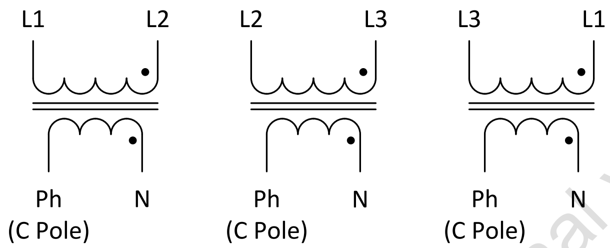
Figure 7 (c), (d) and (e) — Typical busbar connection for 25 kV supplies

5.3 25 kV connection overview

5.3.1 General

5.3.1.1 1 x 25 kV arrangement

To avoid imposing voltages greater than √3*25 kV across the circuit-breakers during normal or emergency feeding, the supply return conductor must be connected in one of the three combinations described in Figure 8.



NOTE: L1 = brown/red, L2 = black/yellow, L3 = grey/blue

Figure 8 – Supply return conductor connection combinations for a 1 x 25 kV arrangement

Figure 9 shows the typical principal connections between the EHV/25 kV transformers and the railway feeder stations, together with the 25 kV busbar and RCBB at the feeder stations.

Circuit-breaker XXXX/F1 should be employed for all arrangements. Circuit-breakers *E0 and *T0 are discretionary, as explained in Clause 5.3.2.

NOTE: Circuit-breaker nomenclature for T or E is dependent on the circuit number. The circuit-breaker controlled by the Railway Infrastructure Manager is dependent on the site identification 'XXXX'.

The responsibility boundary (see Clause 5.4) is typically within the disconnector compound, at which point only, there is a requirement for joint agreements on operational rules and identification standards between the Electricity Network Operator and the Railway Infrastructure Manager.

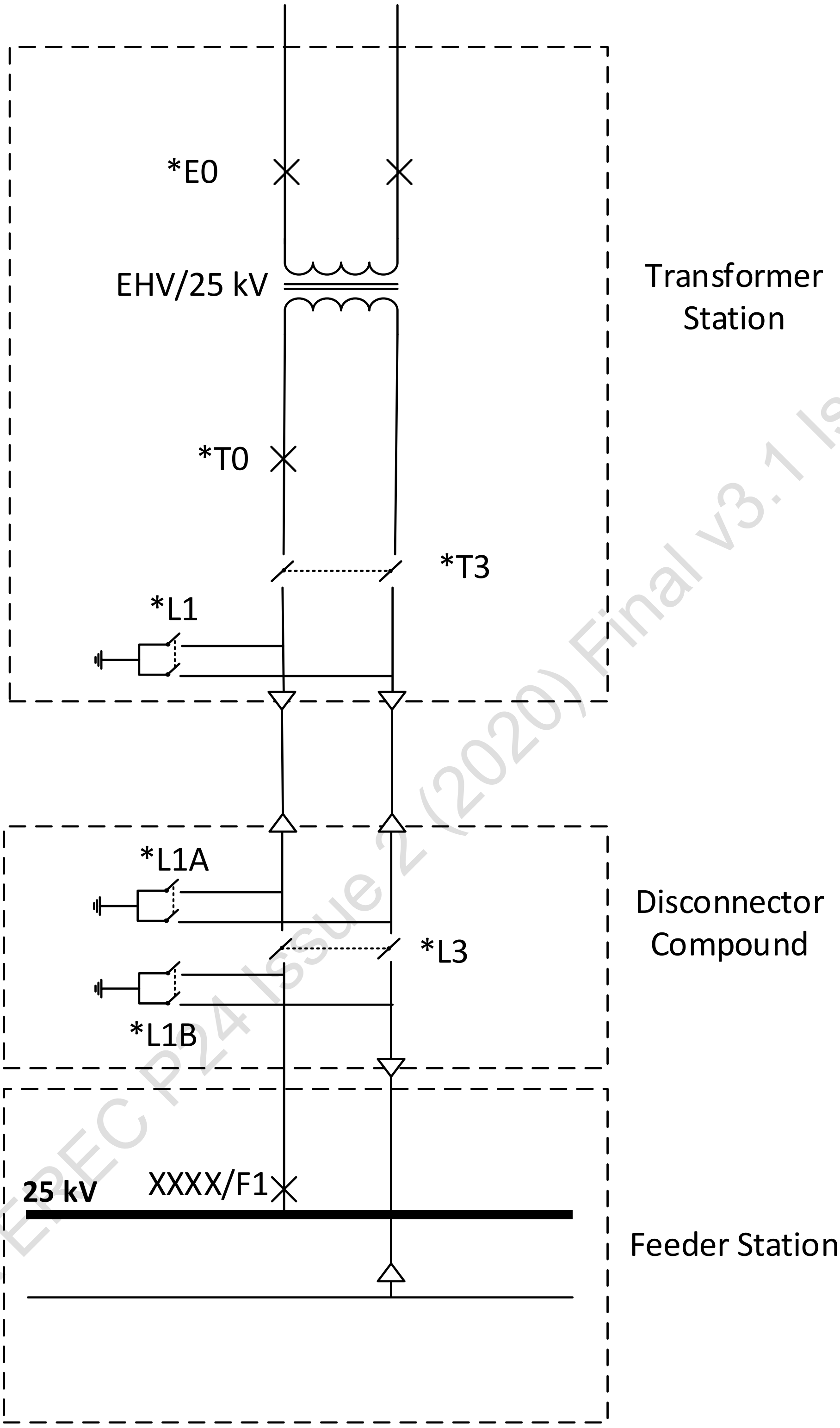
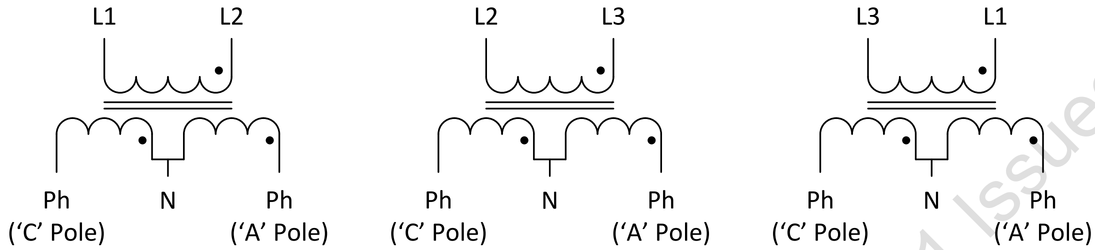


Figure 9 — 1 x 25 kV connection arrangement

5.3.1.2 2 x 25 kV arrangement

The supply return conductor must be connected in one of the three combinations described in Figure 10.



NOTE: L1 = brown/red, L2 = black/yellow, L3 = grey/blue

Figure 10 – Supply return conductor connection combinations for a 2 x 25 kV arrangement

Figure 11 shows the typical principal connections between the EHV/25-0-25 kV transformer and the railway feeder stations.

Circuit-breaker XXXX/F1 should be employed for all arrangements. Circuit-breakers *E0 and *T0 are discretionary, as explained in Clause 5.3.2.

The responsibility boundary (see Clause 5.4) is typically within the disconnector compound, at which point only, there is a requirement for joint agreements on operational rules and identification standards between the Electricity Network Operator and the Railway Infrastructure Manager.

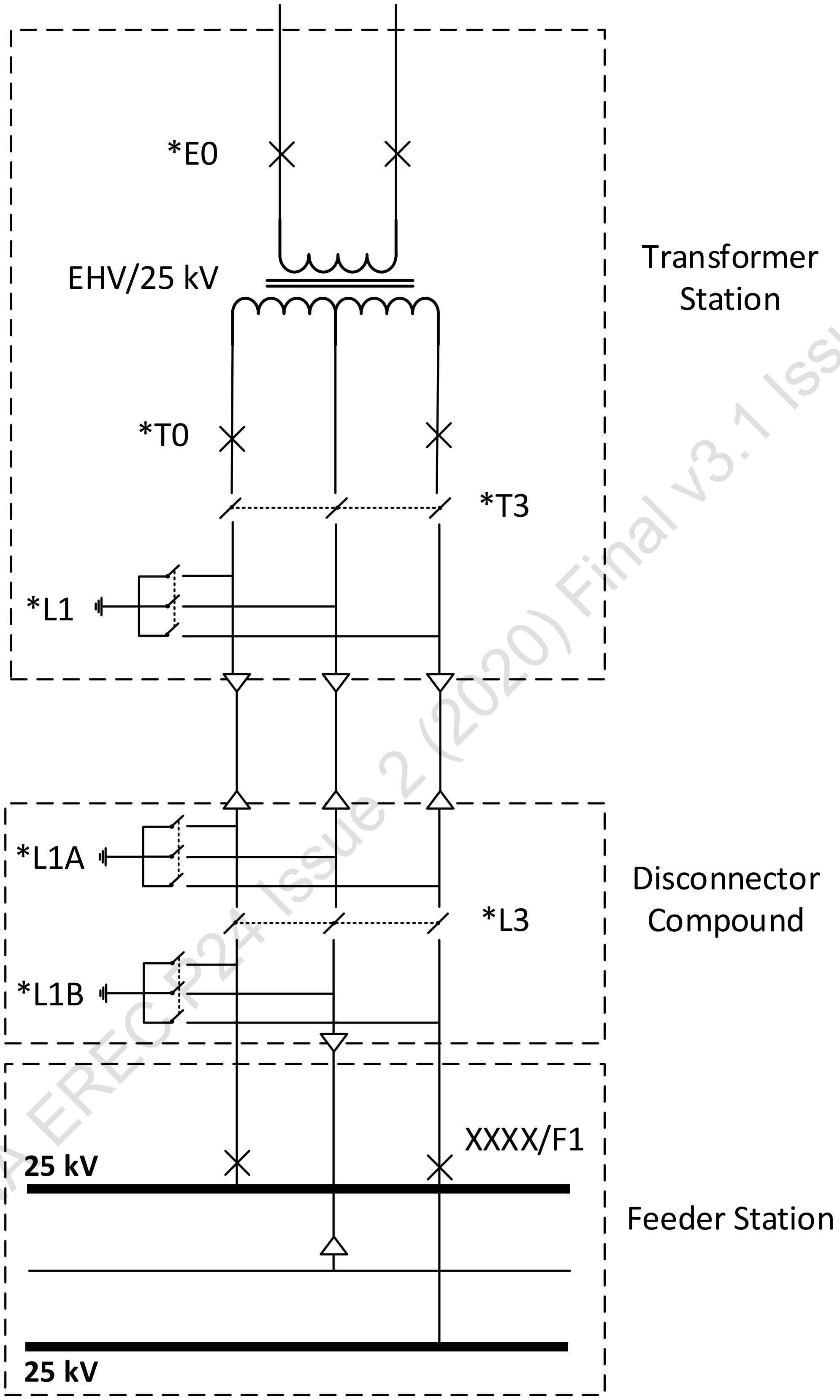


Figure 11 — 2 x 25 kV connection arrangement

5.3.2 25kV circuit-breaker function

A circuit-breaker, XXXX/F1, and associated disconnector, *L3, are required on the 25 kV circuits at the railway feeder station as shown in Figures 9 and 11. The circuit disconnector allows work to be undertaken on the incoming circuit-breaker and the associated section of busbar without requiring the operation of any transformer or line disconnector.

A 25 kV circuit-breaker, *T0, may be provided at the transforming substation where:

a) the absence of such a circuit-breaker to clear faults on the 25 kV circuit between the EHV supply transformer and the feeder station would give rise to an unacceptable risk to the security of supplies to other consumers, connected or teed to the same EHV circuit and/ or

b) the establishment of a Railway Infrastructure Manager supply point by tee-connecting to an existing EHV circuit would otherwise contravene the Electricity Network Operator design policy.

In relation to item a) above, the Electricity Network Operator must satisfy Electricity Safety, Quality and Continuity Regulations 2002 (ESQCR) [N1], Regulation 23; which requires a distributor to ensure that their network is so arranged and so provided with automatic switching devices as to restrict, so far as is reasonably practicable, the number of consumers affected by any fault on their network.

5.3.3 Disconnectors and associated earthing switches function

The function of the disconnector is:

a) for isolation of the EHV supply transformer from the 25 kV system for maintenance purposes without requiring the operation of any disconnector at the feeder station;

b) to ensure that current returning to a transformer still in service (at a two transformer supply point) does not use the supply return conductor of a transformer out of service for maintenance;

c) for isolation of the 25 kV circuit between the transforming station and the remote disconnector compound, without requiring the operation of any disconnector on the high voltage side of the supply transformer.

These disconnectors are fitted with earthing switches on the line side.

Where the transformer station is remote from the feeder station a 25 kV line disconnector of the ganged type, fitted with earthing switches on both sides, is provided in a remote disconnector compound. This allows for isolation of the incoming 25 kV cable or overhead line circuit for maintenance purposes without requiring the operation of any disconnector in the feeder station, thereby obviating the need for Railway Infrastructure Manager personnel presence. The disconnector compound may not be required if the transformer station is local to the feeder station.

5.3.4 Interlocking

The equipment nomenclature denoted in Figure 9 and Figure 11 should be used, unless the equipment is wholly within the Railway Infrastructure Manager responsibility boundary.

Interlocking shall satisfy the following requirements.

- Interlocking shall prevent disconnectors being operated unless the adjacent circuit breakers are open.
- Interlocking shall prevent operation of earthing switches unless the adjacent disconnectors are open.
- At the feeder station, interlocking shall prevent the paralleling of two or more incoming supplies through the, feeder station circuit-breakers (incoming and bus-section circuit-breaker), and bus-sections at mid-point sectioning stations.

The following interlocking technologies should be considered.

a) Mechanical interlocking is acceptable but should be avoided when possible for remote sites.

b) Electrical interlocking is acceptable. The security of the interlocking supply should meet the following minimum requirements.

   – The supply shall be taken from a substation battery or other secure d.c. source.

   – The supply shall be separately fused so as to be maintained during circuit outage conditions unless isolated as part of an operational procedure.

   – If the supplies are taken outside of the substation environment where the d.c. source is located, it shall be monitored and a SCADA alarm provided to highlight a failure.

   In all cases, the scheme will fail safe so that, should the supply be interrupted, it is not possible to defeat the interlock.

Software interlocking is not permitted, except by express agreement of both the Electricity Network Operator and Railway Infrastructure Manager. Where software interlocking is employed, responsibility and accountability for the functional safety of a programmable electronic safety related system (i.e. compliance with BS EN 61508) shall be agreed between the Electricity Network Operator and Railway Infrastructure Manager.

Clause 15 describes the information communication between the Electricity Network Operator and the Railway Infrastructure Manager.

5.3.5 25 kV circuit between the grid supply point and the disconnector compound

5.3.5.1 General

As previously described in Clause 5.1.1 and 5.1.2, the 1 x 25 kV and 2 x 25 kV arrangements employ differing conductor arrangements for the 25 kV circuit. The use of the autotransformer in 2 x 25 kV arrangements has the affect of considerably reducing return current via the earth path, in comparison to the 1 x 25 kV arrangement. None-the-less, there are a number of common considerations for reduction of earth path return current.

Even though the return current is reduced in the 2 x 25 kV system, it is not a fully balanced system, and trains require a neutral return.

For overhead line arrangements of the 2 x 25 kV system it would be expected that a standard three-conductor arrangement would be provided which includes a neutral conductor.

Although an overhead 25 kV circuit can be employed, the ratio of the loop impedance of the 25 kV conductor/earth return path to that of the 25 kV conductor/return current conductor may not be large enough to prevent a significant proportion of the traction current returning via earth.

The use of 25 kV underground cable has the advantage that traction return current via earth is much less than for corresponding lengths of overhead line.

1 x 25 kV system connections generally utilise a concentric cable with an outer neutral conductor, separate from the earth screen. A dedicated neutral in the form of a standard 11 kV cable is an alternative option. 2 x 25 kV connections include dedicated neutral cables, utilising standard 11 kV cable, and forming a close trefoil with the two phase cables.

An explanation of the considerations for earth return currents and cable bonding is provided in Clause 13.2.3.

Should topographical and/or financial considerations dictate that a 25 kV overhead line be established, traction earth return current should be analysed as described in Clause 5.3.5.2.

5.3.5.2 Return current path

Earth return currents can be excessive if transforming stations and feeder stations are non-adjacent. In particular, the high impedance of the return path of overhead circuits, as compared with underground cables, may increase the flow of traction return current via earth. One way of overcoming this problem is to locate the transformers in compounds adjacent to the feeder stations. This could be achieved by laying 132 kV cabled circuits from the nearest convenient source of supply. However, the co-location of the transformer station and feeder station could introduce earthing difficulties (refer to Clause 13).

In previous traction supply arrangements, it was common to install or allow space provision for the installation of a supply booster transformer at the 132/25 kV transformer station. This practice was based on the limitations of predicting earth return currents at the time and hence a supply booster transformer was means to avoid a potential problem.

The connection of supply booster transformers at transformer stations encourages return current to flow via the neutral conductor as opposed to via earth. The drawbacks of using a supply booster transformers include: the increase cost of connection of supply; a small detrimental effect on reliability of supply, and a marginal increase in voltage regulation requirements.

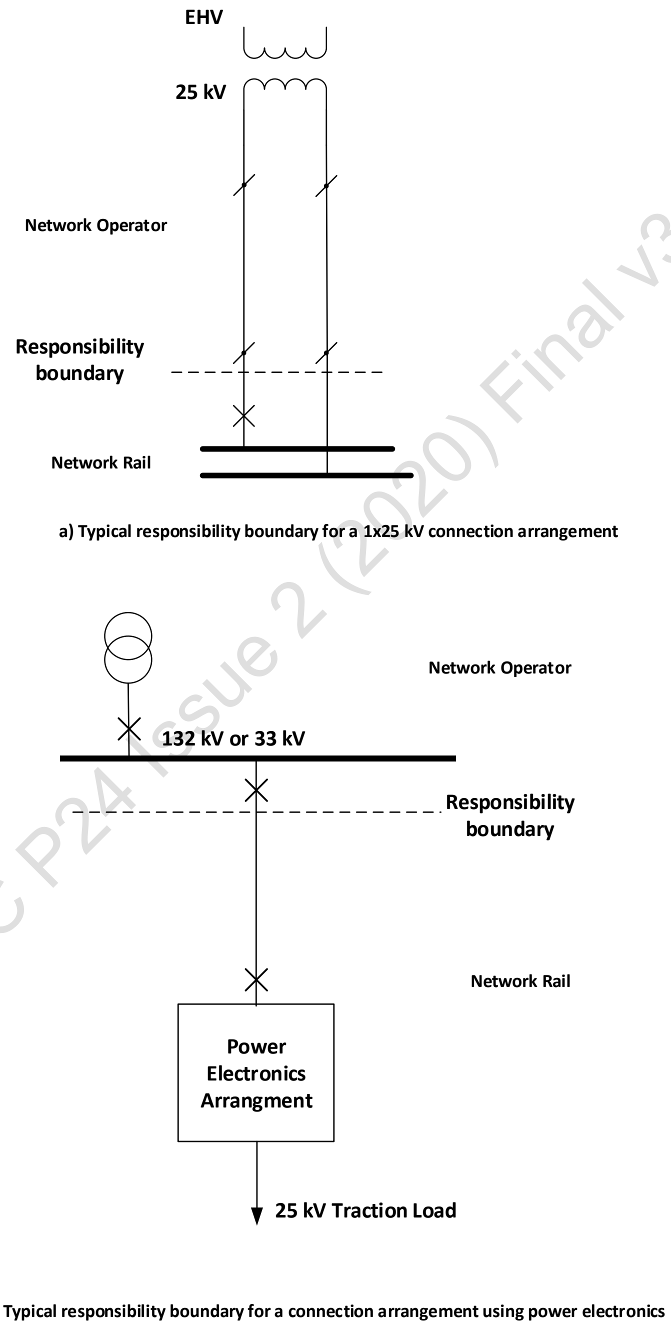
During the design and planning stage, a detailed analysis of the currents in the earth path should be conducted.

In exceptional cases a supply booster transformer may be considered to reduce excessive earth currents, subject to agreement between the Electricity Network Operator and Railway Infrastructure Manager.

5.4 Responsibility boundary

Responsibility of equipment for the 25 kV supply shall be in accordance with the Site Responsibility Schedule between the Electricity Network Operator and Railway Infrastructure Manager. The responsibilities will generally include ownership, maintenance and operation.

Typical responsibility boundaries between the Electricity Network Operator and Railway Infrastructure Manager are shown in Figure 12.



a) Typical responsibility boundary for a 1x25 kV connection arrangement

b) Typical responsibility boundary for a connection arrangement using power electronics

Figure 12 — Typical responsibility boundaries for different supply arrangements

6 Load estimating

6.1 General

This section describes the level of information to be made available to the Electricity Network Operator by Railway Infrastructure Manager at various stages of an electrification scheme.

Modern traction demand modelling is based on sophisticated railway simulation tools. For use on the GB railway network, such tools must conform to the validation standards of British Standard BS EN 50641. This provides a validation governance structure for traction design models across the European Union, and is part of meeting the technical requirements for interoperability across European rail networks.

Traction demand forecasting is part of the strategic development of the railway network, and is generally documented by the Railway Infrastructure Manager e.g. Traction Power System Strategy (TPSS). A typical strategy covers demand and capacity on a single route, or a regional area.

6.2 Preliminary information

Initial demand modelling is undertaken to evaluate existing traction capacity margins against forecast traffic requirements. This provides confirmation of capacity, or else provides peak half-hour demands which can be provided to evaluate the feasibility of new connections – the focus being predominately on the electricity network thermal capacity and voltage unbalance. At this stage, the Railway Infrastructure Manager will produce peak demand values for a number of connection options, and work closely with the Electricity Network Operator on an initial compliance assessment.

6.3 Design stage

Once a connection option is established, more detailed demand modelling is undertaken, from which the Railway Infrastructure Manager can provide 1 minute and 30 minute demand profiles. These are usually based upon the morning peak traffic level, nominally between 0600 and 0900, and reflect the period of maximum demand on the traction power system. The demand profiles produced at this stage are reflective of the maximum capacity required for the network, and so include future strategic demand growth. Additionally, reasonable outage conditions are assessed for both supply and traction networks, so that firm, reserve and conditional supply capacity limits can be established and evaluated.

NOTE: Clause 8.3 describes load flow modelling considerations.

Based upon the detailed strategic demand data, the Railway Infrastructure Manager will work with the Electricity Network Operator to produce additional compliance data. The Railway Infrastructure Manager can produce negative sequence component profiles for a connection based upon assessment of the three-phase system. Alternatively, the Electricity Network Operator may wish to undertake this analysis, which will be supported by the Railway Infrastructure Manager. Additionally, where low order harmonics will be impressed upon a connection, the Railway Infrastructure Manager can provide indicative harmonic profiles for each odd harmonic up to 1 kHz. Additionally, in this phase of analysis, the Railway

Infrastructure Manager will produce detailed rail potential profiles, based upon short-circuit fault conditions and also the strategic demand profile. This is required as part of traction system compliance, and requires earthing details of the connection site from the Electricity Network Operator.

6.4 Timescale

It is normally accepted that a minimum of three years should be allowed for the design, installation and commissioning of a railway transforming station. In practice, every effort is made to give early knowledge of the Railway Infrastructure Manager's long term 25 kV electrification proposals to the Electricity Network Operators.

6.5 Growth forecast and future developments

Beyond development of a new connection, the Railway Infrastructure Manager can provide maximum demand forecasts in line with timetable changes. The national railway timetable changes annually, normally in December, and so indicative predictions of demand growth can be supplied for any notable change. This will normally be presented as a percentage of the strategic demand profile for a connection site. It would normally be expected that demand grows towards the capacity level in accordance with strategic forecasting. To provide a check on this, strategic growth will be re-evaluated every five years.

This process covers feasibility studies, connection compliance assessment and periodic demand forecasting. For individual supplies, traction demand fluctuates with timetable perturbations, passenger and freight load and also with driver action. Nevertheless, by assessing predicted demand and traction capacity margins, this process provides a robust approach for both supply and traction networks.

Where the system design study indicates that any of the disturbance levels approach the limiting value, a consensus between the Electricity Network Operator and the Railway Infrastructure Manager should be established whether there is scope for further increase in load at that point without reinforcement of the supply.

To guard against complaints from other consumers, periodic monitoring of disturbance levels is recommended, particularly where transformers are initially scheduled for operation at less than full load.

7 Standards of security

The following requirements of security are applicable to the connection of 25 kV a.c. railway traction supplies. The requirements are intended as a guide and should be regarded as the broad minimum, but it is recognised that there may be individual cases where relaxation will be justifiable on economic grounds. However, the consent of Railway Infrastructure Manager must be obtained before any relaxation of security can be adopted.

The security standards applicable to each supergrid group from which railway supplies are derived shall be based on those requirements specified in ENA ER P2 [N8]. Account should be taken of the fact that in general the railway demand is independent of season and the daily load pattern is repeated throughout the year.

The Connection Agreement is a long-term contract that establishes a formal relationship between the Electricity Network Operator and their Customer. A site-specific Connection Agreement is normally employed for connections between the Electricity Network Operator and the Railway Infrastructure Manager.

The information contained within the Connection Agreement will include the Reserved Service Capacity, Firm Service Capacity, Conditional Service Capacity and the normal running arrangement for the connection, along with any other details specific to the connection.

The Reserved Service Capacity is the capacity available at a railway supply point to meet the maximum demand under normal operating conditions without allowing for any interruptions in the continuity of supply, either planned or unplanned, and without provision for any emergencies. The Reserved Service Capacity may take account of the load-balancing effect where a railway supply point comprises of two circuits which normally carry load concurrently and which are connected to different phase-pairs.

The Firm Service Capacity is the capacity available at a railway supply point to meet the maximum demand under conditions of single worst-case interruption in the continuity of supply, either planned or unplanned. In the case of a single transformer supply point there is no firm capacity for a transformer outage and the railway load will be transferred to one or more adjacent supply points. Where a railway supply point comprises of two circuits the Firm Service Capacity may be less than the Reserved Service Capacity due to the loss of the load-balancing effect.

The Conditional Service Capacity is the capacity available at a railway supply point to meet the maximum demand under emergency outage conditions, either planned or unplanned, resulting from the loss of an adjacent railway supply point.

In all cases the apparatus in service should be capable of carrying this demand without being overloaded.

The Maximum Import Capacity for each railway supply point should be not less than the ‘conditional service capacity’.

Figures for the reserved, firm and conditional service capacities are the maximum half-hour demands to be declared by Railway Infrastructure Manager as part of their load estimates.

Figure 13 illustrates the demand definitions. The potential maximum demand could result in unequal loading of transformers at a two-transformer supply point. In this event, Railway Infrastructure Manager will split the summated potential maximum demand into two components, one for each transformer.

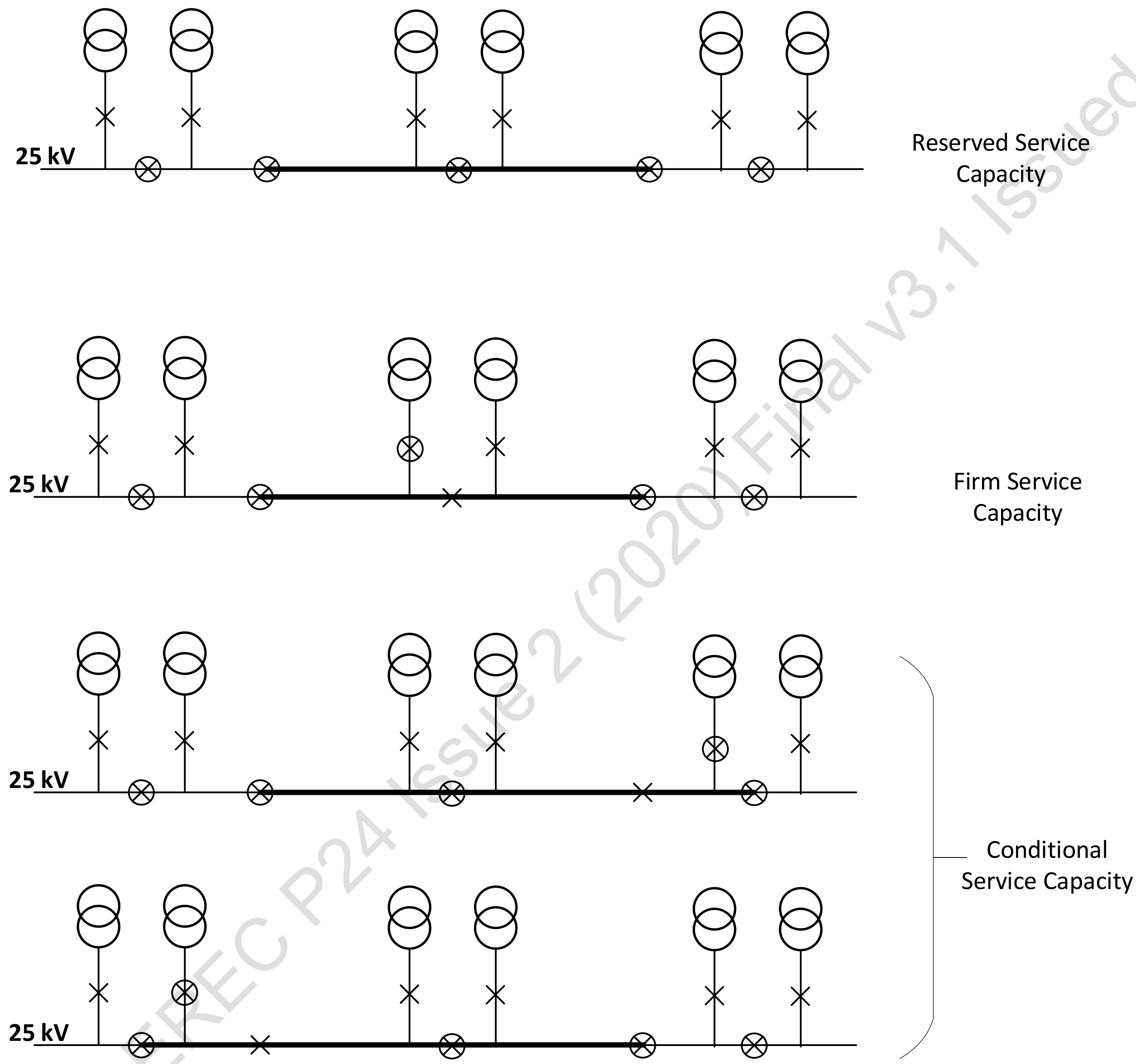


Figure 13 — Illustration of demand demonstrations as applied to normal and emergency feeding.

8 Nature of traction current

Traction loads fluctuate widely in magnitude and to a lesser extent in phase angle and harmonic content. In order to estimate disturbance to other consumers it is necessary to be able to quantify the form of the load current in a manner which will enable a reasonable estimate of maximum disturbance to be obtained. For this it is necessary to be able to define a representative waveform for the traction load as presented at a supply point. The waveshape will be dependent on the type, number and disposition of the locomotive units as well as the operating conditions i.e. acceleration, normal running, coasting and braking. It will also be influenced by the supply circuit parameters.

8.1 Development of traction technology

The history of electric traction is linked with that of the variable speed electric motor drive. These were traditionally based upon the d.c. motor, due to its relatively simple approach for speed control. Consequently, traction drives for 25 kV supplies used either a tapped transformer to supply a rectifier bridge circuit.

Later, in the 1970s, the tapped transformer arrangement was changed to a controlled rectifier, by the introduction of the thyristor. This required the mean a.c. voltage to be controlled by delaying the firing of the thyristor, leading to a phase-angle control voltage waveform containing significant low-order odd voltage harmonics - this has been seen as typical of traction units. However, given that this represents a now-outdated form of traction drive, this view is misplaced.

The significant change in the 1980s was the introduction of the a.c. asynchronous drive, in which an induction motor is used instead of a d.c. motor. Given that the speed of this type of machine follows that of the supply, they were traditionally seen as single-speed drives until the ability to construct a variable frequency a.c. supply was provided by use of an inverter. The early traction inverters were based upon gate turn-off (GTO) thyristors, which overcame the difficulty of the original thyristors by providing a means of forcing switch-off. The result were pulse-width modulated (PWM) drives, with waveforms similar to that in Figure 14.

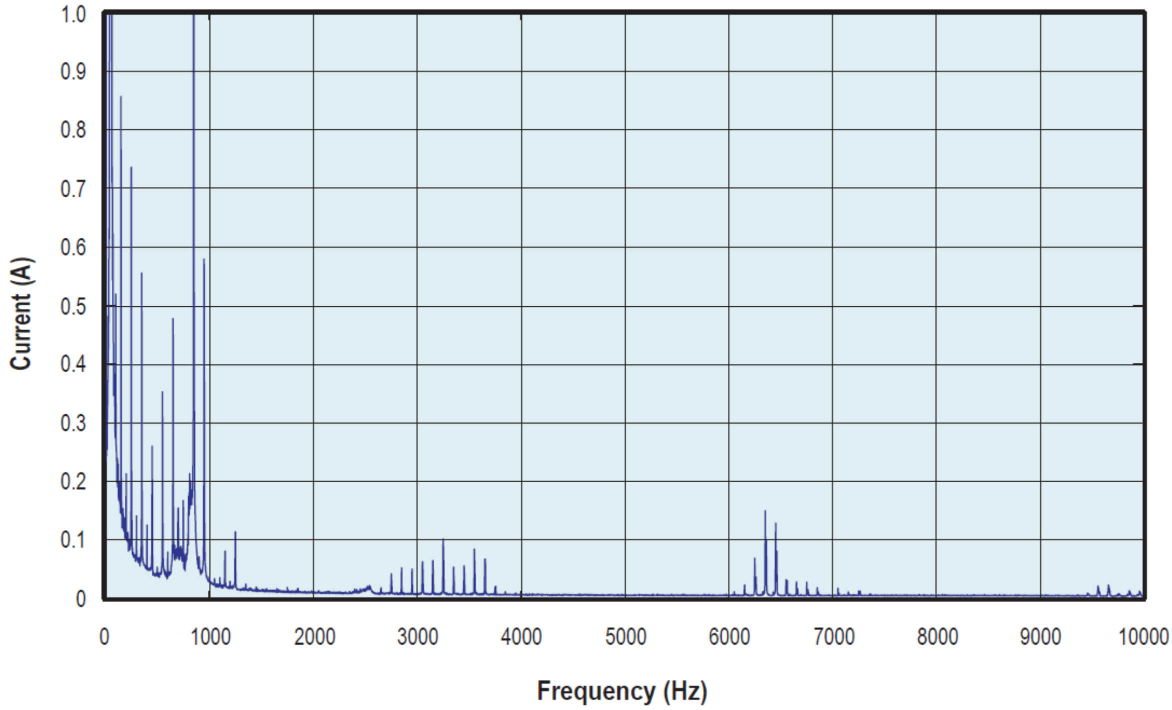


Figure 14 — Typical traction PWM waveforms

The PWM drive is now standard, with four quadrant operation permitting both motoring and regenerative braking. The relatively slow GTO has been replaced with the modern fast insulated-gate bipolar transistor (IGBT) technology.

The latest a.c. traction drives typically exhibit unity power factor and harmonics are predominately in the high frequency order (3-5 kHz).

8.2 Current pattern

Measurements have shown that the current taken by a train is not likely to remain constant for as long as 30 seconds. Variations in gradient, curves and wind resistance all require the driver to make frequent adjustments to maintain constant speed. In addition, speed changes will be required to conform with signals and for station stops. Occasionally the locomotive current may change from zero to full load or vice versa in a few seconds and smaller but still quite large changes are occurring all the time. It is clearly not possible to examine in detail all the separate loading conditions and representative patterns must be assumed.

Whilst the highest currents only occur for very short periods and have only limited effect on the thermal rating of the supply equipment, they persist for longer than the operating time of overcurrent protection. Similarly, harmonic distortion levels, associated with the peak current levels, may only be maintained for periods as short as 30 seconds.

There is at present little guidance on the effect of short duration high harmonic levels and although the thermal effects may not be limiting, the possibility of interference with other equipment may dictate that a short-term peak current level should be used for harmonic injection studies. However, unbalance is likely to be the critical disturbance and as the consequent motor heating effect is not instantaneous the highest one-minute demand is considered to be appropriate. This level can be obtained from detailed load estimates or, from preliminary estimates of maximum half-hour demand and a modifying factor.

Since it is very unlikely that one-minute maximum levels will occur simultaneously on adjacent track sections, it would be appropriate to assume the highest one-minute load on one section and the maximum half-hour demand values for each of the other sections in any interconnected network study.

8.3 Load Flow Considerations

Where conducting an a.c. load flow study for traction connections, it is possible to utilise a balanced a.c. load flow program – run the load flow three times, once for each phase. Balanced load would be represented in the usual way i.e. the three-phase MVA and power factor, but, for example, all yellow-blue loads would appear in the yellow phase study with an extra 30° lead, in the blue phase study with an extra 30° lag and not at all in the red phase study. Also, the traction MVA must be multiplied by √3 to make it compatible with the balanced loads.

9 Disturbance limits

At the design stage, estimates must be made of the disturbance contribution from the railway supply and this must be added to the existing level on the system.

9.1 Voltage unbalance

The equipment most affected by negative phase-sequence (NPS) is rotating electrical machines, the predominant effects being rotor and stator heating and the consequential loss of life of the machine. The limits take account of the long-term effects on the life of motors and the need to avoid nuisance tripping, whilst keeping motor protection settings at suitable levels to safeguard the machines. A historic rationale behind the limits was previously described ENA ETR 116 [1]..

It is recommended that the criteria in Table 1 are satisfied when assessing the likely impact of the railway supply on NPS voltage levels.

Although the criteria in Table 1 should strictly be applied at machine terminals this is impracticable so it is normal to calculate NPS values and apply the criteria at the point of common coupling associated with the EHV traction supply transformer.

Normally the background level of NPS voltage at a 33 kV supply point should be low, however the need for some form of balancing by the Railway Infrastructure Manager at such a low connection voltage places an additional demand on the Electricity Network Operator to determine unbalance levels and harmonic characteristics. Failure to do this may result in balancing equipment and/or filters being overloaded due to unpredicted background levels of disturbance on the three-phase system.

Where a background level exists it may be possible to use it to reduce the level on the system but it is not recommended that this should be used to permit a larger NPS voltage contribution from Railway Infrastructure Manager.

Table 1 — Voltage unbalance limits

Criterion	Maximum NPS voltage level (at secondary side of EHV supply transformer)		Operating conditions for which criterion must be met (NOTE 2)
	≤132 kV (NOTE 1)	275 kV and 400 kV	
1	1.0% averaged over any ½ hour period	Refer to Grid Code [N16] (CC.6.1.5 item b)	Intact system
2	1.0% averaged over 24-hour period	Refer to Grid Code [N16] (CC.6.1.5 item b)	Worst Railway Infrastructure Manager or EHV single circuit supply outage
3	2.0% for any 1-minute period	Refer to Grid Code [N16] (CC.6.1.5 item b)	Worst Railway Infrastructure Manager and/or single or two-circuit EHV supply outage (NOTE 2 & 3)

NOTE 1: At the time of publishing this document, a revision of ENA ER P29 [N10] is underway which will detail new voltage unbalance limits for ≤132 kV that are intended to replace the relevant limits for ≤132 kV in this table.

NOTE 2: The following sequence of checks may be followed for the above criteria.

a) Check criteria 1 for an intact system.

b) Check criteria 2 for a single circuit outage – check for an Electricity Network Operator single outage and a Railway Infrastructure Manager single outage.

c) Check criteria 3 for a double circuit outage – check for an Electricity Network Operator double outage and a Railway Infrastructure Manager double outage. Also check for a coincident Electricity Network Operator and Railway Infrastructure Manager single outage.

NOTE 3: Normally two-circuit outage conditions would give worse NPS levels than single-circuit outages. However, for two-circuit outages Railway Infrastructure Manager may be prepared to accept operating restrictions to limit the peak current and hence NPS voltage. The effect of this may be included in any assessment of whether criteria 1 is met.

NOTE 4: Care must be taken to check that single-circuit outage conditions do not give higher NPS levels than two-circuit outages with operating restrictions applied. It should be appreciated that these operating restrictions would not significantly affect the total energy demand and hence would not limit the average NPS levels which will be raised as a result of the circuit outages.

9.2 Harmonic distortion

To obtain the harmonic distortion from combining background and railway supply harmonics, the aggregation approach defined in ENA ER G5 [N5] shall be applied as described below.

Equation 1 provides a means of aggregating multiple values for each harmonic order based on the summation exponents in Table 2. This accounts for the operation of multiple non- linear equipment through the aggregation of their individual harmonic emissions. This form of aggregation is only valid based on a realistic appreciation of the equipment's operational and location diversity, without which linear addition shall be employed.

$$V^h = \sqrt[\alpha]{\sum_i \left(V_i^h\right)^\alpha} \qquad \text{Equation 1}$$

Table 2 — Harmonic Summation Exponents

Exponent, α	Harmonic order
1.0	h < 5
1.4	5 > h < 10
2.0	h > 10

The exponent is chosen on the basis of the expected average phase angle between the harmonic sources. An exponent of 1.0 implies they are in phase (angle 0°), whilst an exponent of 2.0 implies they are at 90°. An exponent of 1.4 implies an angle in the region of 70°.

Limits for harmonic distortion are described in ENA ER G5 [N5], which presents the percentage harmonic voltage limit for both the:

a) aggregated total harmonic distortion and;

b) individual harmonic orders.

NOTE: Historically, the emphasis has been on low-order harmomics, which has driven much of the approach in ENA ER G5 [N5]. As described in Clause 8.1, the latest a.c. traction drives typically exhibit unity power factor and harmonics are predominately in the high frequency order (3-5 kHz).

9.3 Sudden voltage change

For 1 x 25 and 2 x 25 traction connections, it may be assumed that there would be no coincidence of the voltage steps due to the railway load and those from other sources.

The effect of traction demand transferring between supplies should be considered for power electronic systems in which the primary voltage is derived from a network which may experience demand transfer transients.

The limits for sudden voltage change are described in ENA ER P28 [N9], which presents the percentage limits for various voltage changes, e.g. frequent rapid (sudden), ramped changes, and the associated flicker assessment procedure.

10 System disturbance calculations

AC traction supplies cause unbalance and harmonic distortion on the public supply system voltage. Unbalance exists when the fundamental voltage (and hence currents) on each of the three phases are of different amplitude or are not at 120°. Harmonic distortion refers to the non-sinusoidal shape of a voltage or current waveform. Due to the single-phase loads presented by Railway Infrastructure Manager traction supplies the distortion will not be the same on each phase.

Unbalance and harmonic distortion are described in ENA ER P29 [N10] and ENA ER G5 [N5] respectively – this document describes traction specific guidance to supplement the main Standards.

10.1 Unbalance

Traction loads are continually varying and in order to limit the total number of network studies, it is necessary to identify those conditions likely to give rise to maximum disturbance.

In general, unbalance contribution from traction loads will be greatest for minimum plant conditions and particular attention should be paid to all credible circuit outage conditions. Similarly, outages at railway supply points of the twin or single transformers and the consequent effect on supply point loadings should be considered.

10.1.1 Unbalanced Loading

(a) Single Supply Point

For an isolated supply point, unbalance is proportional to traction load, and the highest load current maintained for one minute should be adopted (10 minutes for ≥ 275 kV). If there are two transformers it is likely that the peaks on each will be simultaneous however, less than the peak on one section could be assumed if this can be shown to be more appropriate. The assumed currents are added arithmetically if the two transformers are fed from the same pair of phases or for the transformer outage condition, otherwise they must be added vectorially at 120°.

(b) Two or More Supply Points

To minimize overall unbalance effects on an interconnected supply system, the traction supply points or individual transformers along the route are, unless otherwise specified by the Electricity Network Operator, sequentially connected to phases L1-L2, L2-L3, L3-L1 etc. Unbalance voltages are not then directly proportional to load due to the interaction from adjacent supply points.

Interaction between supply infeeds may increase or decrease unbalance at a point depending on the nature of the contributions from other parts of the network. An initial assessment of the complete network with peak load at each supply point will indicate where there is significant interaction. The extent and nature of the interaction can be obtained by comparing the study results with estimates for each location considered separately.

To find the worst outage conditions at the planning stage requires some judgement for a system having appreciable interconnection. When choosing outages the following points should be considered.

- Outages that reduce fault level at a site. By reducing system strength, the impact of each unbalanced load is increased thus the unbalanced caused by the traction load.
- Outages that affect the local flow. Unbalance is caused by flow on untransposed circuits therefore outages that affect the flows locally will impact the local unbalance.
- Outages that cause contraflows. For overhead circuits NPS is highest when power is flowing in opposite direction on two sides of a double circuit. Therefore, outages that cause contraflows should be considered.
- Outages that affect the unbalanced load. Outages on the traction system may cause the load to be fed from a remote feeder station. This would increase the load at the remote station and may increase NPS at that point. Therefore, these outages should be considered. Similarly, any outages on one phase pair of a demand will cause the resultant phase angel of the NPS caused by that load to move. This may increase total NPS and this outage should be considered.

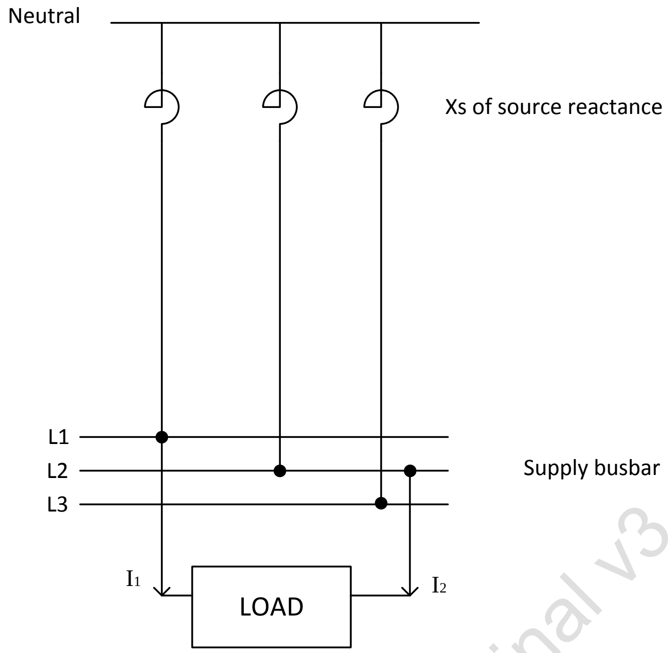
The technique would be to identify the supply transformer that has the highest demand on the pair of phases having the lowest total demand. Assume that that particular supply infeed is lost and that half its peak demand is added to the average at the infeed on either side; all other infeeds being assumed to take their average currents.

10.1.2 Quantifying unbalance

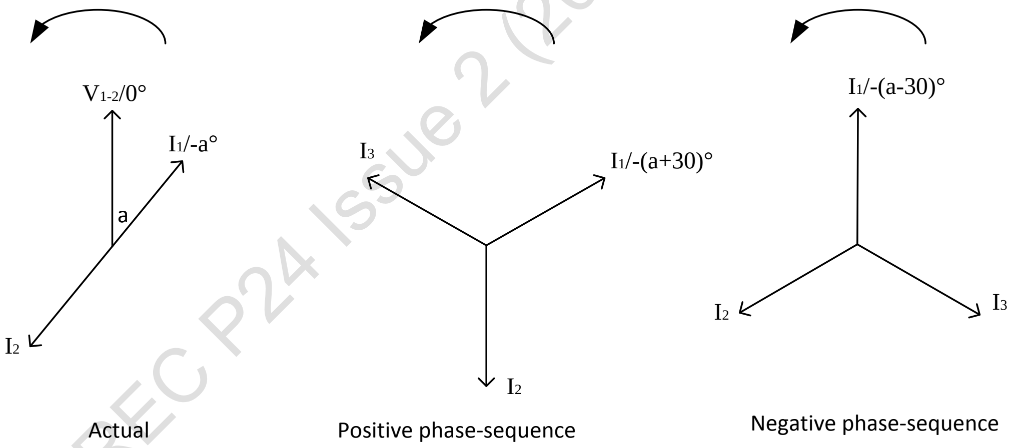
The three-phase unbalance for an isolated traction supply connected to a balanced system is easily calculated. It is the single-phase load, MVA, as a percentage of the three-phase fault level at a given supply busbar. This will be the contribution to negative phase-sequence (NPS) voltage from the connection as a percentage of nominal phase-to-neutral voltage (at fundamental frequency) as required in declared limits. Figure 15 illustrates this and derives the simple formula. It can be shown that if there are two single-phase loads (120° apart) connected to different pairs of phases at this supply point then the 'load' in the formula for NPS voltage must be the vector sum of the two single-phase loads.

The voltage unbalance at the connection point is likely to be different from the value calculated using the fault level equation shown in Figure 15. This is due to the pre-existing background unbalance on the system caused by existing unbalance loads or unbalance caused by network flows through untransposed circuits. This effect can be accounted for using a vector sum of the background NPS and the NPS caused by the connection. The pre-existing background unbalance can be measured or calculated using a computer simulation of the system. A simulation is recommended as a range of system outages can be considered.

It should be noted that due to the pre-existing background the maximum unbalance may not occur at the connection point of the unbalance load. NPS caused by the connection is always attenuated as it travels to nodes remote from the connection point but due to a phase shift or a higher (compared to adjacent networks) background it may cause a remote node to be outside the limits described in Table 1.



a) Supply connections



b) Fundamental positive and negative phase-sequence components

Magnitude of $I_{1\ PPS} = I_{1\ NPS} = I_1/\sqrt{3}$

NPS voltage at supply busbar = $I_{1\ NPS}\ X_S$

Expressed at a % of phase-neutral voltage $V_{NPS}\% = 100\ X_S\ I_1/\sqrt{3}V_{PHASE} = X_S I_1/10$ kV line

substituting (kV line)^2/fault MVA for X_S

$$V_{NPS}\% = \frac{line - line\ load\ MVA}{fault\ level\ MVA\ at\ supply\ busbar} \times 100$$

Figure 15 — Unbalance from an a.c. traction load

10.2 Harmonic Loading

Generally, the distortion severity is regarded as being proportional to the total harmonic content of a voltage or current. On this basis the worst cases can be derived as below.

(a) Single Supply Point

The current waveform assumed per transformer is that which has the greatest harmonic content expressed in amperes. This is normally expected to occur when the load on the supply point is greatest. It makes no difference if there are twin transformers connected to different pairs of phases as one would be assumed to be out of service to calculate the worst harmonics.

(b) Two or More Supply Points

When there are a number of supply points, experience has shown the worst harmonics are likely to arise from a particular pair of adjacent supply points. It can be shown that when two loads connected to different pairs of phases combine, the harmonics do not all combine in the same way. The worst odd triplen harmonics occur when the difference of the two load levels is highest, but most other harmonics will be highest when the vector sum of the two loads at 60° is a maximum. Hence if detailed load estimates are given then this rule can identify the worst time and place for studies, under normal and outage conditions.

10.2.1 Traction harmonic currents

Details of traction harmonic currents will be available from the traction drive manufacturer. A worst case aggregation of this current seen on the supply network, taking into account typical train numbers, should be provided by Railway Infrastructure Manager.

10.2.2 System data

Modelling of the transmission and distribution networks for a traction harmonic study should be conducted in accordance with the requirements of ENA ER G5 [N5].

For both distribution and transmission connections, railway system data is required and as total section loads are assumed in harmonic penetration studies, only the lumped 25 kV capacitance is normally included. This is typically 0.01 mF per single track kilometre. The capacitance between live and return conductors of any 25 kV line or cable to the feeder station, must be added.

10.2.3 Harmonic penetration studies

To calculate harmonics on the system, the waveform of each traction supply current must be specified so that the magnitude of each harmonic order can be derived. These harmonic currents multiplied by system impedance produce the harmonic voltages which need to be estimated. This current should be assumed to be injected equally across all phases for the purpose of the harmonic studies and thus the methodologies described in ENA ER G5 [N5] can be adhered to.

10.3 25 kV short-circuit level

The Electricity Network Operator approach to short-circuit calculation on their system is described in ENA EREC G74, which provides methodologies for the determination of network fault levels and characteristics (X/R) necessary for system design and operation.

A fault on the 25 kV system is equivalent to a line-to-line short-circuit on a three-phase system. The fault current is driven through twice the system reactance per phase by the line voltage. The r.m.s. symmetrical fault current calculated in terms of the usual X% values on 100 MVA base is:

$$\text{r.m.s. short circuit kA} = \frac{1000}{\left(2X_S + 2X_t + 2X_1\right)25}$$

Where,

X_S = source reactance to the primary terminals of the railway supply transformer

X_t = the nameplate % reactance of the transformer multiplied by 100 divided by MVA rating.

X_1 = the "go" and "return" reactance of any 25 kV line or cable to the feeder station, plus that of the 25 kV traction system if the fault is along the track

Observed fault currents have been virtually sinusoidal and constant in amplitude throughout the duration of the fault. There is no appreciable decrement as generator reactances pass from subtransient to synchronous, because the generation reactance is a very small part of the total fault reactance.

The above calculation gives the r.m.s. value of the fault current. However, it must be remembered that depending on the voltage at the instant of fault the current could be completely asymmetrical initially. It could take up to four cycles to become symmetrical about the zero axis.

11 Reduction of disturbances

11.1 General

Where studies made at the preliminary design stage show that the connection of the railway supply point will cause excessive disturbance to the supply system, consideration will have to be given to modifying the design. Selection of an alternative supply point or connection to a higher system voltage level are possible options. Rearrangement of the phase connection for one or more supply points may be beneficial, mainly in respect of the unbalance giving rise to excessive negative phase-sequence (NPS) voltage levels. The Railway Infrastructure Manager would specify, own and operate such equipment and the Electricity Network Operator would provide a standard three-phase metering circuit breaker connection, unless otherwise agreed. Where measures of this type are inadequate, then an alternative or modified supply arrangement may be considered, such as the Scott transformer connection (see Annex A.1), or the use of power electronics alongside the transformer connection (see Annex A.2). Where power electronic devices are employed the requirements of ENA EREC G5 [N5] shall also apply.

COMMENTARY ON: Phase balancing and harmonic filters

Both phase balancing and harmonic filtering have been used in Great Britain. Phase balancing is not used on operational routes but was installed as part of the Alstom Test Track at Old Dalby to test the West Coast Main Line (WCML) Pendolino Class 390 train. This installation is now used as a test track. Filtering has been used on the East Coast Main Line (ECML) in the North East due to nearby industrial harmonic sources. Additionally, the HS1 Channel Tunnel Rail Link employs phase balancing and filtering at two 400 kV connections.

11.2 Phase Balancing

Where studies show that the unbalanced nature of the railway supply load is likely, in conjunction with existing system unbalance, to exceed the permissible limit, consideration may be given to provision of phase balancing equipment. This can be useful where system fault level is low and may permit the railway to be supplied from a lower voltage point, e.g. 33 kV provided there is sufficient supply capacity.

There are several phase balancing technologies now available.

a) The ‘traditional’ phase balancing technology utilises switched inductor/capacitor balancers. The resultant current of suitably proportioned inductors and capacitors across the three phases and the unbalanced load presents a more balanced three-phase demand on the supply. Further details of the balancing action and the calculation of component values for this technology are described in Annex A.2.

b) The ‘modern’ phase balancing technologies are principally developed from power electronic static compensation systems, increasingly using multi-level converters. These may be stand-alone balancers or embedded within the operation of power electronic supply converters. Where power electronic devices are employed the requirements of ENA EREC G5 [N5] shall also apply.

The Railway Infrastructure Manager would specify, own and operate such phase balancing equipment and the Electricity Network Operator would provide a standard three-phase metering circuit breaker connection, unless otherwise agreed.

11.3 Harmonic Filtering

Harmonic filtering solutions for legacy traction connections were based upon dominant low-order harmonics. This position has now been largely replaced with high frequency harmonics. Filtering will be dominated by that required to facilitate power electronic converter technology within connections, or where background levels of low-order harmonics in the grid system affect the operation of railway converters. In these situations, the requirements of ENA EREC G5 [N5] shall also apply.

12 Equipment

12.1 General

Equipment for use on the 25 kV system shall be rated for the upper limit (highest non-permanent voltage) of 29 kV in accordance with BS EN 50163 i.e. this is the nominal phase-earth voltage.

NOTE: Equipment for use at a system voltage of 33 kV is not sufficiently rated for a 25 kV system.

Although much of the equipment associated with providing a.c. supplies for railway traction is the same as for any other load, some plant items differ or have special requirements. There are no specific ENA Technical Specifications which refer to electrical equipment for traction supply applications. When specifying equipment, the intention shall be to reference the relevant National Standard and the most relevant parts of the appropriate ENA engineering document.

For ‘classic’ 1 x 25 kV transformer connections up to 15 MVA or ‘autotransformer’ 2 x 25 kV connections up to 30 MVA, it may be possible to utilise 25 kV overhead line arrangements to provide connection between the grid supply point and the feeder station. When using standard overhead line arrangements care should be taken to note that the 25 kV phase voltage is greater than the 19 kV phase voltage of a standard 33 kV system, and hence the lowest standard voltage design for this purpose is 66 kV.

For traction power capacities greater than 15 MVA 1 x 25 kV and 30 MVA2 x 25 kV , the current rating requirements at 25 kV generally exceed those of standard overhead line arrangements. In such circumstances special twin- conductor, or more normally cabled connections, are required

The following guidance indicates the relevant standards, special features or ratings required and provides details of typical equipment examples.

12.2 Transformers

12.2.1 General

Transformers shall conform to BS EN 60076-1 and BS EN 50329.

It should be recognised that the nature of traction overhead contact systems means that they are more susceptible to short-circuit faults, of greater frequency than experienced on other electricity networks. Transformer design, particularly in relation to winding construction and withstand of short circuit forces, should particularly take into account the effect of this over the life of the transformer.

12.2.2 Power and voltage

For a typical 1 x 25 kV transformer, there should be a single LV winding designed to supply 27.5 kV between phase and earth, in accordance with BS EN 50163. The winding connection symbol is Ii0 EHV/27.5 kV. A separate fully insulated neutral connection is required.

NOTE: BS EN 50163 Table 1 stipulates a ‘highest non-permanent voltage’ of 29 kV for a nominal voltage of 25 kV.

For a typical 2 x 25 kV transformer, there should be two LV windings designed to supply 55 kV between phases. The winding connection symbol is Ii0i6 EHV/27.5/27.5 kV. The transformer should be arranged so that the LV windings can be loaded separately and the windings should be arranged so that the LV windings have a high impedance between them (for example on separate limbs of the core), it is normally expected that the HV winding will consist of two coils connected in parallel one for each LV winding. A separate fully insulated neutral connection is required for each LV winding.

The transformer should satisfy the overload requirements given in BS EN 50329 and the limits should be agreed between Railway Infrastructure Manager and the Electricity Network Operator.

12.2.3 Tapping

The use of a tap-changer may be optional and dependent upon the criticality of the supply and its voltage regulation on both sides.

Any fitted tap-changer should conform to the requirements of BS EN 60214-1, be fitted on the secondary side and provide a tapping range of 0 to +12.5% in 2½% steps. On-load tapping is preferable but not mandatory.

Tap selection should be based on overvoltage requirements – under sudden loss of loss of load, the 25 kV line voltage must not exceed 29 kV and then must not exceed 27.5 kV for more than two minutes.

A tap-changer monitoring system capable of detecting slow operation, increased mechanical resistance (increased motor torque), high temperature in the diverter switch and drive shaft failure may be considered, but is not essential.

NOTE: Given that 25 kV load current can be greater than 1000 A, it is the case that all on-load tap changers will be of a vacuum interrupter tap-changer design.

12.2.4 Impedance requirements

The transformer impedance should be determined from the fault levels studies for the connection. Where necessary, a neutral reactor may be required, as described in Clause 12.2.

Historically, the fault level on the 25 kV railway network has been 6 kA. For new connections, the design fault level for the 25 kV system is 12 kA, in accordance with BS EN 50388, unless the new connection is for an existing 25 kV system with a 6 kA fault level.

12.2.5 Terminations

The transformer terminations should be determined by the switchgear and busbar arrangements on site, e.g. gas insulated switchgear or open terminal equipment.

12.2.6 Testing

In addition to the Electricity Network Operators' typical transformer testing requirements for transformer, the following should be considered as routine tests. Testing shall be conducted in accordance with BS EN 60076-1.

- A short-circuit type test in accordance with BS EN 60076-5.

- An applied voltage and partial discharge test on the HV winding at the highest equipment voltage level.
- An induced voltage and partial discharge test producing 2 x nominal voltage between the HV terminals.
- A full sequence of impulses applied to both HV terminals connected together (double-ended LI test)
- Full and chopped wave lightning impulse tests on each LV line terminal.
- An applied voltage test on each LV winding separately.
- An overload test to verify the temperature rise performance at 150% of rated current including direct hotspot measurement. The test shall be arranged to determine the hotspot temperature response to a step change in loading.
- A measurement of the harmonic impedance of the transformer from LV to earth and LV to HV with the HV open-circuit and short-circuit will be required. This is an extension of the frequency response measurement and may be performed with the same measuring equipment.

12.2.7 Neutral reactor winding

It is preferable to avoid the use of a neutral reactor by selection of any appropriate transformer impedance. However, in certain cases, a neutral reactor winding may be required to limit fault current. The specification of the neutral reactor winding shall be prepared in conjunction with the Railway Infrastructure Manager and shall be in accordance with BS EN 60076-6, Clause 8.

The neutral reactor unit is separate to the transformer unit as depicted in Figure 16.

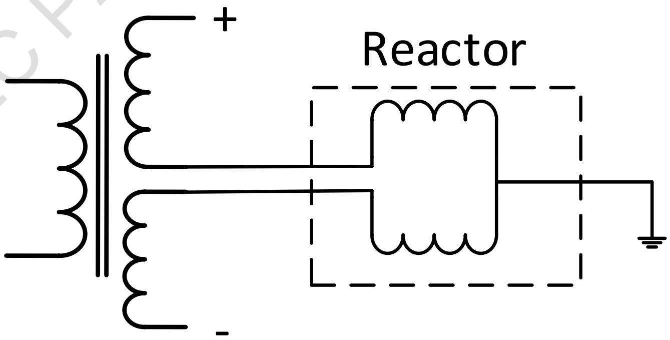


Figure 16 — Typical winding configuration for a neutral reactor

12.3 Underground Cables

Concentric and single core cables are suitable and the choice will be dependent on the current carrying capacity required and the availability of the cable. Single-core cables will increase the loop impedance (compared with concentric type) resulting in greater earth return currents and greater sheath circulating current.

Cables shall be rated for the upper limit (highest non-permanent voltage) of the nominal phase-earth voltage on the 25 kV system, in accordance with BS EN 50163 i.e. 29 kV. This would require 66 kV (a phase-earth voltage of 38 kV) cables to be used, if Electricity Network Operator specifications are employed. Alternatively, a Railway Infrastructure Manager specification for 25 kV cables may be applied.

Single point bonding and solid bonding are both applicable. However, before solid bonding is employed, the effect on the earthing arrangements should be considered (see Clause 13.2.2), and that the rating of the cable and cable sheath must take account of any alternative conductor return current (see Clause 13.2.3). Cable bonding and associated equipment, e.g. sheath voltage limiters, shall meet the requirements of ENA EREC C55 [N4].

12.4 Overhead Lines

For 1 x 25 kV connections up to 15 MVA or 2 x 25 kV connections up to 30 MVA, it may be possible to utilise 25 kV overhead line arrangements to provide connection between the grid supply point and the feeder station.

When considering overhead line arrangements - given that the 25 kV phase voltage is greater than the 19 kV phase voltage of a standard 33 kV system - the standard voltage design for this purpose should be 66 kV.

For traction power capacities greater than 15 MVA 1 x 25 kV and 30 MVA 2 x 25 kV, the current rating requirements at 25 kV generally exceed those of standard overhead line arrangements. In such circumstances special twin- conductor, or more normally cabled connections, are required

The recommended overhead line construction should be as follows.

a) Overhead system designed in accordance with ENA TS 43-50 [N12] and BS EN 50341-1.

b) Overhead conductor arrangement consisting of one of the following options.

   – 1 x 400 mm^2 equivalent (e.g. Zebra, Centipede)

   – 2 x 200 mm^2 equivalent (e.g. Jaguar)

Note: The above conductor suggestions are a guide only. The appropriate conductor size shall be selected at the overhead line design stage.

12.5 25 kV Switchgear

12.5.1 Circuit-breaker

25 kV single-phase vacuum circuit-breakers conforming to BS EN 50152-1 shall be employed. Where two circuit-breakers are required to operate together on 2 x 25 kV arrangements, the interlocking design should take account of the separate mechanisms. The operating time of the mechanism is not critical, as it would be for a 3-phase system.

Switchgear rated for 36 kV (phase-to-phase) is inadequate for use on 25 kV railway systems (upper limit of phase-to-earth on a 25 kV system is 29 kV in accordance with BS EN 50163).

12.5.2 Disconnector and earth switch

Disconnectors and earth switches conforming to BS EN 50152-2 shall be employed.

For the 1 x 25 kV arrangements – a 25 kV disconnector of the ganged double-pole type conforming to BS EN 50152-2 shall be employed.

For the 2 x 25 kV arrangements – a 25 kV disconnector of the ganged triple-pole type conforming to BS EN 50152-2 shall be employed

12.6 Protection equipment

All protection equipment and associated components shall satisfy the requirements of Clause 14.

Solid bonding of pilot or multicore auxiliary cable armouring on cables which are laid between transformer compound, disconnector compound and feeder station may create an alternative path for traction return current and also interconnect the earth electrodes at each end of the cable. Before solid bonding is employed, or individual cores are earthed at both ends, the effect on the earthing arrangements should be considered (see Clause 13.2.2), and that the rating of the cable and cable sheath must take account of any alternative conductor return current (see Clause 13.2.3).

12.7 Site layout/arrangement

For sites/stations/compounds associated with the railway supply, segregated arrangements and independent access for the Railway Infrastructure Manager and Electricity Network Operator are preferred. Such arrangements avoid complexities of safety rule authorisations and the application of different safety rules within a single compound.

For sites/stations/compounds containing both Railway Infrastructure Manager and Electricity Network Operator equipment, ‘dual access’ arrangements for both the Network Operator and the Railway Infrastructure Manager would be needed to ensure timely access for either party in the event of operational activities.

Access to metering equipment should be as described in Clause 12.9.1.2 (b).

12.8 DC supplies

On shared sites the Railway Infrastructure Manager and Electricity Network Operator should make their own provisions for d.c. supplies unless otherwise agreed between the two parties.

12.9 Metering

12.9.1 Metering requirements

12.9.1.1 General

The metering equipment and arrangement should conform to the requirements of Section L of the Balancing & Settlement Code and the associated (metering) Codes of Practice.

AC traction supplies to Railway Infrastructure Manager will typically come under the auspices of Code of Practice 2: *Code of practice for the metering of circuits with a rated capacity not exceeding 100 MVA for settlement purposes*. This requires main and check metering to be provided.

12.9.1.2 Metering location

a) Metering CTs and VTs

Metering current transformers (CTs) & voltage transformers (VTs) are usually provided by the Electricity Network Operator, but could be provided by the Railway Infrastructure Manager.

Traditionally the metering CTs and VTs have been located at the Electricity Network Operator's transforming station, accommodated within a 25 kV circuit-breaker, the EHV/25 kV transformers, or freestanding instrument transformers. However, this does not mean that the metering CTs & VTs could not be located at the Electricity Network Operator's disconnector compound.

It should be noted that for Railway Infrastructure Manager supplies, a standard voltage transformer ratio of 26,400/110 V has previously been used for metering purposes. However, for new connections a VT ratio of 27,500/110 V shall be employed.

Since metering CTs and VTs have a limited VA rating, there is a maximum permissible length of multicore cable that interconnects the instrument transformers and the meter cabinet. As a consequence, it is important to consider the position of the meter cabinet carefully, and 1A CTs enable a much greater length of multicore cable to be used.

A means of isolating the meters from the metering CTs and VTs shall be provided on the meter cabinet adjacent to meters. This will normally be a test terminal block and potential fuses.

b) Meters

As the meters and associated equipment will need to be accessed at regular intervals by meter readers, Meter Operators, Electricity Network Operator staff or by Railway Infrastructure Manager's staff, they must be placed in areas that have safe and easy access and at a height that makes interaction with the meter straightforward.

There is a strong preference for these to be located outside of the Electricity Network Operators' operational areas so independent rather than escorted access can be provided.

The meters shall be installed within suitably secure enclosures and/or buildings and sufficient space shall be provided both to accommodate all of the equipment and also to provide sufficient working space for installation work, commissioning testing, and for reading the meter.

Where multiple connections are provided, comprehensible and durable labelling should be provided to unambiguously identify the circuit associated with the meter.

12.9.2 MPANs/MSIDs

12.9.2.1 Premises from a distribution network

a) Role of MPANs

Each metering point has a unique 13 digit Metering Point Administration Number, usually known as the MPAN or by its official title of Supply Number so that the electricity market can process the sales and purchases of energy from Customers, known generally as 'Settlement'. The MPAN is a number unique to the Metering Point and remains allocated to that metering point from the time the development starts until the service is disconnected.

The first 2 digits of an MPAN identify which distribution business has issued it, and receives metering data in respect of that site, and the final digit is a check digit to ensure uniqueness and correct reporting.

b) Issuing authority

The issuing authority is the licensed distributor in respect of that Premises.

c) Creation process

MPANs are usually created by the distribution Electricity Network Operator once a connection has been agreed with Railway Infrastructure Manager.

An MPAN is required for each metered connection on a site with multiple circuit connections.

Note that an MPAN is also required in the event that a temporary supply is provided to Railway Infrastructure Manager whilst the ac traction supply point is constructed (e.g. to power a temporary site cabin) is installed. It is not possible for this MPAN to be re-assigned to one of the 25 kV connections at a later date.

Railway Infrastructure Manager will need to register this MPAN with a chosen Supplier before a meter can be installed.

12.9.2.2 Premises supplied from the transmission network

a) **Role of MSIDs**

Each Metering Point has a unique Metering System Identifier, usually known as the MSID, which performs an equivalent role to the MPAN.

b) **Issuing Authority**

The issuing authority is Central Registration Agent (Elexon).

13 Earthing

The earthing system for an a.c. traction supply can involve separate sites (Electricity Network Operator transformer stations & disconnector compounds, and Railway Infrastructure Manager feeder, intermediate and mid-point stations). It will also include a distributed earth associated with the railway supply return conductor, and in the case of 2 x 25 kV systems, additional neutral point earthing at Railway Infrastructure Manager auto-transformers.

The purpose of this section is not to cover earthing requirements per se but to consider issues that are peculiar to a.c. traction supply points.

13.1 Earthing arrangements

13.1.1 Earthing arrangements on Railway Infrastructure Manager's track system

Both running rails of the Railway Infrastructure Manager's track are, in effect, lightly insulated from earth. Traditionally one rail is used for signalling purposes and the other used as a conductor for traction current, however, it is now increasingly the case that double-rail traction return is used, as double rail track circuits and axle counters become the standard for train detection.

The traction return rail is bonded to the overhead line supporting structures at the side of the track, thereby forming a multiple earthed system through the footing resistances of the supports. Periodically, cross-track bonds join the traction return rails of adjacent tracks together. The aerial earth conductor is periodically bonded to the traction return rail, generally at cross-bond locations, typically every 400 m.

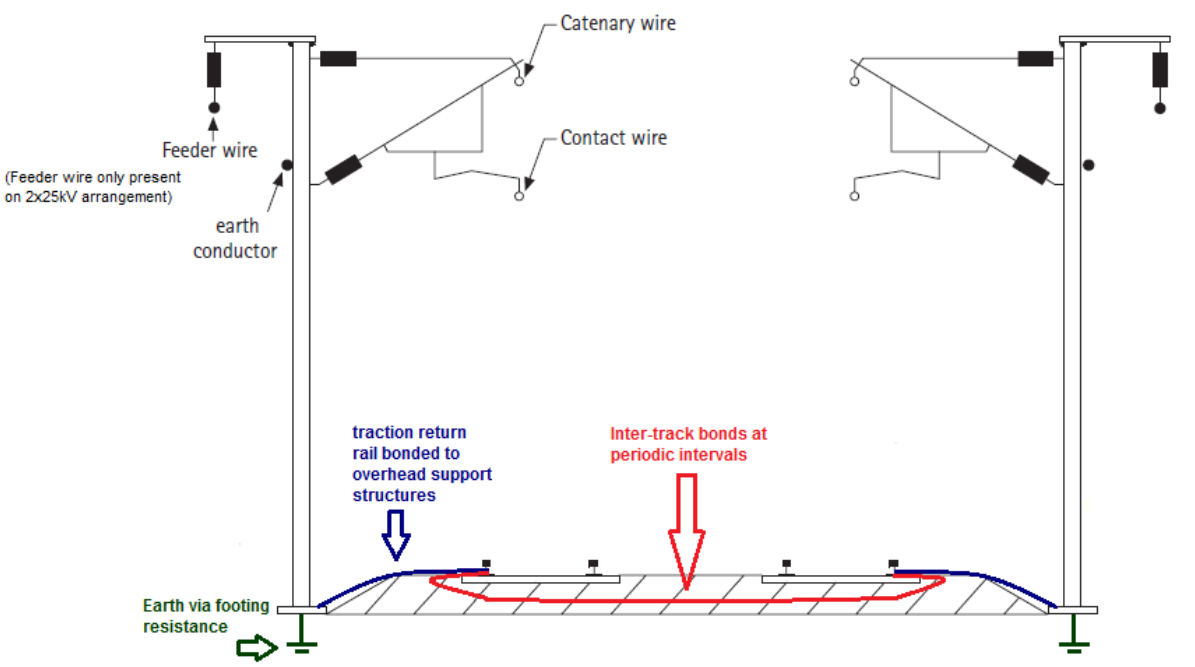


Figure 17 — Overview of conductors and bonding used for a.c. traction

All bonds are made of flexible cables but, due to the passage of trains and the resulting movement of the rails, or due to track maintenance work, it is not unknown for the continuity of bonds to become interrupted. Due to the value of scrap metal, the Railway Infrastructure Manager does occasionally suffer from theft of bonding cables and other earthing conductor. Whilst it is rare, it is not unknown for the return current busbar to become completely disconnected from earth. For this reason, this EREC specifies and mandates the use of loss-of-return protection on all new connections.

13.1.2 Earthing of the Electricity Network Operator's 25 kV system

Regulation 8 of ESQCR [N1] requires an Electricity Network Operator to ensure that its network is connected with earth at, or as near as is reasonably practicable to, the source of voltage, and also to ensure that its network does not become disconnected from earth in the event of any foreseeable current due to a fault.

These responsibilities, coupled with the vulnerability of the track bonds, means that the 25 kV winding of the EHV/25 kV transformer is usually connected to earth in the Electricity Network Operator's transformer station, or alternatively at the Electricity Network Operator's disconnector compound.

Apart from the track earths, the Railway Infrastructure Manager's return current busbar is also connected to earth. A 2 x 25 kV system is additionally earthed at each auto-transformer, as shown in the diagrams below.

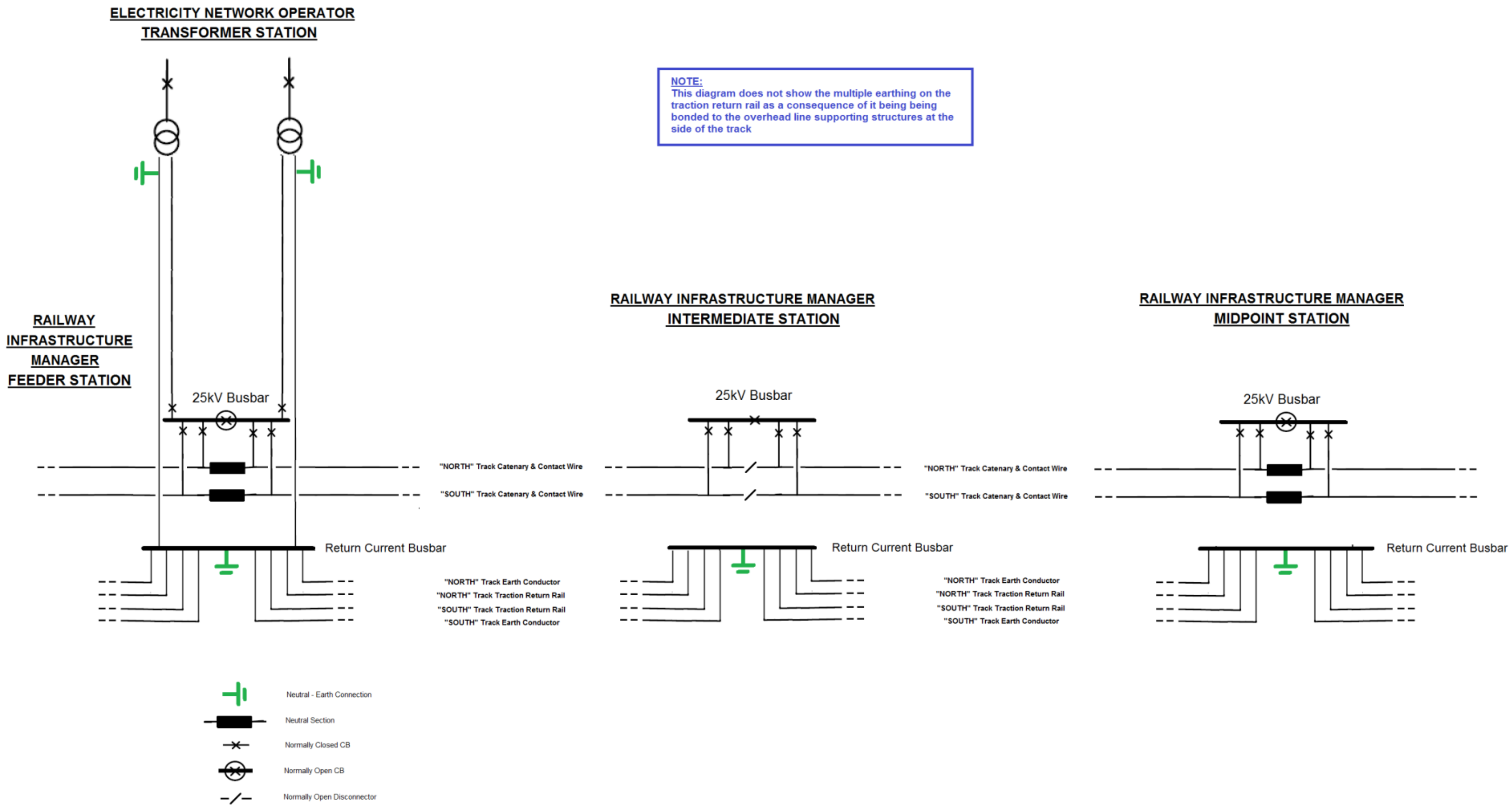


Figure 18 — Earthing arrangement on a 1 x 25 kV supply system

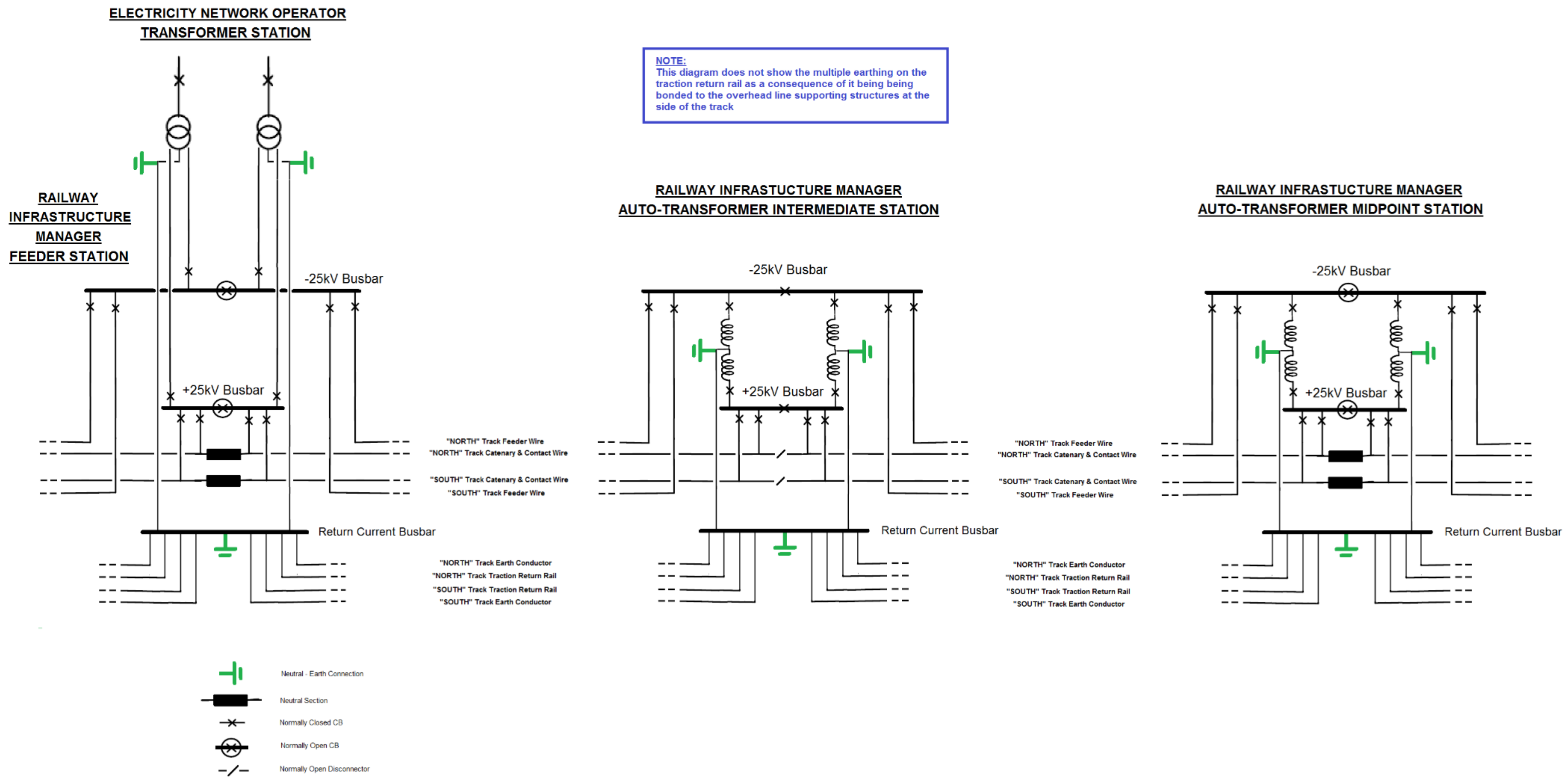


Figure 19 — Earthing arrangement on a 2 x 25 kV supply system

13.2 Fundamental requirements

13.2.1 General

The design of the earthing systems, including non-current carrying metalwork of plant and equipment, must be such as to prevent:

a) danger to personnel and plant due to the possibility of transferred potentials between Railway Infrastructure Manager's railway feeder substations and Electricity Network Operator's transformer substations and disconnector compounds during faults on the 25 kV or higher voltage systems

b) damage to equipment or devices due to stress voltages between earthed parts and any other of its parts during earth faults on the 25 kV or higher voltage systems

c) the overheating of equipment by the passage of alternative conductor return current

d) the possibility of work being undertaken on equipment undermining the control measures put in place for items a), b) and c) above.

13.2.2 Provisions against step, touch and transfer potentials

Where the Electricity Network Operator 25 kV and higher voltage (EHV) earthing systems exist in proximity to each other, part of the earth potential rise (EPR) from the higher voltage system can be impressed on the 25 kV system (and vice-versa).

Two practices are presently used.

- Interconnection of the 25 kV and higher voltage earthing systems.
- Segregation of the 25 kV and higher voltage earthing systems.

In order to determine which arrangement is most appropriate, the following points shall be considered.

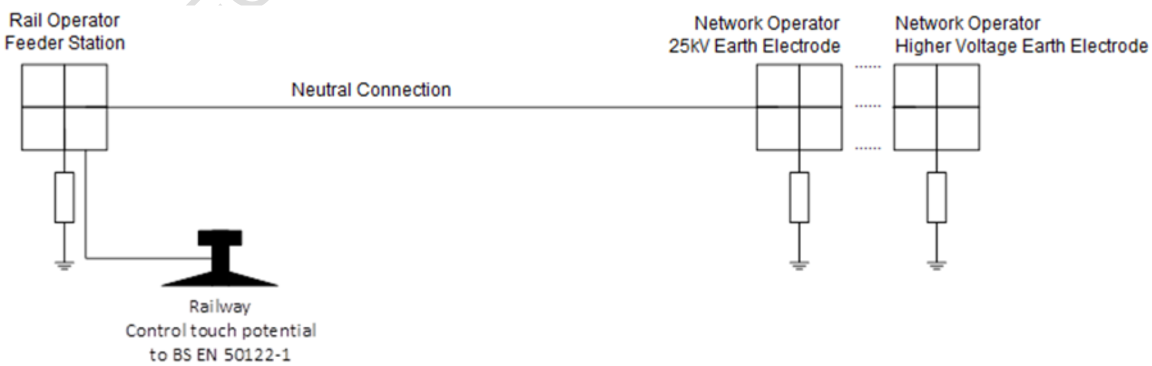


Figure 20 — Earthing arrangements on 25 kV and higher voltage systems

a) The earthing of the Electricity Network Operator transformer station shall meet the requirements of ENA TS 41-24 [N11], which is based on BS EN 50522.

b) The earthing of electrical installations on Railway Infrastructure Manager systems shall meet the requirements of BS EN 50122-1 and the Railway Group Standard GL/RT1255 [N3].

The standards employed by the electricity and rail industries make different assumptions about body impedance and footwear resistance, which results in dissimilar permissible touch voltages, as shown in Table 3 below.

Table 3 — Comparison between BS EN 50122-1 and BS EN 50522

Fault Clearance Time (s)	Permissible Touch Voltages (V)		
	BS EN 50122-1	BS EN 50522	
		Bare Soil	75mm Chippings
>300	60	153	170
300	65	153	170
1	75	233	259
0.9	80	250	279
0.8	85	281	314
0.7	155	332	371
0.6	180	420	471
0.5	220	578	650
0.4	295	837	944
0.3	480	1179	1331
0.2	645	1570	1773
0.1	785	2070	2341

Where the earthing of the Electricity Network Operator transforming station is such that the permissible touch voltages at the Railway Infrastructure Manager's feeder station (taking account of any attenuation provided by the 25 kV cables) also meet the limits specified in BS EN 50122-1 then the earth electrodes of the 25 kV and higher voltage earthing systems can be interconnected.

Where the limits specified in BS EN 50122-1 are exceeded then the earth electrodes of the 25 kV and higher voltage earthing systems should be segregated in order not to export high 'transfer potential' to the Railway Infrastructure Manager's installation. This usually requires meticulous attention to detail in order to realise in practice.

One of the challenges with a segregated arrangement is keeping the earth loop impedance to a low level such that a 25 kV fault at the Electricity Network Operator's transformer station does not result in a high earth potential rise (EPR) at the Railway Infrastructure Manager site, even though the EPR from a higher voltage fault is not seen at the Electricity Network

Operator's substation. Other challenges are ensuring segregation is maintained when 25 kV equipment at the Electricity Network Operator's transformer station is isolated and earthed for maintenance purposes.

The EPR of the Electricity Network Operator transforming station may not be known at the feasibility study stage and consequently it is recommended that the Electricity Network Operator transforming station and the Railway Infrastructure Manager feeder station are planned to be some distance apart from the outset in order to avoid high EPR contours crossing the railway. Undertaking an earthing study at the feasibility stage is highly advisable.

13.2.3 General provisions against alternative conductor return current

AC traction return current and short-circuit current encourages (by induction) current to flow along conductive paths which run in parallel with the return circuit and which are connected to earth at each end.

Alternative conductor return current is carried by a conductive path which is not the neutral conductor of the supplying transformer. Examples of the latter include the following:

- Metal sheath, screen wires or tapes associated with traction (supply and return) power cables if earthed at both ends.
- Earth continuity conductors laid with traction (supply and return) power cables if bonded to the earth electrode at each end.
- Metal armour, screen wires or tapes associated with auxiliary (multicore, multipair, pilot) cables if earthed at both ends
- Bonding conductors which interconnect separate earth electrodes
- Non-traction a.c. power supply connections (e.g. for lighting, heating etc) from the Electricity Network Operator’s system to Railway Infrastructure Manager’s trackside equipment (either local to or remote from the traction supply point) where an earth terminal has been provided on this connection and there is a continuous metallic path via the Electricity Network Operator’s system back to the EHV/25 kV transforming station

Return current and short-circuit current from a.c. traction systems should be prevented from flowing along these alternative parallel paths and be confined to the intended return circuit where possible. Where this is not reasonably practicable, suitable measures should be taken to address the risk from overheating as a result of this alternative conductor return current.

13.2.4 Additional provisions against alternative conductor return current where there are multiple circuit connections to the railway

Where an Electricity Network Operator’s transformer station includes multiple circuit connections to the railway then alternative conductor return current could also flow along:

- The return conductor associated with an adjacent circuit
- The phase conductor associated with an adjacent circuit which has been switched out of service and had circuit main earths applied

- The substation earth mat

The diagrams below show an indicative 1 x 25 kV arrangement.

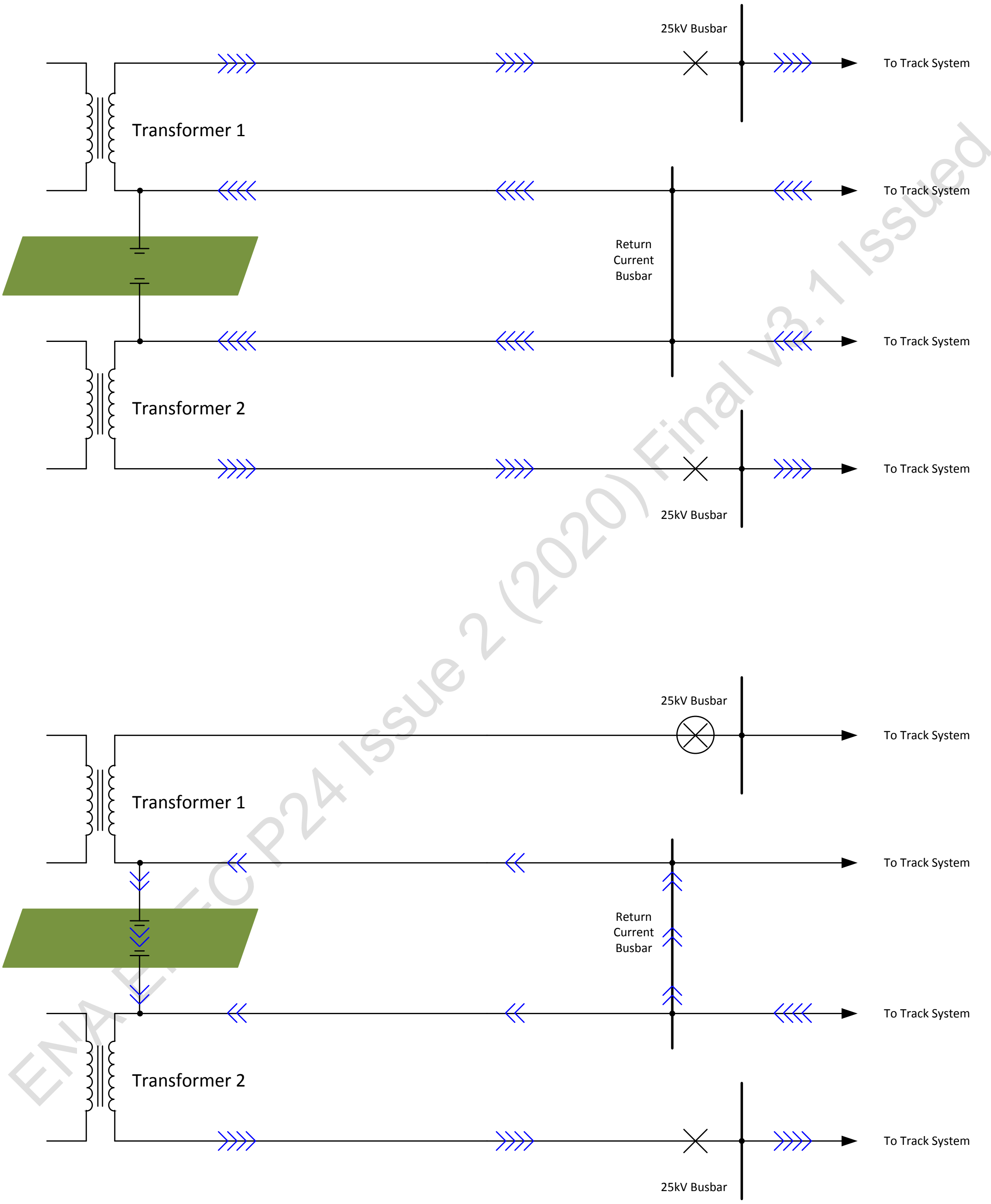


Figure 21 — Alternative conductor return current flows when there are multiple circuit connections to the railway

The upper diagram shows the traction return current (and short circuit current) flows when both transformers are in service. Note that the diagram assumes all current returns to the transformer station via the 25 kV return current cables, however in practice, some current will return via the soil.

The lower diagram shows the traction return current (and short circuit current) flows when Transformer 1 is out of service. Current is shared by the 25 kV return current cables because they are bonded together at both ends by the earth electrode and the feeder station return current busbar respectively. Load current will flow through the earth electrode for the duration of the outage, and as a consequence, some thought must be given to the design of the earth electrode between transformer neutral points, and also the possibility of the heating effect drying out the soil.

A similar effect will occur when phase and neutral conductors have been switched out of service and circuit main earths applied. In these instances load current may flow through these conductors via the circuit main earths for the duration of the outage

Consequently when construction / maintenance / repair activities are to be undertaken the following issues must be given consideration.

- The possible existence of transferred potentials
- The possibility of traction return / fault current associated with adjacent in-service circuits flowing in:
  - earthed phase and return conductors on the 25 kV circuit being worked on
  - earthed metal sheaths, screen wires or tapes on the 25 kV cable being worked on
  - earth continuity conductors associated with the 25 kV cable being worked on
  - earthed metal armour, screen wires or tapes associated with auxiliary (multicore, multipair, pilot & optical) cables being worked on
  - earth electrodes / bonding conductors

The design of the earthing system may need to take into account the consequences of equipment being isolated and earthed for construction / maintenance / repair purposes. However, it is recognised that in the main, the hazards will need to be controlled by the use of suitable operational procedures, for example:

- ENA EREC G38 [N7]: Operational Procedure Associated with Electricity Supplies for Traction Purposes on AC and DC Electrified Lines
- National Grid National Safety Instruction 26 (NSI 26) [2]: Railway Connection Circuits

13.3 Design criteria

13.3.1 Location of earth electrodes

The earth potential rise of the Electricity Network Operator transformer station may not be known at the feasibility study stage and consequently it is recommended that the Electricity Network Operator transformer station is planned from the outset to be some distance apart from the Electricity Network Operator disconnector compound and the Railway Infrastructure Manager feeder station in order to avoid high EPR contours crossing the railway.

The distance required is dependent on the fault level of the Electricity Network Operator's higher voltage system and the soil resistivity. Undertaking an earthing study at the feasibility stage is highly advisable.

The distance should be such that both the Electricity Network Operator's disconnector compound and Railway Infrastructure Manager's feeder station earth electrodes are located clear of the relevant voltage contour associated with the higher voltage electrode. For example, where the fault clearance time for the higher voltage system is (i) 200 ms and (ii) 600 ms, the disconnector compound and feeder station earth electrodes should be located outside the 645V and 180V contours respectively. The Railway Infrastructure Manager's track must also be located clear of this voltage contour.

A 600 ms fault clearance time is probable where the Electricity Network Operator transformer station is covered by distance protection zone 2

The siting of the disconnector compound and feeder station electrodes must also consider other equipment outside the Electricity Network Operator transformer station which may be subject to a high earth potential rise, for example, a steel tower / pole associated with a high voltage overhead line. As before, where the fault clearance time for a fault at this pole / tower is (i) 200 ms and (ii) 600 ms, the disconnector compound and feeder station earth electrodes must be located outside the 645 V and 180 V contour surrounding this pole / tower respectively. As before, Railway Infrastructure Manager's track must also be located clear of this voltage contour.

The Electricity Network Operator disconnector compound earth electrode shall be segregated from the Railway Infrastructure Manager feeder station earth electrode by not less than two metres. Where an independently earthed fence surrounds the Electricity Network Operator disconnector compound the Railway Infrastructure Manager feeder station earth electrode shall be segregated from the fence earth electrode by not less than two metres.

The Electricity Network Operator disconnector compound earth electrode shall be bonded to the Railway Infrastructure Manager feeder station earth electrode by duplicate fully rated connections.

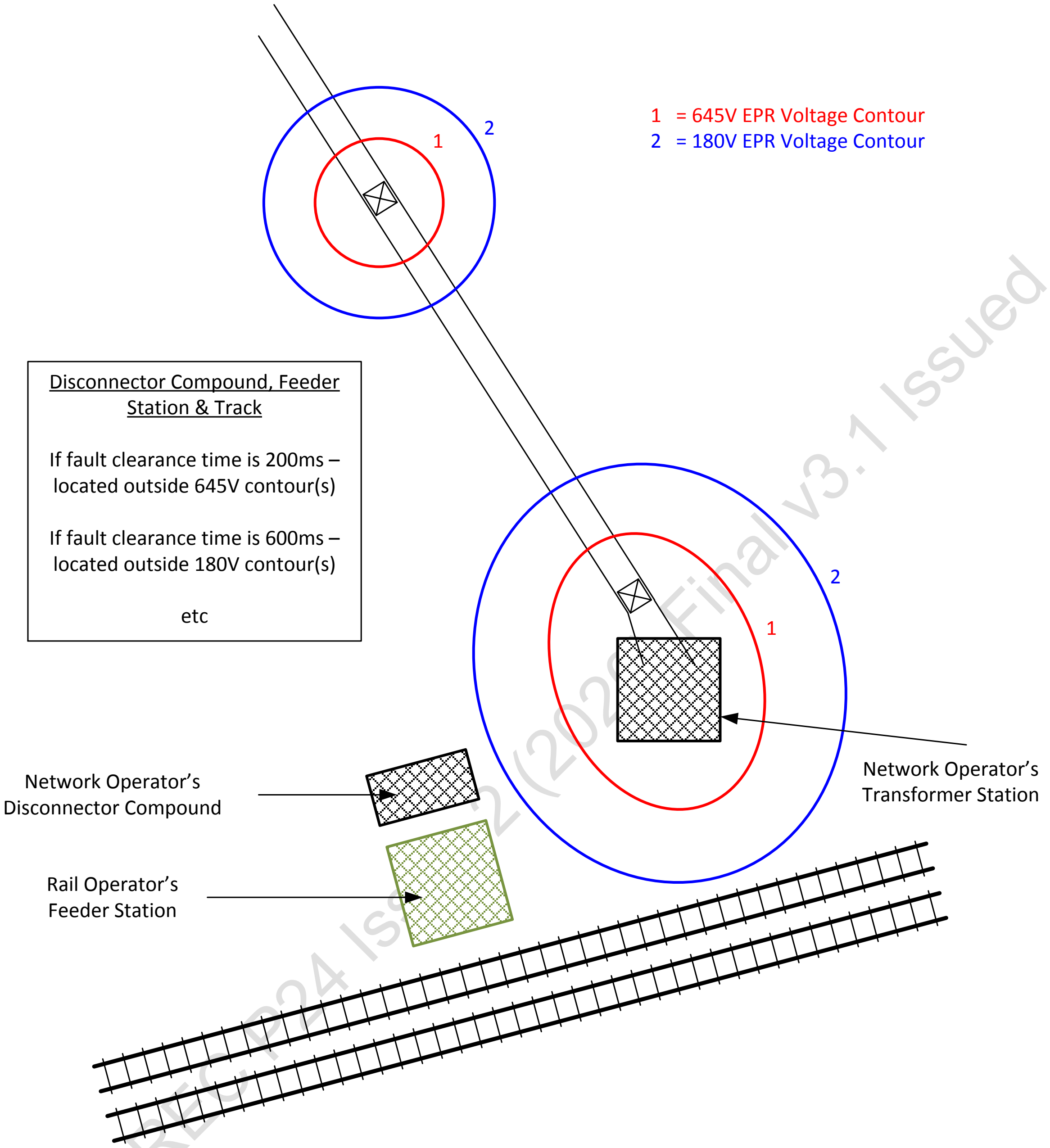


Figure 22 — Location of Electricity Network Operator transformer station in order to avoid high EPR contours crossing the railway

13.3.2 Earthing and Bonding Connections

13.3.2.1 Equipment at the transformer station

The non-current carrying metalwork of transformers, reactors, circuit breaker, disconnectors and earth switches shall, together with the earth switch terminal, be connected to the transformer station earth electrode.

A bonding conductor should not ordinarily be provided between the transformer station earth electrode and the disconnector compound or feeder station earth electrodes since this will provide a path for transferred potentials and alternative conductor return current.

Where a metallic fence is provided around the transformer station a separation of not less than two metres shall be provided between the fence and exposed items of metalwork which are not bonded to the same earth electrode as the fence.

13.3.2.2 25 kV phase & return current cables between the transformer station and disconnector compound

Where 25 kV phase and return current connections are made using individual cables, rather than a concentric cable, then metallic sheaths or screen wires / tapes shall be connected to earth at one point only i.e. single point bonding.

For the purpose of this EREC the metallic sheaths or screen wires / tapes are shown connected to the earth electrode (via links) at the transformer station end and unearthed (with sheath voltage limiters fitted where necessary) at the disconnector compound end. However, the opposite way around is equally acceptable.

It is customary practice to lay an earth continuity conductor in parallel with a cable employing single point bonding. However, this will provide a path for transferred potentials and alternative conductor return current and consequently such a conductor should not normally be provided.

13.3.2.3 Equipment at the disconnector compound

The non-current carrying metalwork of disconnectors and earth switches should, together with the earth switch terminal, be connected to the disconnector compound earth electrode.

Where a metallic fence is provided around the disconnector compound a separation of not less than two metres shall be provided between the fence and exposed items of metalwork which are not bonded to the same earth electrode as the fence.

A bonding conductor should not ordinarily be provided between the disconnector compound earth electrode and the transformer station earth electrodes since this will provide a path for transferred potentials and alternative conductor return current.

As a minimum requirement, at least two fully rated bonding conductors shall be provided between the disconnector compound earth electrode and the feeder station earth electrodes.

13.3.2.4 25 kV phase & return current cables between the disconnector compound and feeder station

These cables are normally the responsibility of the Railway Infrastructure Manager rather than the Electricity Network Operator.

Where 25 kV phase and return current connections are made using individual cables, rather than a concentric cable, then metallic sheaths or screen wires / tapes shall be connected to earth at one point only i.e. single point bonding.

For the purpose of this EREC the metallic sheaths or screen wires / tapes are shown connected to the earth electrode (via links) at the feeder station end and unearthed (with sheath voltage limiters fitted where necessary) at the disconnector compound end. However, the opposite way around is equally acceptable.

It is customary practice to lay an earth continuity conductor in parallel with a cable employing single point bonding. However, no earth continuity conductor is required as the duplicate, fully rated bonding conductors between the disconnector compound earth electrode and the feeder station earth electrodes provide this functionality.

13.3.2.5 Auxiliary cables between the transformer station and the disconnector compound

Auxiliary cables means multi-core, multi-pair and pilot cables.

Metallic sheaths / armouring shall be connected to earth at one end only. It is recommended that the cable is landed onto an insulated gland plate at both ends, with the gland at one end connected to earth via a connection which is able to be disconnected.

It is recommended that the earthed end mirrors the arrangement used for the metallic sheaths or screen wires / tapes on the 25 kV phase and return current cables where possible. For the purpose of this document the following arrangement is proposed:

Table 4 — Recommended auxiliary cable earthing arrangements for cables between transformer station and disconnector compound

End "A"	End "B"	End To Be Earthed
Transforming Station	Disconnector Compound	End A

Spare conductors shall not be bonded to earth at both ends.

The individual conductors in the auxiliary cables shall be terminated at both ends on insulated terminal blocks equipped with insulated isolation plugs in order to allow work on secondary wiring to be carried out safely i.e. allow work to be carried out on conductors at one end when they have a functional or protective earth connection at the other end. The terminal blocks shall be able to withstand 5 kV or the stress voltage that may exist during a rise of earth potential event on one earth electrode, whichever is the greater.

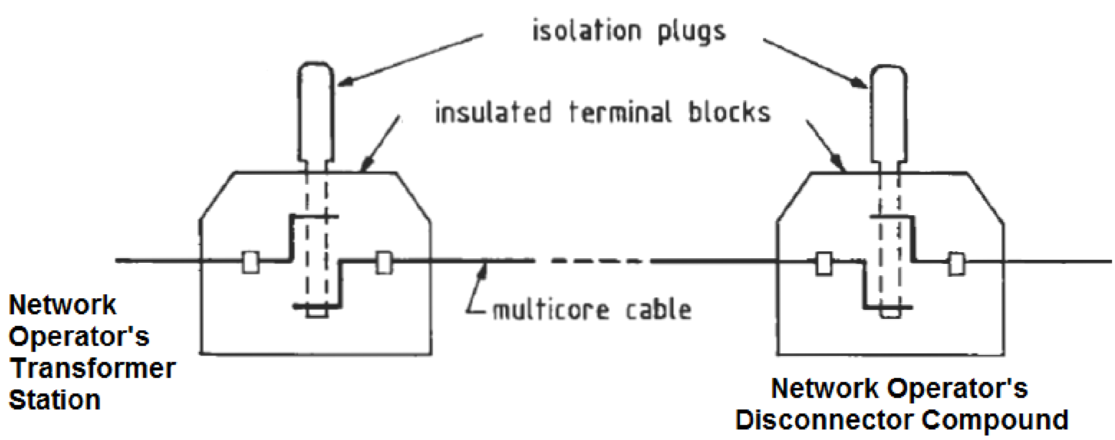


Figure 23 — Typical multicore cable circuit between transformer station and disconnector compound

13.3.2.6 Auxiliary cables between the disconnector compound & feeder station

Auxiliary cables means multi-core, multi-pair and pilot cables.

Auxiliary cables between the disconnector compound and feeder station are normally the responsibility of the Railway Infrastructure Manager rather than the Electricity Network Operator.

Metallic sheaths / armouring shall be connected to earth at one end only. It is recommended that the cable is landed onto an insulated gland plate at both ends, with the gland at one end connected to earth via a connection which is able to be disconnected.

It is recommended that the earthed end mirrors the arrangement used for the metallic sheaths or screen wires / tapes on the 25 kV phase and return current cables where possible. For the purpose of this document the following arrangement is proposed:

Table 5 — Recommended auxiliary cable earthing arrangement for cables between disconnector compound and feeder station

End "A"	End "B"	End To Be Earthed
Disconnector Compound	Feeder Station	End B

Spare conductors shall not be bonded to earth at both ends.

13.3.2.7 Protection & control equipment and other apparatus connected to auxiliary cabling

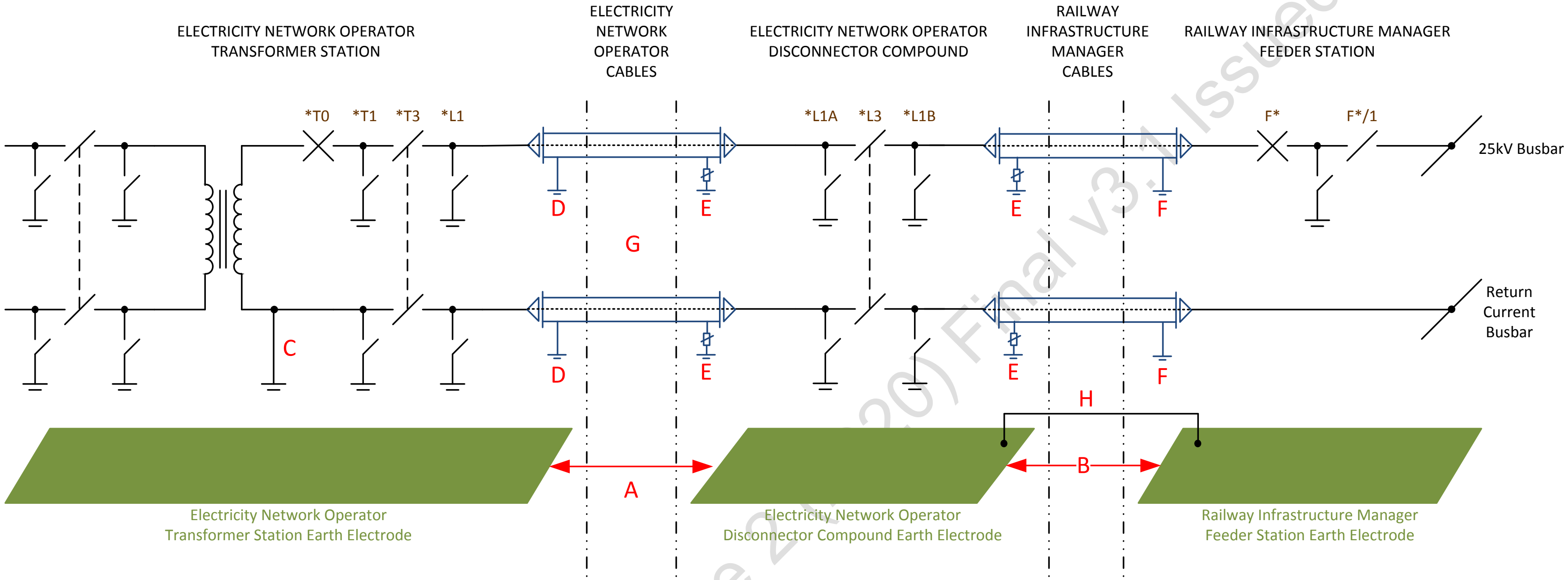
Where individual conductors are connected to earth (by virtue of the functional or protective earthing arrangements on their associated electrical circuit) then this shall be at one end only.

The stress voltage that may exist during a rise of earth potential event on one earth electrode shall also be taken into account when selecting equipment for connection to the auxiliary cabling. Consideration should be given to sleeving the secondary wiring and/or mounting equipment on insulating boards for additional electrical insulation.

13.4 Additional design criteria for interconnected 25 kV & higher voltage earth electrodes

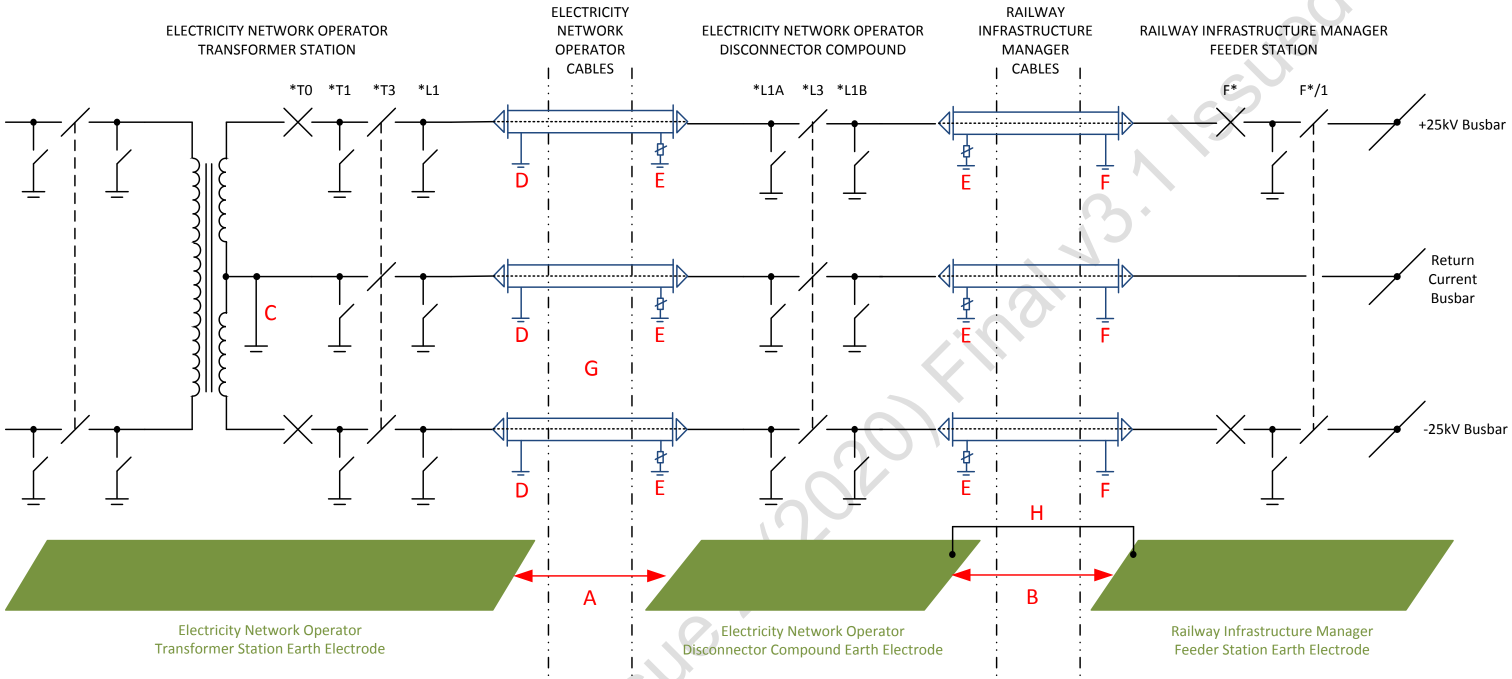
25 kV and higher voltage earth electrodes can be interconnected where the earth potential rise due to a fault on the Electricity Network Operator's higher voltage system would not result in the step, touch and transferred potential limits specified in BS EN 50122-1 from being exceeded in the Railway Infrastructure Manager installation.

This section makes reference to the following drawings, which show indicative 1 x 25 kV and 2 x 25 kV arrangements respectively.



A	Separation between transformer station and disconnector compound earth electrodes
B	Separation between disconnector compound and feeder station earth electrodes
C	25kV winding neutral point earthed in transformer station
D	Cable sheath / screen wires earthed at transformer station end
E	Cable sheath / screen wires unearthed at disconnector compound end (sheath voltage limiters fitted where necessary)
F	Cable sheath / screen wires earthed at feeder station end
G	No earth continuity conductor to be laid with cables
H	Duplicate, fully rated bonding conductors between disconnector compound and feeder station earth electrodes

Figure 24 — Typical arrangement for a 1 x 25 kV supply with interconnected 25 kV and higher voltage earth electrodes



A Separation between transformer station and disconnector compound earth electrodes

B Separation between disconnector compound and feeder station earth electrodes

C 25kV winding neutral point earthed in transformer station

D Cable sheath / screen wires earthed at transformer station end

E Cable sheath / screen wires unearthed at disconnector compound end (sheath voltage limiters fitted where necessary)

F Cable sheath / screen wires earthed at feeder station end

G No earth continuity conductor to be laid with cables

H Duplicate, fully rated bonding conductors between disconnector compound and feeder station earth electrodes

Figure 25 — Typical arrangement for a 2 x 25 kV supply with interconnected 25 kV and higher voltage earth electrodes

13.4.1 Earthing and bonding connections

13.4.1.1 Equipment at the transformer station

The neutral point on the Electricity Network Operator 25 kV transformer winding shall be connected to the transformer station earth electrode. This arrangement means that Electricity Network Operator's higher voltage earth electrode is bonded to the Railway Infrastructure Manager's 25 kV earth electrode via the return current conductor.

An advantage of this arrangement is that if the EHV/25 kV transformer is energised with *T3 open, or with a break in the return current conductor, then the 25 kV system always remains connected to earth.

However, a downside of this arrangement is that traction return current and short circuit current is able to return to the transformer station via the earth and also along conductive paths which run in parallel with the return circuit conductor and which are connected to earth at each end.

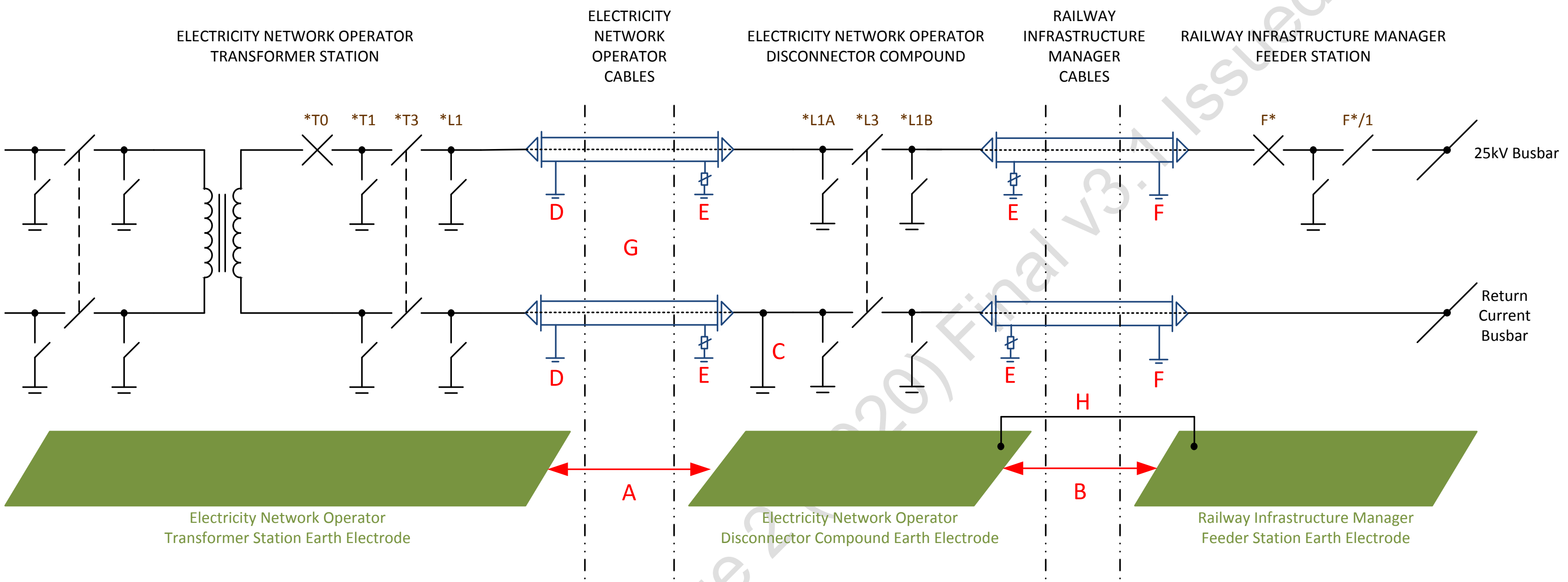
Where there are multiple circuit connections to the railway then traction return current will flow between transformer neutral connection via the transformer station earth electrode under outage conditions. Some thought must be given to the design and layout of the earth electrode between transformer neutral points, and also the heating effect of sustained traction return current on the soil - electrode interface.

13.5 Additional design criteria for segregated 25 kV & higher voltage earth electrodes

Segregation of the 25 kV and higher voltage earth electrodes is required where the earth potential rise due to a fault on the Electricity Network Operator's higher voltage system would result in the step, touch and transferred potential limits specified in BS EN 50122-1 being exceeded in the Network Infrastructure Manager's installation.

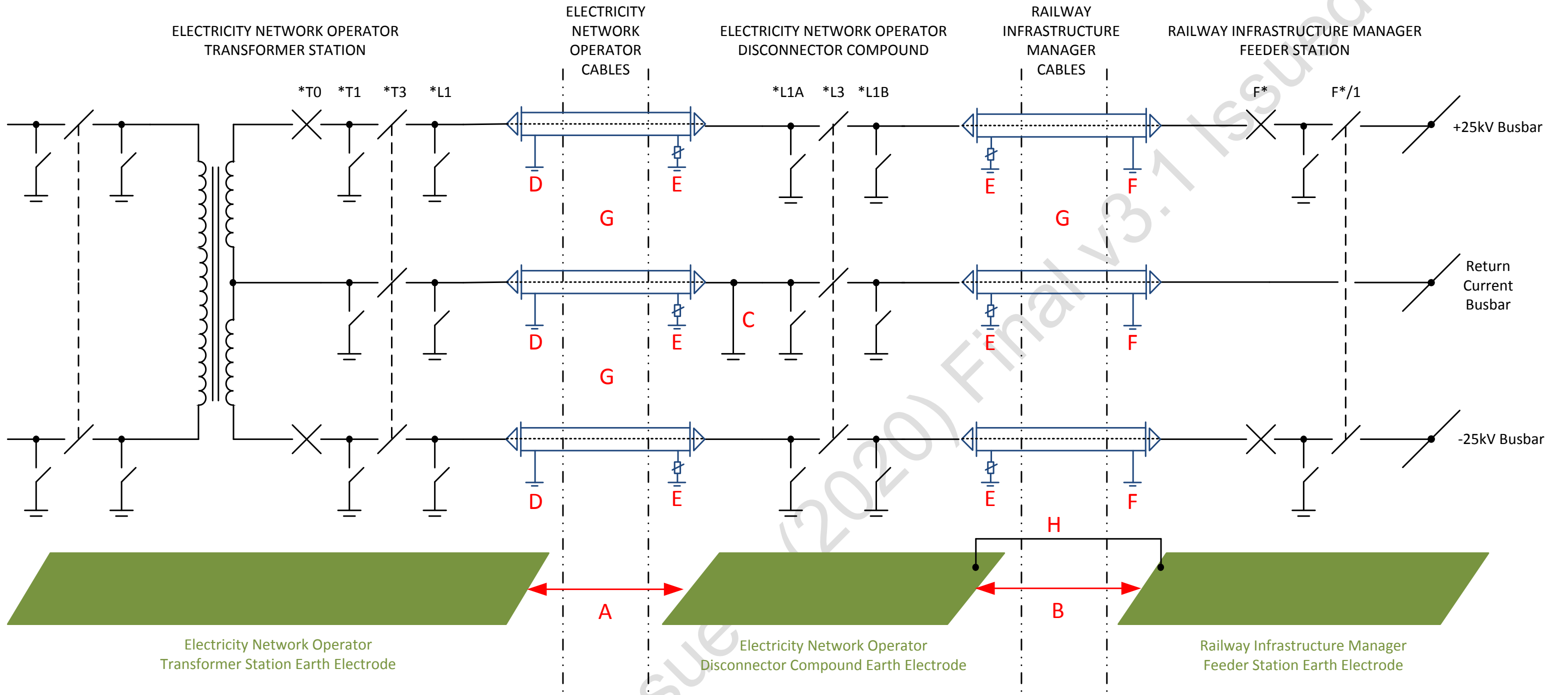
This document recommends that the 25 kV earth electrode is located at the Electricity Network Operator's disconnector compound; however, other arrangements are possible.

This section makes reference to the following drawings, which show indicative 1 x 25 kV and 2 x 25 kV arrangements respectively.



A	Separation between transformer station and disconnector compound earth electrodes
B	Separation between disconnector compound and feeder station earth electrodes
C	25kV winding neutral point earthed in disconnector compound
D	Cable sheath / screen wires earthed at transformer station end
E	Cable sheath / screen wires unearthed at disconnector compound end (sheath voltage limiters fitted where necessary)
F	Cable sheath / screen wires earthed at feeder station end
G	No earth continuity conductor to be laid with cables
H	Duplicate, fully rated bonding conductor between disconnector compound and feeder station earth electrodes

Figure 26 — Typical arrangement for a 1 x 25 kV supply with segregated 25 kV and higher voltage earth electrodes



A Separation between transformer station and disconnector compound earth electrodes

B Separation between disconnector compound and feeder station earth electrodes

C 25kV winding neutral point earthed in disconnector compound

D Cable sheath / screen wires earthed at transformer station end

E Cable sheath / screen wires unearthed at disconnector compound end (sheath voltage limiters fitted where necessary)

F Cable sheath / screen wires earthed at feeder station end

G No earth continuity conductor to be laid with cables

H Duplicate, fully rated bonding conductor between disconnector compound and feeder station earth electrodes

Figure 27 — Typical arrangement for a 2 x 25 kV supply with segregated 25 kV and higher voltage earth electrodes

13.5.1 Earthing and bonding connections

13.5.1.1 Equipment at the Transformer Station

25 kV wound voltage transformers cannot be connected between the return current conductor and the higher voltage earthing system since this would introduce a metallic connection between the 25 kV and higher voltage earth electrodes. Where Neutral Voltage Displacement (NVD) protection is required, a capacitor VT or a condenser bushing type scheme will have to be employed.

No electrical bond shall be established between the transformer station earth electrode and the disconnector compound earth electrode (or the feeder station earth electrode). This requires meticulous attention to detail in order to realise in practice for normal running conditions, and may be impossible to realise when equipment is isolated and earthed for construction / maintenance / repair purposes.

13.5.1.2 Equipment at the Disconnector Compound

The neutral point on the Electricity Network Operator 25 kV transformer winding shall be connected to the disconnector compound earth electrode. This arrangement means that Electricity Network Operator's higher voltage earth electrode is not bonded to the Railway Infrastructure Manager's 25 kV earth electrode via the return current conductor.

Note that the location of the neutral point earth means that under normal conditions the Electricity Network Operator's disconnector compound earth electrode and Network Infrastructure Manager's feeder station earth electrodes are bonded together via the return current conductor.

As well as achieving segregation between the 25 kV and higher voltage earth electrodes this arrangement also means that traction return current can only return to the transformer station via the return current conductor.

However, downsides of this arrangement are as follows:

- If the EHV/25 kV transformer is energised with *T3 open, or with a break in the return current conductor then the 25 kV side of the transformer will be unearthed, leading to potential overstressing of the 25 kV winding, phase current conductor and return current conductor. Neutral Voltage Displacement (NVD) protection is required to safeguard against this condition.

- A short-circuit to earth on the 25 kV connections in the Electricity Network Operator's transformer station will result of the fault current having to flow through both the transformer station earth electrode and the disconnector station earth electrode. The relatively high impedance of this path will result in a consequential effect on the earth potential rise experienced at the Railway Infrastructure Manager's feeder station.

Where there are multiple circuit connections to the railway then traction return current will flow between transformer neutral connection via the disconnector compound earth electrode under outage conditions. Some thought must be given to the design and layout of the earth electrode between the neutral points, and also the heating effect of sustained traction return current on the soil - electrode interface.

14 Protection

14.1 General

The application of protection for the arrangements, 1 x 25 kV and 2 x 25 kV, should follow the requirements of a protection concept design, which sets out the principles of the scheme. The high-level principles are described in this Clause.

Protection design shall be divided into three zones and conform to the requirements stated under each.

a) EHV protection zone

The EHV circuit protection up to the EHV supply transformer primary bushings shall be specified owned and operated by the Electricity Network Operator.

b) EHV supply transformer zone

The EHV supply transformer zone would extend between the incoming CTs on the HV side of the transformer and the outgoing CTs on the LV side of the transformer.

The protection for this zone shall satisfy the requirements of the Electricity Network Operator and the minimum protection requirements of Railway Infrastructure Manager.

c) 25 kV feeder circuit zone

The 25 kV feeder circuit zone would extend between the transformer outgoing CTs on the LV side and the incoming CTs on the 25 kV feeder circuit-breaker at the feeder station.

The protection for this zone shall satisfy the protection philosophy specified by Railway Infrastructure Manager. The principles for a.c. traction system protection are described in BS EN 50633. Consideration should be given to the clearance of fault conditions on the 25 kV network that may have an effect on the Electricity Network Operator network. For example, a busbar fault on the 25 kV network instigating a trip beyond the incoming circuit 25 kV circuit-breaker, to safeguard against catastrophic failure of that equipment.

The protection scheme(s) for the feeder station, including the incoming circuit-breaker, shall be owned and operated by the Railway Infrastructure Manager (see Clause 14.6).

Indicative protection schemes for typical 1 x 25 kV arrangements are depicted in Figures 28, 29 and 30. An indicative protection scheme for a typical 2 x 25 kV arrangement is depicted in Figure 31. The details in these figures is for information only.

14.2 Protection across boundary

Protection communication across operational boundary between the Electricity Network Operator and Railway Infrastructure Manager shall conform to the requirements of Clause 15 of this document.

Protection across boundary should include co-ordination of protection settings. Where numerical feeder current differential protection is employed it is necessary to co-ordinate relay choice, relay configuration, and CT specifications. It may also be necessary to accommodate equipment owned by the other party.

14.3 Protection equipment

All protection and automatic switching relays shall be assessed for use by the ENA Protection Assessment Panel.

All other components shall meet the requirements of ENA TS 50-18 [N14] at the appropriate ambient class for the location of the component.

Pilot cables used for protection equipment should be terminated in accordance with ENA TS 12-4 [N13].

14.4 Protection commissioning

During protection commissioning, it is standard procedure for Railway Infrastructure Manager to carry out testing with the system live. In particular, Railway Infrastructure Manager require a short-circuit test to be completed by grounding a live conductor on the railway system using rated device. This grounding is intended to mimic the frequent phase-earth faults experienced on the railway overhead system.

The live conductor testing carried out by the Railway Infrastructure Manager should require the prior consent of the Electricity Network Operator, who should have the right to intervene if repetitive short-circuit tests create power quality / nuisance issues for other customers.

Regarding Electricity Network Operators protection commissioning, it is standard procedure to carry out final testing of protection using load current. The Railway Infrastructure Manager will be required to provide suitable traction load, or load banks, to enable this testing to be completed.

14.5 Indicative protection schemes

14.5.1 General

The following protection arrangement are indicative only and may need to be varied depending on the preferred protection design and the connection arrangement, e.g. additional 25 kV and EHV circuit-breakers are used by the Electricity Network Operator.

The protection schemes should include the tripping/intertripping of the 25 kV CB XXXX/F1 from the EHV circuit-breaker. This requirement ensures

d) the railway is not re-energised by auto-reclose but only following express consent of a Railway Infrastructure Manager control engineer.

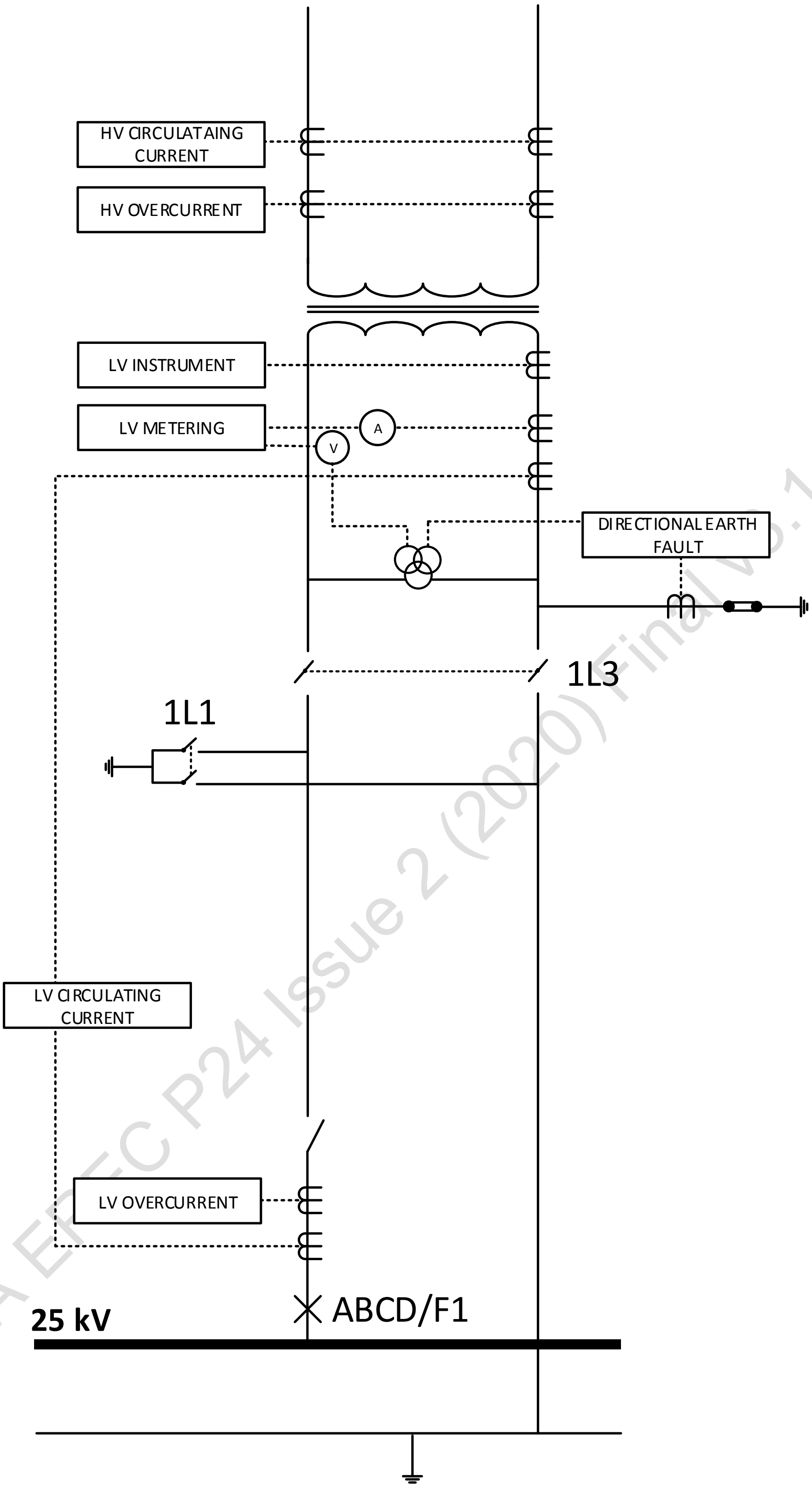
e) closure of bus section circuit-breaker by the Railway Infrastructure Manager control engineer cannot inadvertently back energise the EHV system, with consequential risk of out-of-phase closure of circuit breakers by Electricity Network Operator.

14.5.2 1 x 25 kV Supply Arrangement A (Figure 28)

Here the transforming and feeder stations are adjacent and the transformer neutral end is solidly earthed at the transformer. Switching is by a single-pole 25 kV circuit-breaker at the feeder station.

The transformer LV winding and 25 kV phase conductor should be protected by a high impedance circulating current protection while the neutral is unprotected (a separate transformer LV circulating current scheme and 25 kV phase protection scheme is also valid). To detect a broken neutral conductor condition, suitable earth current protection should be provided, driven from a CT in the transformer neutral earth connection (a protection scheme for the neutral conductor is also valid). The directional feature is necessary to cater for the two transformer arrangement where return current from the faulted circuit may use the healthy circuit neutral and transformer earth connection. The healthy circuit directional earth current protection would be polarised to be unresponsive to this current.

Overcurrent protection should be provided at the 25 kV circuit-breaker.



NOTE: Diagram excludes a disconnector compound, which may be required in practice

Figure 28 — Indicative protection scheme for 1 x 25 kV arrangement, transformer station and feeder station in same location.

14.5.3 1 x 25 kV Supply Arrangement B (Figure 29)

Here the transforming and feeder stations are distant from each other and the transformer neutral end is not earthed at the transformer. Switching is by a single-pole 25 kV circuit-breaker at the feeder station.

The transformer LV winding should be separately protected by a circulating current protection while the 25 kV phase conductor should be covered by pilot wire/fibre protection. Overcurrent protection should be provided at the 25 kV circuit-breaker and there should be appropriate intertripping from the transforming station to the feeder station.

The neutral conductor should be covered by pilot wire/fibre protection and neutral voltage displacement protection. These are necessary to cater for two types of fault. A broken neutral conductor clear of earth, results in a rise of potential on the transformer side of the break which if sustained would be detrimental to cable insulation. Neutral voltage displacement protection detects and clears this fault. A broken neutral conductor to earth on the transformer side however would not be detected by neutral voltage displacement protection but would be a hazard since load current from the faulted neutral would return via pilot cable sheaths (where cables are present), third party property, etc. To detect and clear this fault, neutral pilot wire/fibre protection should be provided.

While there is a third fault condition (broken conductor to earth on the Railway Infrastructure Manager feeder station side) this is electrically no different from the broken conductor clear of earth case since, with interruption of load, the earthed conductor carries no current.

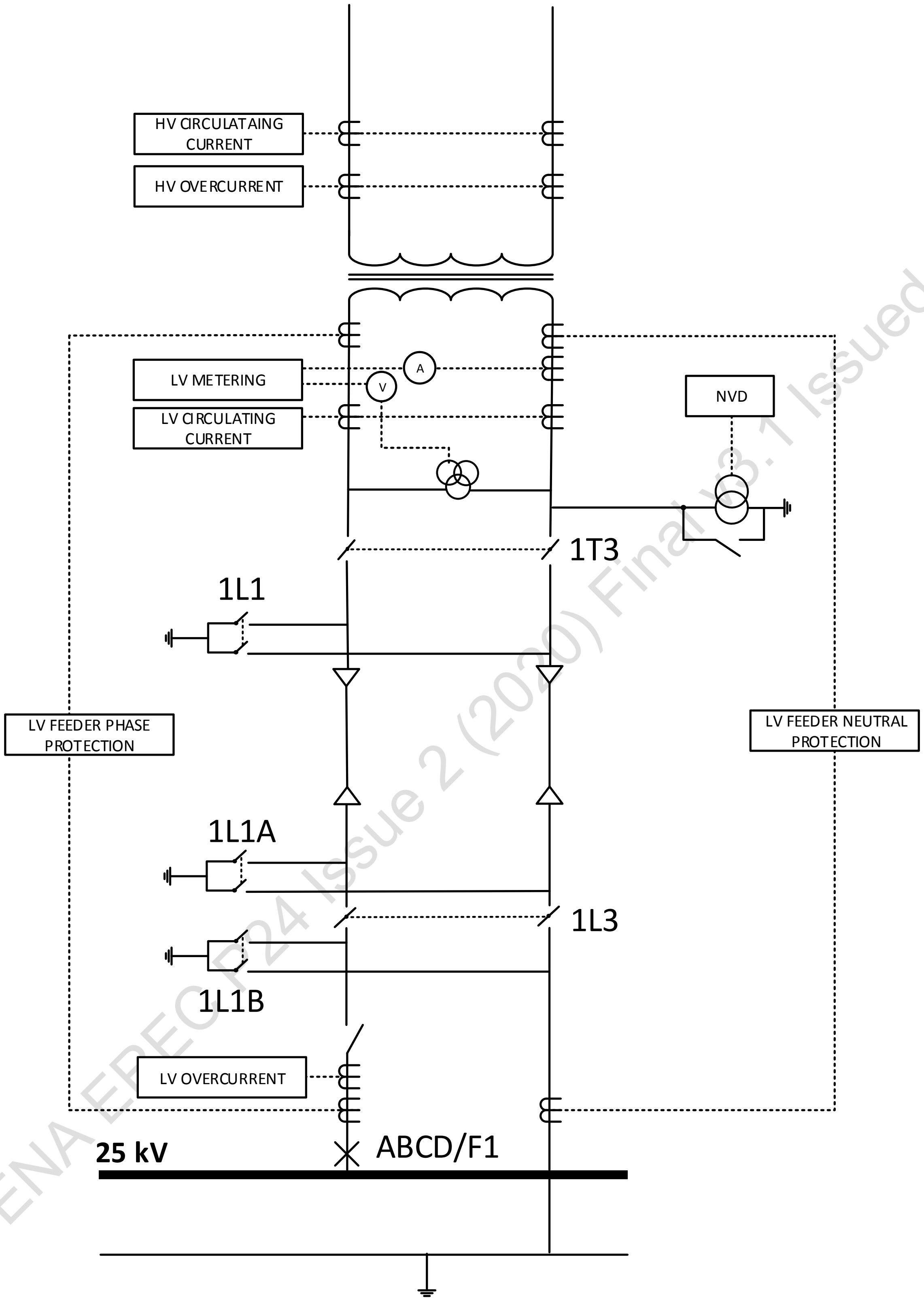


Figure 29 — Indicative protection scheme for 1 x 25 kV arrangement, transformer station and feeder station remote to one another, return conductor unearthed at transformer

14.5.4 1 x 25 kV Supply Arrangement C (Figure 30)

Here the transforming and feeder stations are distant from each other and the transformer neutral end is earthed at the transformer. Switching is by a single-pole 25 kV circuit-breaker at the feeder station.

The transformer LV winding should be separately covered by a circulating current protection while the 25 kV feeder phase conductor should be covered by pilot wire/fibre protection. Overcurrent protection should be provided at the 25 kV circuit-breaker and there should be appropriate intertripping from the transforming station to the feeder station.

Because the transformer neutral is solidly earthed at the transformer there can be no rise of neutral potential as a result of a broken neutral conductor. In the case of a broken neutral conductor clear of earth, the return current from the faulted circuit uses an earth path (and the neutral of parallel circuit if such exists) and a directional earth current protection relay should be provided, driven from a CT in the transformer neutral earth connection, to trip the circuit for this unhealthy condition.

In the case of a broken neutral conductor to earth on the transformer side, the return current from the faulted circuit has several paths, namely:

a) From the track earths to the faulted neutral and thence by neutral conductor to transformer neutral,

b) From track earths via earth path and transformer neutral earth connection to transformer neutral,

c) From feeder station return current busbar to the faulted circuit transformer neutral via the parallel circuit neutral and earthing system of any other available healthy transformer circuit.

Depending upon the position of the fault and upon the resistance of the fault earth, the proportion of load current in the faulted circuit neutral earth connection may be insufficient to operate the directional earth current protection. To cater for this condition the neutral conductor should be covered by pilot wire/fibre protection.

Where the broken neutral is to earth on the feeder station side, all the faulted circuit current returns via the transformer neutral earth connection and the circuit is tripped by directional earth current protection.

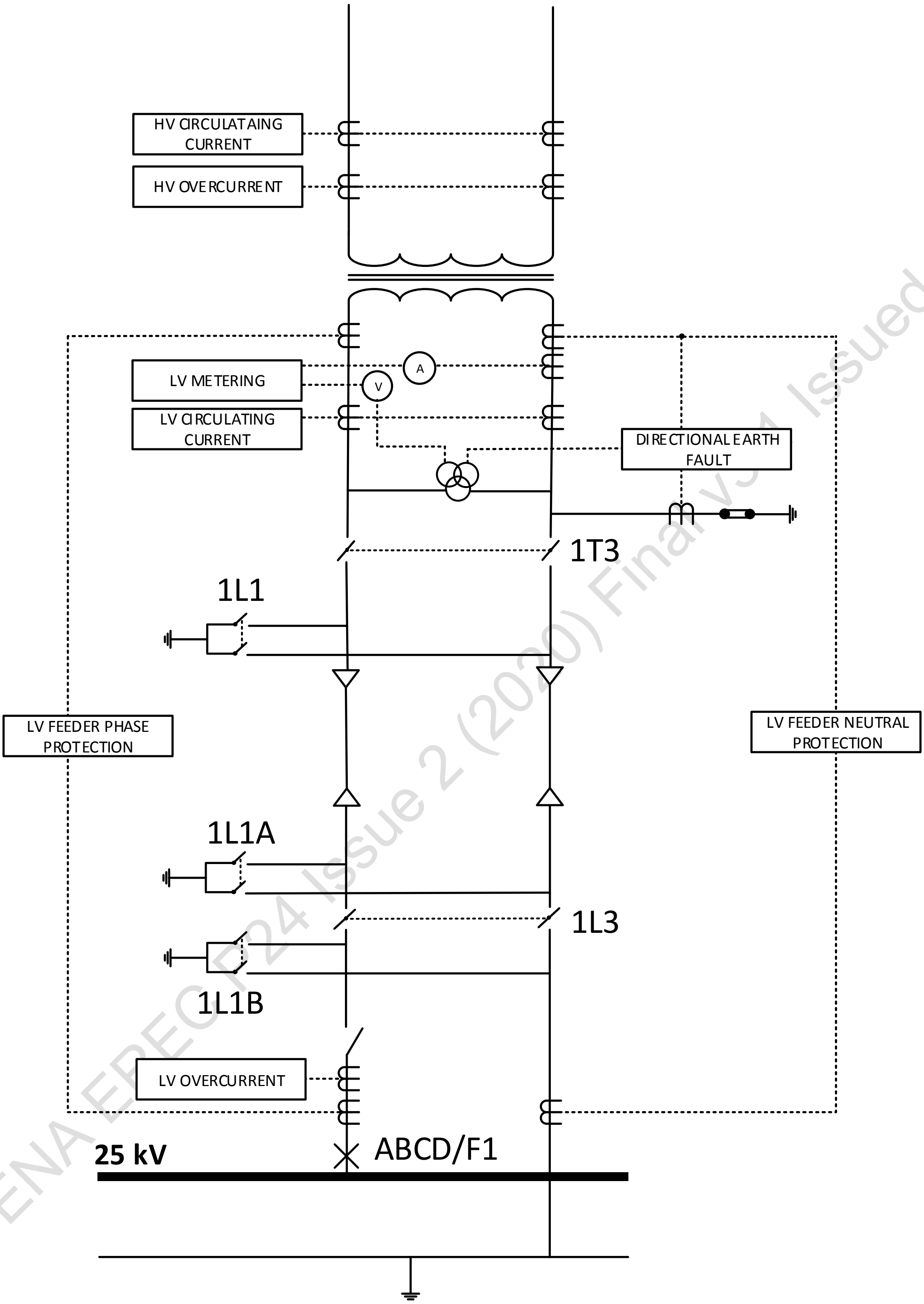


Figure 30 — Indicative protection scheme for 1 x 25 kV arrangement, transformer station and feeder station remote to one another, return conductor earthed at transformer

14.5.5 2 x 25 kV arrangement — indicative protection scheme

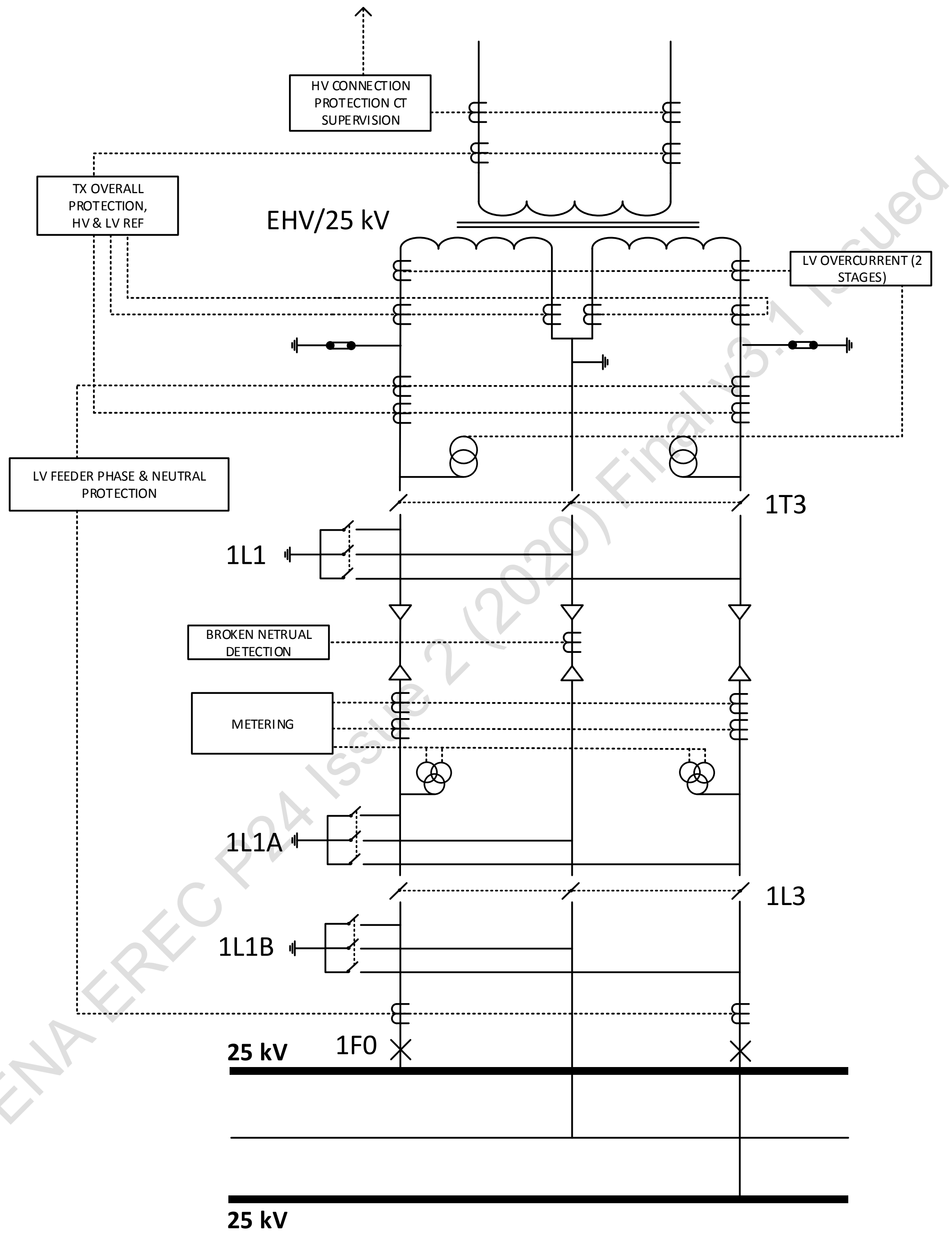


Figure 31 — Indicative protection scheme for 2 x 25 kV arrangement

14.6 Railway Infrastructure Manager Protection Policy

The primary protection scheme on the incoming 25 kV feeder circuit-breakers is co-ordinated with and forms an integral part of the protection system provided at the transformer, see Figures 28 to 31. In addition, an inverse definite minimum time over-current relay is provided to cover 25 kV busbar faults or sustained over-current, and to afford back-up protection to the outgoing track feeder circuit-breakers.

The protective system provided for the track feeder circuit-breakers is a single-phase version of the standard high-voltage transmission distance-measuring relay scheme. This employs a three-zone scheme of distance protection having a mho characteristic, with zone 1 providing protection for 80 to 85% of the protected section and zones 2 and 3 providing time-delayed protection for faults not covered by zone 1 as well as back-up protection for faults in adjacent sections. Zone 1 fault clearance time is about 90 ms.

Protection against high impedance faults or sustained overloads on track feeder circuit-breakers is provided by thermal over-current relays.

All bus section circuit-breakers are equipped with instantaneous overcurrent protection. This is operative only whilst the breaker is being closed in order to prevent mal-discrimination with the protection on the track feeder circuit-breakers.

Alongside the protection design, the Railway Infrastructure Manager shall demonstrate to the Electricity Network Operator that there are suitable and sufficient means to prevent out-of-phase closure of circuit-breakers, as required by Clause 5.3.4 (interlocking). Such scenarios are:

- incoming circuit-breakers at feeder stations supplied by an alternative railway supply point; and
- bus section circuit-breakers at mid-point sectioning stations. An example of a method to prevent paralleling of alternative supplies is the use of voltage sensing relays which allow closure only when one of the busbar sections is not energised.

15 System monitoring and control

15.1 Scope of signals

The indications and alarm schedule at traction supply substations should satisfy the following requirements as a minimum.

a) Zone 1 – Electricity Network Operator HV feeder up to transformer

There is no requirement for the Electricity Network Operator to provide the Railway Infrastructure Manager with indication/alarm. Alternatively, provision of the following indications/alarms to the Railway Infrastructure Manager may be agreeable.

- Feeder protection healthy/operation
- Status of circuit-breaker and/or line isolator (where applicable)

b) Zone 2 – Transformer

Both Railway Infrastructure Manager and the Electricity Network Operator should be provided with indication/alarm for the following.

- Transformer protection healthy/operated
- VT healthy/alarm

c) Zone 3 – 25 kV feeder

Railway Infrastructure Manager should provide the Electricity Network Operator with indication/alarm for the following.

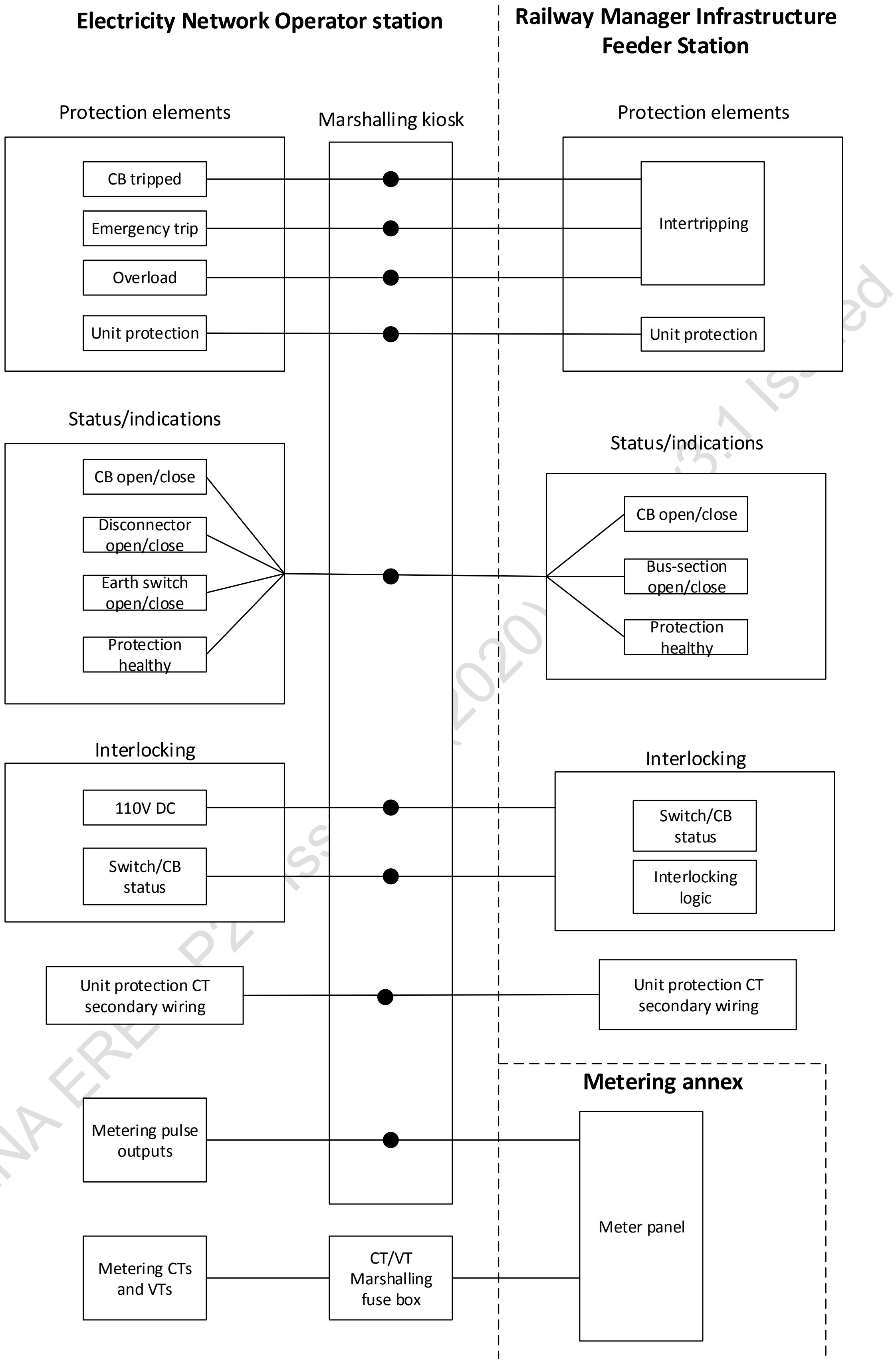
- 25 kV feeder protection healthy/operated
- Status of 25 kV circuit-breaker and disconnector.
- Busbar protection healthy/operated

15.2 Protection, signals and wiring interface

The Electricity Network Operator and the Railway Infrastructure Manager shall agree the exchange and interface arrangements for protection (see Clause 14), signals (see Clause 15.1) and metering (see Clause 12.9).

Responsibility for communicating the information between a transformer station and feeder station which are remote shall be agreed between the Electricity Network Operator and the Railway Infrastructure Manager.

A typical interface arrangement is depicted in Figure 32.



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2286 **Figure 32 – Typical signals and monitoring interface between Electricity Network**
2287 **Operator and the Railway Infrastructure Manager**

15.3 Communication protocol

Traditionally, communication between Railway Infrastructure Manager and Electricity Network Operators has been achieved with using wired communication for I/O schedules. Marshalling cabinets are normally the interface or exchange for the I/Os as depicted in Figure 32. The wired communications may make use of copper or fibre-optic cable and may be privately owned or provided by a telecommunications company.

The Railway Infrastructure Manager preference for new sites is to use an ethernet based communication protocol, compliant to BS EN 61850. Railway Infrastructure Manager and the Electricity Network Operator should agree if the application of a BS EN 61850 system is appropriate and reasonably achievable.

15.4 Investigation monitoring

It is important that adequate facilities exist for connection of suitable monitoring equipment, either during commissioning or when any special investigation is required.

It is anticipated that the facilities will be used for the following investigations.

15.4.1 Harmonic distortion

If harmonic complaints are received, these are most likely to be due to problems on the lower voltage distribution network and the question to be resolved will be the contribution of the railway distortion to the level i.e. the local 33 kV busbar. Facilities should be available for harmonic voltage or current measurements at 33 kV substations and these could be correlated with simultaneous measurements of harmonic current at the railway supply point.

Monitoring of harmonic distortion can only be achieved with installed transducers if these are of known accuracy and flat through the required frequency range. Given that harmonic distortion due to traction supplies is now generally at frequencies greater than 1 kHz, this is unlikely to be achievable without special additional transducers for test purposes. In practice, these are installed as required for testing and then removed.

15.4.2 Earth currents

The separate earths of the supply transformer and of the track, are likely to give rise to some earth return current. Facilities should be available for checking this when the supply is commissioned. A recording ammeter connected to a CT on the transformer earth connection will establish whether remedial measures have to be adopted.

15.4.3 Unbalanced load

Where problems associated with plant loading occur, recording ammeters can be installed to monitor 25 kV feeder current. Recording ammeters would also be useful for investigating system unbalance leading to excessive negative phase sequence voltages. It should be appreciated that depending on the phase relationship of the railway supply and other unbalanced loads from industrial or domestic sources, the railway supply may reduce or increase the negative phase-sequence (NPS) level. It is essential before any remedial action be attempted that the relationship between the unbalanced components due to the railway and other loads be correctly assessed.

16 Operational safety aspects

16.1 General

Operational Procedures associated with electricity supplies from grid supply points to railway feeder stations for traction purposes are formulated and agreed by Railway Infrastructure Manager and the Electricity Network Operator and are included in ENA ER G38 [N7]. Details of the supply points covered by the procedures are normally catered for by the inclusion of appendices to the Operational Procedures.

In drawing up appendices for new supply points, it may be necessary to include Operational Limitations to avoid earthing system hazards (see Clause 16.2):

Switching, isolation and earthing procedures shall comply with the Electricity Network Operator Safety Rules and those of Railway Infrastructure Manager, as appropriate.

On 25 kV a.c. single-phase systems a supply return conductor must be treated with caution since:

a) a current may still be flowing in the conductor even though its associated live conductor is out of commission;

b) it is ultimately connected to Railway Infrastructure Manager's return current busbar which may rise in potential when faults occur on the track system.

When appropriate, the isolation of the return conductor should be agreed with Railway Infrastructure Manager. In general, isolation may be achieved via a removable link at the substation earth bar connections.

16.2 Considerations for the earthing system

Whilst the design of the earthing system may need to take into account the consequences of equipment being operated, isolated and earthed for construction / maintenance / repair purposes, it is recognised that in the main the hazards will need to be controlled by the use of suitable operational procedures (ENA EREC G38 [N7] and National Grid National Safety Instruction 26 (NSI 26) [2]).

16.2.1 Main hazards

The main dangers are electric shock, burns and effects on eyes of arc flash arising from:

- Transferred potentials
- Touch, step and transferred potentials as a consequence of the interconnection or disconnection of separate earth electrode systems
- The application / removal of an earth to equipment capable of carrying alternative conductor return current, earth fault current and induced current
- The connection or disconnection of equipment capable of carrying alternative conductor return current or earth fault current

- The opening or closing of an earth link associated with a return current conductor, return current busbar or cable sheath

16.2.2 Control Method

The principal method of controlling touch, step and transferred potentials is to prevent the interconnection of separate earth electrode systems.

The principal method of controlling alternative conductor return current and short circuit current is to prevent such current from flowing through the point of work by eliminating paths along which such current could flow. This is achieved by one or more of the following:

- Opening and preventing the closure of disconnectors in order to stop return and short circuit current flowing via the phase and neutral conductors
- Opening and preventing the closure of earth switches in order to stop return and short circuit current flowing via the earth switch and the phase and neutral conductors
- Preventing the application of portable earths in order to stop return and short circuit current flowing via the portable earths and the phase and neutral conductors
- Opening and preventing the closure of cable sheath bonding links in order to stop return and short circuit current flowing via the cable sheath

16.2.3 Work on particular equipment

The precautions to be taken to avoid transferred potentials and alternative conductor return current / short circuit current from flowing through the work zone when working on one circuit connection to the railway whilst other circuits to the railway remain in service are outlined below.

Note that these precautions only relate to avoiding transferred potentials and alternative conductor return current and do not include a description of the necessary steps to achieve safety from the system, such as establishing points of isolation and applying circuit main earths.

16.2.3.1 Work On Transformer & *T0

The following applies to work in the Electricity Network Operator’s transformer station on the EHV/25kV transformer and circuit breaker *T0, but excluding work on disconnector *T3 and earth switches *T1 & *L1.

- Open Disconnector *T3 and prevent its closure in order to stop return and short circuit current flowing via the phase and neutral conductors

16.2.3.2 Work on Transformer, *T0, *T1, *T3 & *L1

The following applies to work in the Electricity Network Operator's transformer station, including infringing the safety distance to the 25 kV cable sealing ends, but excluding work on the cables or cable sheath connections.

- Open Disconnector *L3 and prevent its closure in order to stop return and short circuit current flowing via the phase and neutral conductors
- Open Earth Switch *L1A and prevent its closure in order to stop return and short circuit current flowing via the earth switch and the phase and neutral conductors
- Remove 25 kV Neutral - Earth link and prevent its re-insertion in order to stop return and short circuit current flowing via the neutral - earth connection and the neutral conductor ***(Segregated 25kV & higher voltage earth electrode arrangement only).***
- Prevent the application of earths onto the phase and neutral conductors on the transformer side of *L3 in order to stop return and short circuit current flowing via these earth connections and the phase and neutral conductors
- Remove the cable sheath bonding links at both ends of the cable and prevent their re-insertion in order to stop return and short circuit current flowing via these earth connections in the event that a sheath voltage limiter is faulty (i.e. it provides a path for alternative conductor return current).

16.2.3.3 Work on the 25 kV phase & neutral cables between transformer station and disconnector compound

The following applies to work on the cables, cable sealing ends or cable sheath connections on the 25 kV phase & neutral cables between the Electricity Network Operator's transformer station and disconnector compound.

- Open Disconnectors *T3 & *L3 and prevent their closure in order to stop return and short circuit current flowing via the phase and neutral conductors
- Open Earth Switches *L1 & *L1A and prevent their closure in order to stop return and short circuit current flowing via these earth switches and the phase and neutral conductors when an earth is placed on a cable conductor at the work position
- Prevent the application of earths onto the phase and neutral conductors on the transformer side of *L3 and the line side of *T3 in order to stop return and short circuit current flowing via these earth connections and the phase and neutral conductors when an earth is placed on a cable conductor at the work position
- Remove the 25 kV Neutral - Earth link and prevent its re-insertion in order to stop return and short circuit current flowing via the neutral - earth connection and the neutral conductor ***(Segregated 25 kV & higher voltage earth electrode arrangement only).***
- Remove the cable sheath bonding links at both ends of the cable and prevent their re-insertion in order to stop return and short circuit current flowing via these earth connections and the cable sheath when an earth is placed on a cable sheath at the work position, or where a sheath voltage limiter is faulty (i.e. it provides a path for alternative conductor return current).

- Work should, where reasonably practicable, be performed at one location at any one time in order to ensure that earths are applied to cable sheaths or conductors at a single point only. Concurrent working on the same cable at multiple locations should only be performed after a risk assessment has been carried out.

16.2.3.4 Work on auxiliary cables between transformer station and disconnector compound

The following applies to work on the auxiliary cables the Electricity Network Operator's transformer station and disconnector compound.

- Remove the earth connection from the auxiliary cable gland and prevent its re-connection in order to stop return and short circuit current flowing via this earth connection and the cable sheath / armouring when an earth is placed on the cable sheath / armour at the work position.
- Remove the (5 kV) insulated isolation plugs associated with the (5 kV) insulated terminal blocks at both ends of the auxiliary cable and prevent their re-insertion in order to stop return and short circuit current flowing via the conductors in the auxiliary cable when an earth is placed on a conductor at the work position.
- Work should, where reasonably practicable, be performed at one location at any one time in order to ensure that earths are applied to auxiliary cable sheath at a single point only. Concurrent working on the same cable at multiple locations should only be performed after a risk assessment has been carried out.

16.2.3.5 Work on *L1A, *L3, & *L1B

The following applies to work in the Electricity Network Operator's disconnector compound, including infringing the safety distance to the 25 kV cable sealing ends, but excluding work on the cables, cable sealing ends or cable sheath connections.

The precautions to be taken to avoid alternative conductor return current and short circuit current from flowing through the work zone are as follows:

- Open Disconnector *T3 and prevent its closure in order to stop return and short circuit current flowing via the phase and neutral conductors
- Open Earth Switch *L1 and prevent its closure in order to stop return and short circuit current flowing via the earth switch and the phase and neutral conductors
- Prevent the application of earths onto the phase and neutral conductors on the line side of *T3 in order to stop return and short circuit current flowing via these earth connections and the phase and neutral conductors
- Remove the cable sheath bonding links at both ends of the cable and prevent their re-insertion in order to stop return and short circuit current flowing via these earth connections in the event that a sheath voltage limiter is faulty (i.e. it provides a path for alternative conductor return current).

Whilst it is possible for alternative conductor return current and short circuit current to flow from the Railway Infrastructure Manager's system via the 25 kV phase and neutral cables between the disconnector compound and the feeder station, the bonding conductors between the disconnector compound earth electrode and the feeder station earth electrodes effectively bridges these connections and removes any risk to personnel.

16.2.3.6 Work on the 25 kV phase and neutral cables between disconnector compound and feeder station

These cables are the responsibility of the Railway Infrastructure Manager.

16.2.3.7 Work on the auxiliary cables between disconnector compound and feeder station

These cables are the responsibility of the Railway Infrastructure Manager.

16.2.3.8 Work on protection & control secondary circuits which have connections onto the auxiliary cables laid between the transformer station and disconnector compound

The (5 kV) insulated isolation plugs associated with the (5 kV) insulated terminal blocks should be removed in order to allow work on secondary wiring to be carried out safely i.e. allow work to be carried out on conductors at one end when they have a functional or protective earth connection at the other end.

17 Non-traction power supplies

This section applies to non-traction power supplies where a part of the installation or its earthing system has a connection to the return circuit of an a.c. traction system. It includes supplies to stations, level crossings, points heaters, signalling, feeder stations, intermediate stations, midpoint stations etc.

Where a non-electrified railway is electrified the requirements of this section apply retrospectively.

BS EN 50122 states that an electrical connection to non-railway earthing systems is undesirable, and that in case of an intended connection an agreement is required between the railway side network infrastructure owner and the owner of the other network infrastructure. In the UK this agreement is in the form of:

- ENA EREC P24 (this document)
- ENA EREC G12 [N6]
- Distribution or Transmission Electricity Network Operator company specific engineering policy or standards
- Network Rail NAT/TW/InfraInv/ENG/EP6248683 [N15]: *Design and Installation of New, Renewed or Refurbished Distribution Electricity Network Operator's (DNO's) Intakes and Consumer Facilities*

Non-traction power supplies should be subject to appropriate metering provision, and operated in accordance with the MOCoPA [N2].

17.1 LV non-traction power supplies to the Railway Infrastructure Manager

17.1.1 Hazards

Care must be taken to address transferred potentials and overheating of cables.

The Electricity Network Operator's system (and consumer installations connected to that system) may be endangered by:

a) The rise of voltage on the traction rail due to traction return current or short circuit current being transferred to protective conductors or combined protective and neutral conductors, and consequently to exposed conductive parts that are intentionally connected to those conductors.

b) Alternative conductor traction return current overloading protective conductors or combined protective and neutral conductors.

c) Both of a) and b) above but in the event of a break in the traction return current connection.

The Railway Infrastructure Manager's system may be endangered by:

d) The rise of voltage on the main earth terminal in the event of a broken combined protective and neutral conductor on the Electricity Network Operator's system.

17.1.2 Control Measures

Control measures to safeguard the Electricity Network Operator's system (and consumer installations connected to that system) are as follows:

a) The Electricity Network Operator's earth and the Railway Infrastructure Manager's earth shall be kept separate on any low voltage non-traction power supply to a 25 kV traction substation.

b) An earth terminal may be provided on a low voltage non-traction power supply to the Railway Infrastructure Manager at other locations provided:

- The rise of voltage on the traction rail due to traction return current does not exceed 25 V under traction peak starting or running current conditions.
- The rise of voltage on the traction rail due to short circuit current does not exceed 430 V for faults with a duration greater than 0.2 seconds, or does not exceed 650 V for faults with a duration of 0.2 seconds or less.
- Protection is provided at each feeder station and/or grid supply compound which detects breaks in traction bonds (red bonds) and supply return conductors and initiates the disconnection of the associated traction supply infeed.

Control measures to safeguard the Railway Infrastructure Manager's system are as follows:

c) Housings at the Electricity Network Operator intake position and other locations shall not expose members of the public to dangerous touch potentials.

- Non-metallic housings are preferred.
- In the event that a metallic housing is employed, the Railway Infrastructure Manager shall provide and bond an earth electrode to the main earth terminal of a sufficiently low resistance as to limit the voltage between the main earthing terminal of the installation and earth to 70 V or less in the event of broken combined protective and neutral conductor on the Electricity Network Operator's system.

d) The Railway Infrastructure Manager shall assess and control the risks to railway personnel because the measures described in c) above do not necessarily provide full protection against touch potential for those individuals.

17.2 HV non-traction power supplies to the Railway Infrastructure Manager

17.2.1 Hazards

Care must be taken to address transferred potentials and overheating of cables.

The Electricity Network Operator's system (and consumer installations connected to that system) may be endangered by:

a) The rise of voltage on the traction rail due to traction return current or short circuit current being transferred to the Electricity Network Operators HV earth electrode where the two are bonded together (and consequentially transferred to LV protective conductors or combined protective and neutral conductors and to exposed conductive parts that are intentionally connected to those conductors where Electricity Network Operator HV and LV earth electrodes are bonded together).

b) Alternative conductor return current overloading protective conductors or combined protective and neutral conductors.

c) Both of a) and b) above but in the event of a break in the traction return current connection.

d) The rise of voltage on the Electricity Network Operator's HV earth electrode (due to short-circuit current flowing through that electrode as a consequence of a fault on the Railway Infrastructure Manager's HV network) being transferred to Electricity Network Operators HV earth electrode where the two are bonded together.

The Railway Infrastructure Manager's system may be endangered by:

e) The rise of voltage on the Electricity Network Operator's HV earth electrode (due to short circuit current flowing through that electrode as a consequence of a fault on the Electricity Network Operator's HV network) being transferred to Railway Infrastructure Manager's HV earth electrode where the two are bonded together.

f) The rise of voltage on the Electricity Network Operator's HV earth electrode or the Rail Infrastructure Manager's HV earth electrode as a consequence of d) or e) above may endanger the Rail Infrastructure Manager's LV system where the Rail Infrastructure Manager's HV and LV earth electrodes are bonded together.

NOTE: The Electricity Network Operator has a statutory duty under the Electricity Safety, Quality and Continuity Regulations [N1] to prevent danger occurring in any low voltage network as a result of any fault in the high voltage network.

17.2.2 Control Measures

Ideally the Electricity Network Operator and Railway Infrastructure Manager HV earthing systems should be designed such that they are not dependent on each other for safety. However, an interdependent earthing design where both HV earthing systems have to be interconnected in order to achieve safety is acceptable.

17.2.2.1 Control Measures where independent HV earthing systems are provided

Control measures to safeguard Electricity Network Operator and Railway Infrastructure Manager systems where their respective HV earthing systems are not dependent on each other for safety are as follows:

a) The Railway Infrastructure Manager's HV earthing system shall, as a minimum requirement, be designed in accordance BS EN 50522.

b) The Railway Infrastructure Manager's HV and LV earth electrodes shall be kept physically separate where the earth potential rise on the HV electrode exceeds 466 V. Separation shall be by a sufficient distance such that the voltage rise on the LV electrode is acceptable (see ENA TS 41-24 [N11] for further details on separation distances).

c) Protection shall be provided on each associated traction supply point connection which detects breaks in the traction return current connection and initiates the disconnection of the associated traction supply infeed.

17.2.2.2 Control Measures where interdependent HV earthing systems are provided

Control measures to safeguard the Electricity Network Operator and Railway Infrastructure Manager systems where their respective HV earthing systems are dependent on each other for safety are as follows:

a) Duplicate interconnections shall be provided between the Electricity Network Operator and Railway Infrastructure Manager HV earth electrodes.

b) The earth resistance of the combined HV earth electrode shall be in accordance with the local Electricity Network Operator's policy in order to ensure correct source protection operation (typically 10-20 ohms).

c) The earth potential rise on the combined HV electrode shall be in accordance with the local Electricity Network Operator's policy in order to ensure equipment insulation withstand capabilities are not exceeded (typically 2-3 kV).

d) Sufficient surface area in contact with the soil shall be provided on the combined HV electrode in order to ensure the soil around the electrode does not dry out and increase in resistance during an earth fault (see ENA TS 41-24 [N11] and ENA EREC S34 [N14] for further details).

e) Touch and step voltages on the combined HV electrode shall be within the limits specified in ENA TS 41-24 [N11].

f) The Railway Infrastructure Manager's HV and LV earth electrodes shall be kept physically separate where the earth potential rise on the HV electrode exceeds 466 V. Separation shall be by a sufficient distance such that the voltage rise on the LV electrode is acceptable (see ENA TS 41-24 [N11] for further details on separation distances).

g) Protection is provided at each feeder station and/or grid supply compound which detects breaks in traction bonds (red bonds) and supply return conductors and initiates the disconnection of the associated traction supply infeed.

17.3 LV power supplies to the Electricity Network Operator

The purpose of this section is not to cover ac auxiliary power supplies to Electricity Network Operator substations or disconnector compounds per se but to consider issues that are peculiar to ac traction supply points.

17.3.1 General

LV power supplies will be required for some or all of the following: transformer fans and pumps, battery chargers, lighting and heating etc.

The security of the LV power supply should reflect the connection i.e. a double EHV/25 kV transformer connection will generally require a main and a standby LV power supply.

The following options may be considered for LV power supply provision.

a) Supplies derived from an auxiliary transformer associated with the Electricity Network Operator's transformer station or disconnector compound.

b) Supplies derived from the local LV electricity network.

c) Supplies derived from an auxiliary transformer associated with the Railway Infrastructure Manager's 25 kV system.

The LV power supplies should be subject to appropriate metering provision, and operated in accordance with the MOCoPA [N2].

17.3.2 Supplies from an auxiliary (or earthing/auxiliary) transformer located within The Electricity Network Operator's Transformer Station / Disconnector Compound

This section applies where LV power supplies are derived from an auxiliary or earthing/auxiliary transformer located within the earth 'mesh/grid' of the EHV/25 kV transformer station or 25 kV disconnector compound. For example, from a 25 kV / LV auxiliary transformer associated with the EHV/25kV transformer, or from an auxiliary or earthing/auxiliary transformer associated with a Grid or Primary transformer installed on the same site.

The auxiliary transformer HV metalwork and LV neutral will be connected to the earthing system of the transformer station or disconnector compound. In other words, a protective neutral bond (PNB) type supply arrangement.

Since the LV power supply is derived within the earthing system of the transformer station or disconnector compound there are no issues with transferred potentials or traction return current whilst the associated LV installation is wholly contained within the earth 'mesh/grid'.

In the event that this supply is also used to provide an LV supply to Railway Infrastructure Manager's feeder station then consideration should be given to transferred potentials and to alternative conductor return current. An isolation transformer should be provided inside the Railway Infrastructure Manager's feeder station, with the sheath/screen/armour of the incoming LV supply cable isolated from the feeder station metalwork. Alternatively, a TT supply could be provided.

17.3.3 Supplies derived from the local electricity network

The preferred arrangement is for dedicated LV supplies to be provided to the Electricity Network Operator's transformer station / disconnector compound i.e. without connections to customers external to the substation. This avoids transfer potentials to customer installations and simplifies the design.

Where the LV supply is derived from a transformer outside of the earth 'mesh/grid' it is necessary to control transfer potentials.

Permitted arrangements are as follows:

a) Supply via a dedicated pole or ground mounted transformer located outside the 'mesh/grid'

b) Supply from the local LV network

17.3.3.1 Supply via a dedicated pole or ground mounted transformer located outside the 'mesh/grid'

"Dedicated" means that the transformer is used exclusively for providing LV supplies to the Electricity Network Operator's transformer station / disconnector compound and is not used to provide LV supplies to other customers.

The pole or ground mounted transformer LV neutral shall be connected to the Electricity Network Operator's transformer station / disconnector compound earthing system i.e. a PNB connection.

The pole or ground mounted transformer HV metalwork shall be earthed via either:

a) The Electricity Network Operator’s transformer station / disconnector compound earthing system or;

b) Its own local HV earth separated from the Electricity Network Operator’s transformer station / disconnector compound earth electrode by a minimum of 2 m.

Note that a pole transformer utilising arrangement a) may be more vulnerable to lightning damage because of the lead length to the earth electrode.

A ground mounted transformer utilising arrangement a) may require a potential grading electrode around it to control touch potentials.

The arrangement in b) above shall not be used where the earth potential rise of the:

- Electricity Network Operator’s transformer station / disconnector compound exceeds equipment insulation withstand capabilities (typically 2-3 kV).

- Pole or ground mounted transformer HV earth exceeds equipment insulation withstand capabilities (typically 2-3 kV).

17.3.3.2 Supply from the local LV network

The TN-C-S or TN-S earth terminal of the LV supply shall be connected to the earthing system of the transformer station / disconnector compound in order to prevent local potential differences. This creates the following problems:

a) The rise of voltage on the traction rail due to traction return current or short-circuit current being transferred to protective conductors or combined protective and neutral conductors, and consequently to exposed conductive parts that are intentionally connected to those conductors.

b) Alternative conductor return current overloading protective conductors or combined protective and neutral conductors.

c) Both of a) and b) above but in the event of a break in the traction return current connection.

d) The rise of voltage on the earthing system of the Electricity Network Operator’s transformer station / disconnector compound due to short circuit current being transferred to protective conductors or combined protective and neutral conductors, and consequently to exposed conductive parts that are intentionally connected to those conductors.

To control these problems, this type of supply shall only be permitted where:

- – The rise of voltage on the traction rail due to traction return current does not exceed 25 V under traction peak starting or running current conditions.

- – The rise of voltage on the traction rail due to short circuit current does not exceed 430 V for faults with a duration greater than 0.2 seconds, or does not exceed 650 V for faults with a duration of 0.2 seconds or less.

- – Protection is provided on each traction supply point connection which detects breaks in the traction return current connection and initiates the disconnection of the associated traction supply infeed.

- The rise of voltage on the earthing system of the Electricity Network Operator's transformer station / disconnector compound due to short-circuit current does not exceed 430 V for faults with a duration greater than 0.2 seconds but less than 3 seconds, or does not exceed 650 V for faults with a duration of 0.2 seconds or less.

17.3.4 Supplies derived from an auxiliary transformer associated with the Railway Infrastructure Manager's 25 kV system

This section applies where LV power supplies are derived from a Railway Infrastructure Manager's 25 kV / LV auxiliary transformer,

The auxiliary transformer HV metalwork and LV neutral will be connected to the Railway Infrastructure Manager's earthing system. In other words, a protective neutral bond (PNB) type supply arrangement.

Consideration should be given to transferred potentials and to alternative conductor return current. An isolation transformer should be provided inside the Electricity Network Operator's EHV/25 kV transformer station, with the sheath/screen/armour of the incoming LV supply cable isolated from the transformer station metalwork. Alternatively a TT supply could be provided.

17.4 Loss of return protection

17.4.1 General

The traction return connections from running rails to the return current busbar are provided with redundancy, in order to mitigate full loss of current in the normal traction return circuit. As a result, such a loss is extremely rare. However, in the event that it occurs, the traction return current will leak from the running rails into earth and into Electricity Network Operator's HV & LV networks in the event that an earth connection is provided and the main earth terminal is bonded to the traction rail.

Traction supply connections for the 1 x 25 kV and 2 x 25 kV arrangements should be provided with protection against such loss of the return circuit. This may be achieved through the use of current differential protection on the 25 kV incoming feeders. A typical scheme is described in Clause 17.4.2.

It is accepted that for all configurations, a relatively small amount of traction current flows via earth, and that the purpose is to protect against full loss of the traction return system. Hence, the differential protection scheme selected should be capable, through bias or other means, of permitting a spill current setting. A reasonable initial setting is 15%, which provides security against false tripping. It is recommended that measurements of typical earth currents are made as part of commissioning such a system, particularly where significant earth return paths exists, such as at co-located supply point and feeder station sites, with interconnected earths. Where traction return is not switched as an integral part of the incoming feeder switching arrangement, a single differential system should be provided across all incoming feeders. In all cases, operation of this protection indicates loss of the traction return circuit, and should initiate suitably appropriate action by the Railway Infrastructure Manager.

17.4.2 Typical broken neutral and neutral overload protection

All EHV/25kV transformers are equipped with broken neutral and neutral overload protection, as shown diagrammatically in Figure 33.

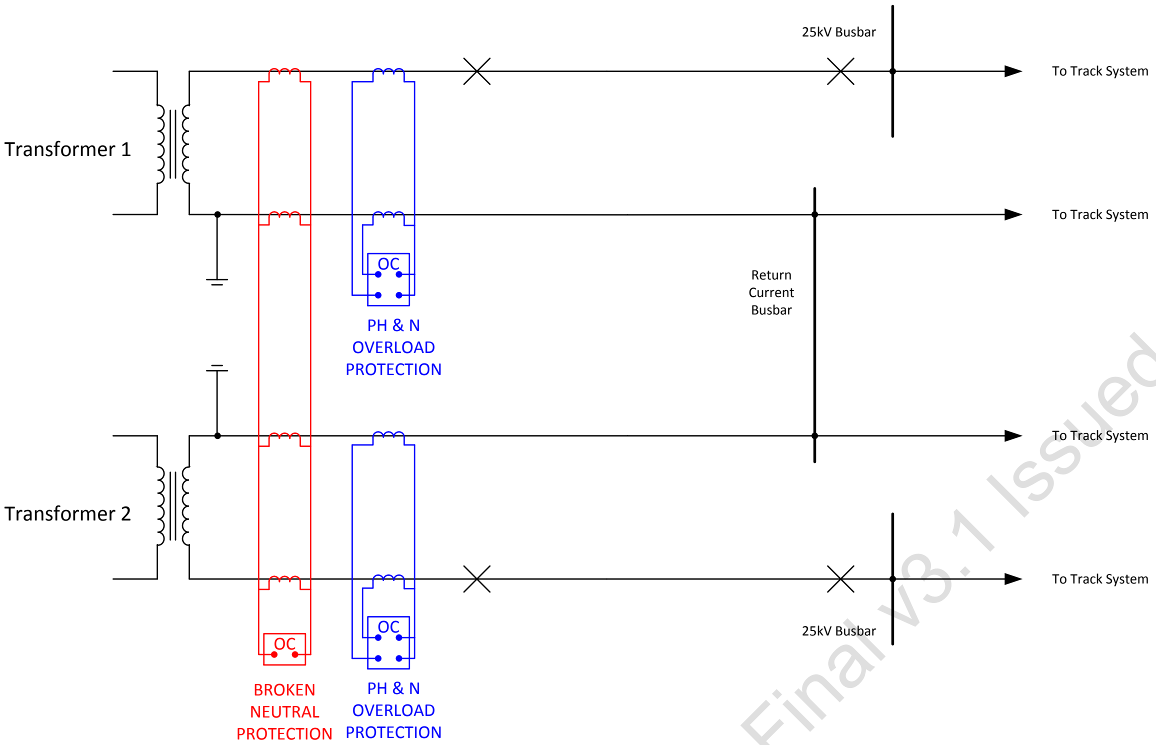

Figure 33 – Typical broken neutral and neutral overload protection scheme

Overcurrent class protection CTs are located on the load side of the transformer neutral-earth point, and in both phase and neutral connections.

Phase and neutral overload protection comprises of definite-time overcurrent protection, with a current setting in excess of the phase and neutral conductor rating and a definite time delay in excess of 30 seconds.

Broken neutral protection comprises of definite-time overcurrent protection, with a current setting in excess of the load current which normally returns via the earth / alternative conductors rather than via the neutral return conductors. The definite time delay shall be in excess of 30 seconds.

Protection operation for various scenarios is described below.

a) Normal Conditions – both transformers in service

- Current in the phase conductor is less than the phase conductor rating, and hence less than the phase overload protection setting
- Current in the neutral conductor is less than the neutral conductor rating and hence less than the neutral overload protection setting
- Current in the broken neutral protection is equivalent to the load current which normally returns via the earth / alternative conductors rather than via the neutral return conductor, and hence is less than the broken neutral protection setting

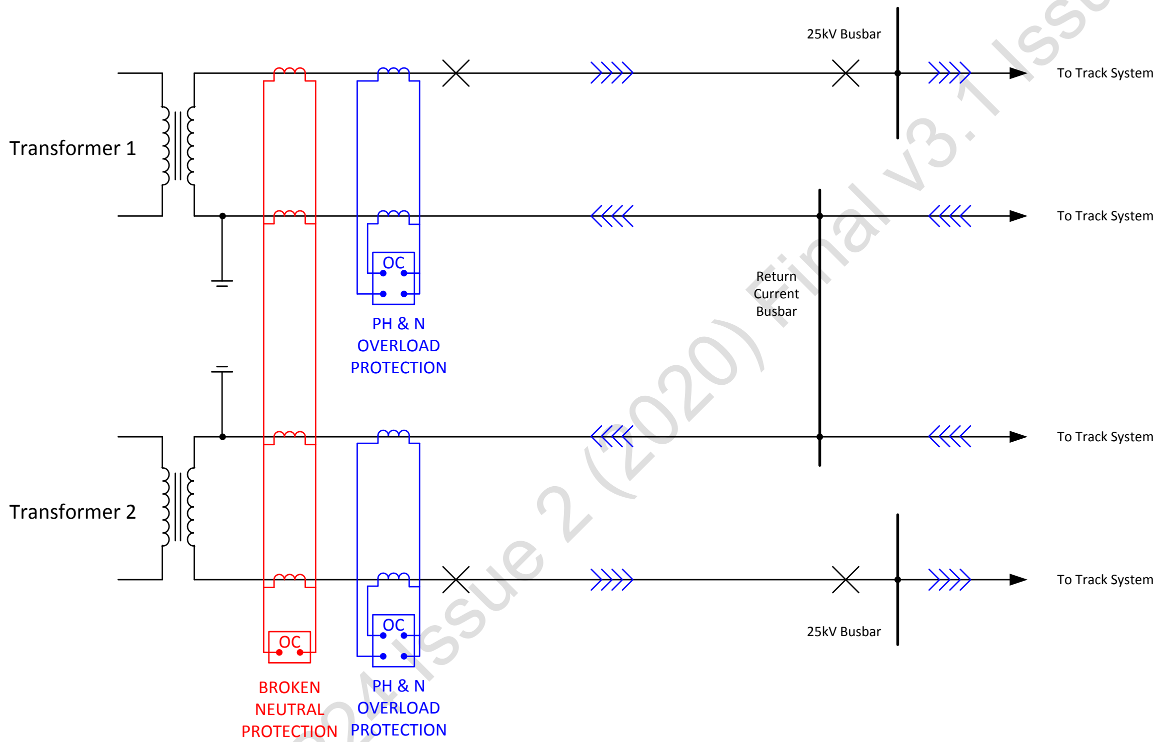

Figure 34 – Neutral protection scheme with both transformers in service

b) Normal Conditions – one transformer out-of-service

- The current in the phase conductor should be less than the phase conductor rating, and hence less than the phase overload protection setting. However, if the circuit is overloaded above its rating then the phase overload protection would operate if the overload persists for longer than the definite time delay
- The current in the neutral conductor is less than the neutral conductor rating and hence less than the neutral overload protection setting
- The current in the broken neutral protection is equivalent to the load current which normally returns via the earth / alternative conductors rather than via the neutral return conductors, and hence is less than the broken neutral protection setting

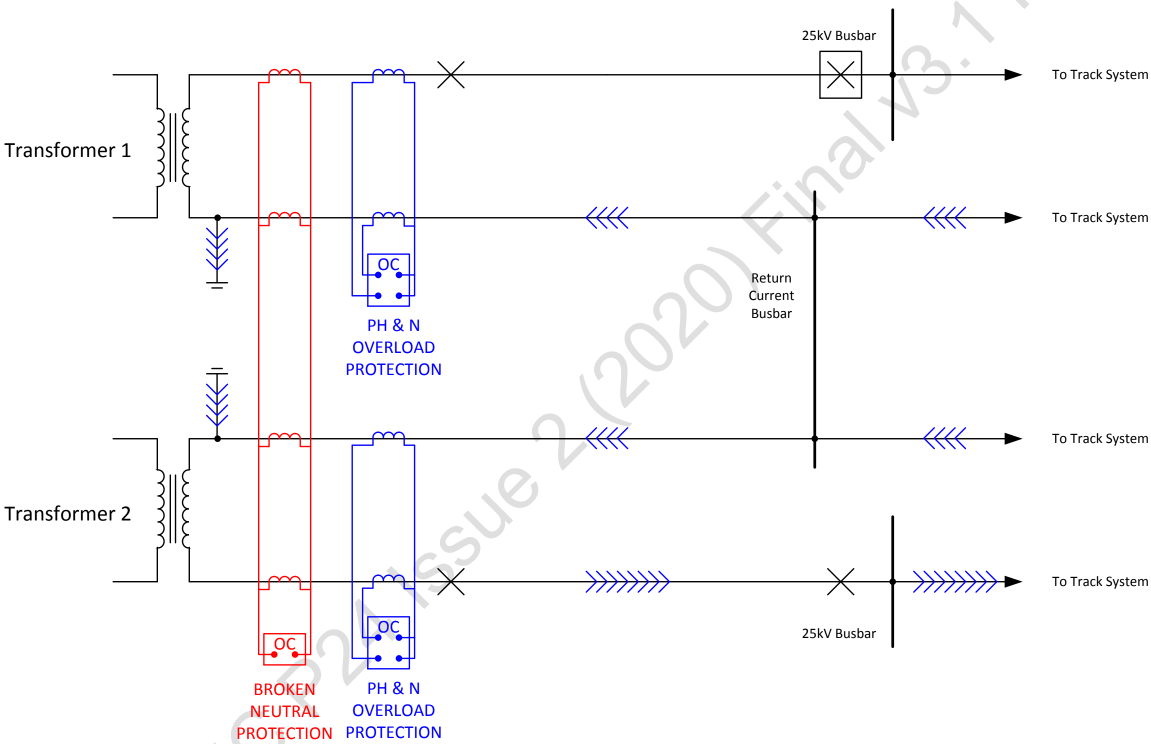

Figure 35 – Neutral protection scheme with one transformer out-of-service

c) Broken neutral return conductor on one circuit

- The current in the phase conductor should be less than the phase conductor rating, and hence less than the phase overload protection setting
- If the current in the neutral conductor exceeds the neutral conductor rating then the neutral overload protection would operate if the overload persists for longer than the definite time delay. Note that the neutral protection that operates will be associated with the healthy circuit rather than the defective one, hence configuring the protection to alarm rather than trip should be considered
- The current in the broken neutral protection is equivalent to the load current which normally returns via the earth / alternative conductors rather than via the neutral return conductors, and hence is less than the broken neutral protection setting

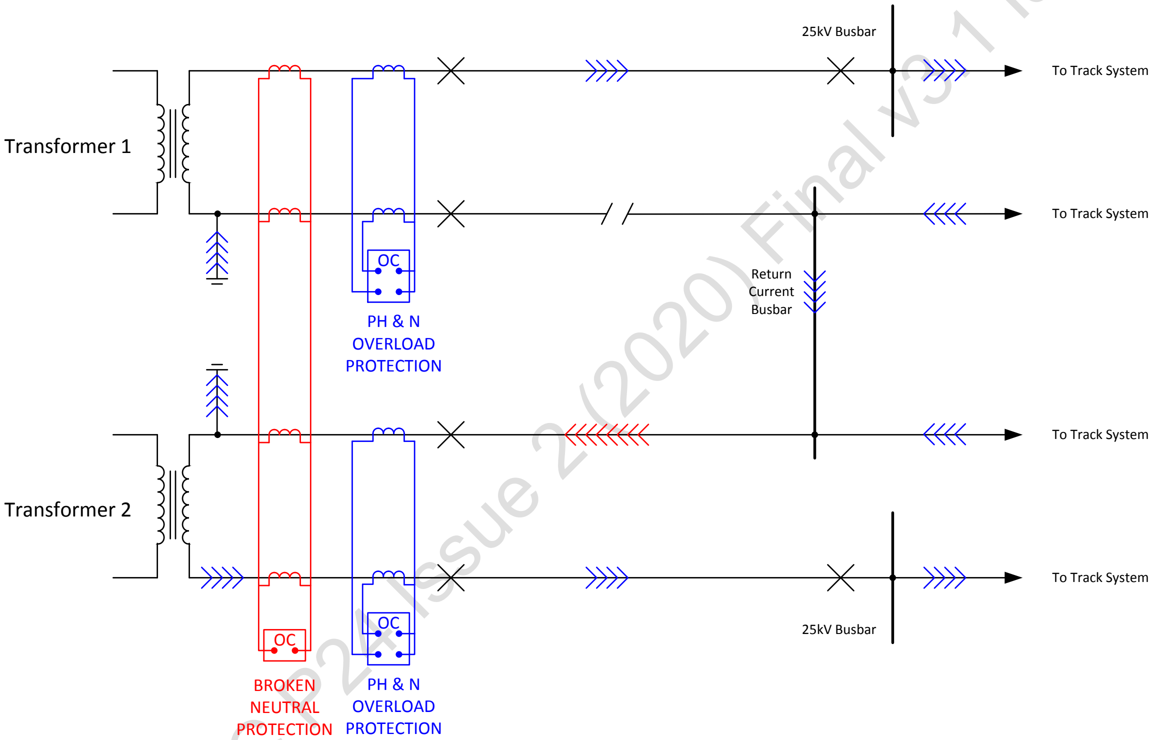

Figure 36 – Neutral protection with broken neutral return conductor on one circuit

d) Broken neutral return conductors on both circuits

- The current in the phase conductor should be less than the phase conductor rating, and hence less than the phase overload protection setting
- There is no current in the neutral conductors, and hence nothing to operate the neutral overload protection
- The current in the broken neutral protection is equivalent to the total load current since all current will be returning via the earth / alternative conductors. The broken neutral protection will operate if this current is in excess of the broken neutral protection setting and persists for longer than the definite time delay

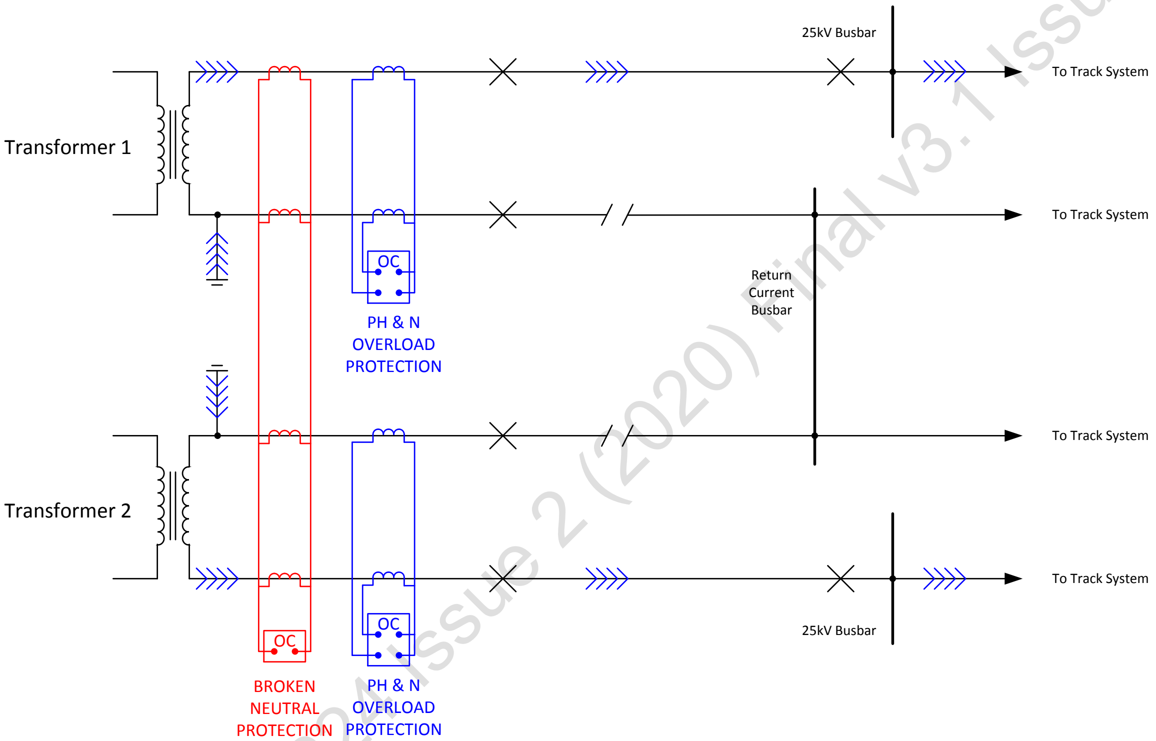

Figure 37 – Neutral protection with broken neutral return conductors on both circuits

e) Broken traction (red) bonds

– The current in the phase conductor is less than the phase conductor rating, and hence less than the phase overload protection setting.

– There is no current in the neutral conductors, and hence nothing to operate the neutral overload protection

– The current in the broken neutral protection is equivalent to the total load current since all current will be returning via the earth / alternative conductors. The broken neutral protection will operate if this current is in excess of the broken neutral protection setting and persists for longer than the definite time delay

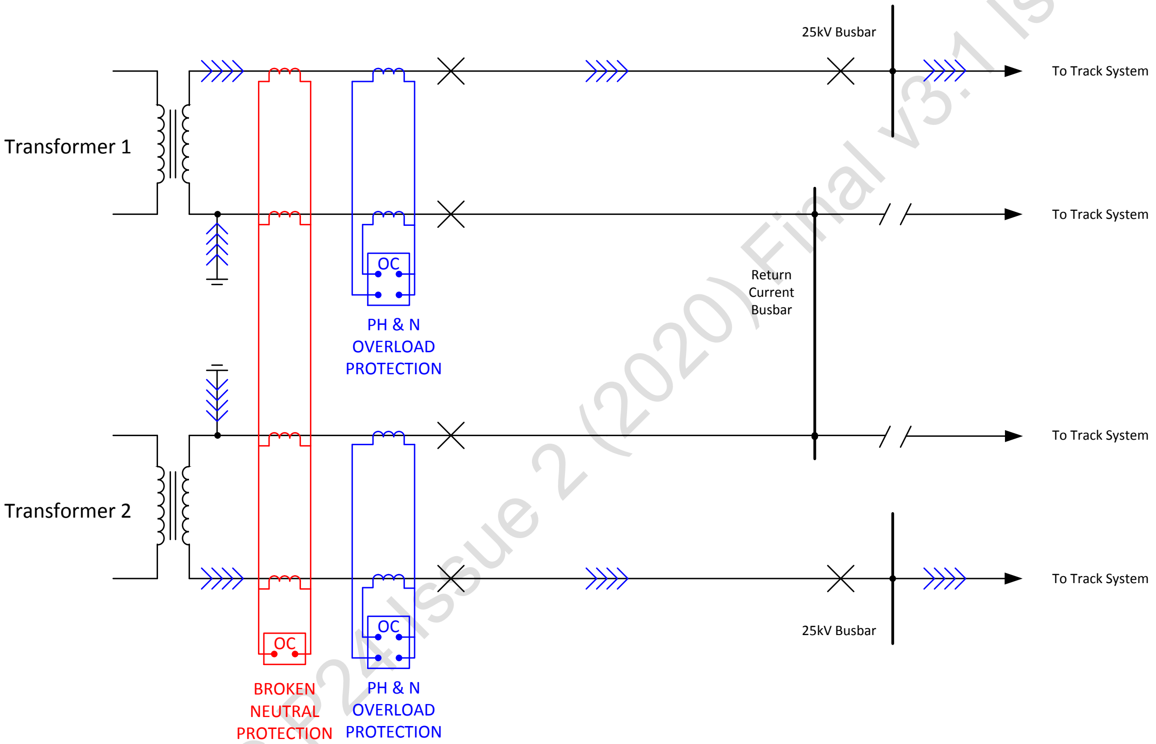

Figure 38 – Neutral protection with broken traction (red) bonds

Annex A
(informative)

Alternative Transformer Supply Arrangements

A.1 Scott transformer

A typical Scott transformer winding is depicted in Figure A1.

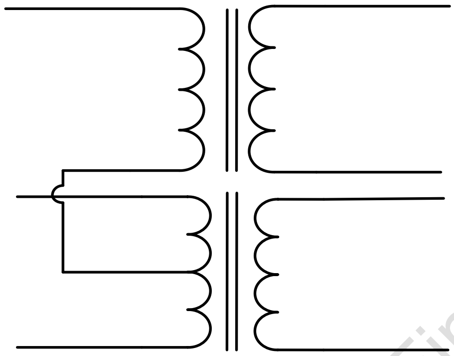

Figure A.1 — Scott transformer winding configuration

The use of three/two-phase transformers (Scott connected and Roof-Delta) could, if the two single-phase secondary windings were equally loaded, present a fully balanced three-phase current on the primary side.

NOTE: The purpose of any balancing system is not to achieve full balance, rather to provide a compliant level of balancing so as not to exceed agreed unbalance levels. The use of balancers, such as the Scott transformer does not change the permissible unbalance levels, nor reduce them to zero.

In practice, for a Scott transformer, the two secondary windings will seldom be equally loaded as the transformer must feed two isolated sections of track, as a result of the secondary windings being 90° out of phase with one another.

The Railway Infrastructure Manager would specify, own and operate the Scott transformer unless otherwise agreed by the Electricity Network Operator.

Depending on the system design (whether each LV winding is connected separately to a section of railway or not), account must be taken of the possibility of a number of outage conditions and therefore further unbalance between the loading on the secondary windings. The outage of at least one transformer in the supply system which could result in additional loading on one secondary winding at each adjacent track feeder station, unbalanced conditions would then prevail. Under this condition the use of three/two phase transformers will have limited impact on the negative phase-sequence (NPS) voltage rise due to the unbalance. Each load on the secondary windings of the transformer introduces an NPS in the opposing direction. This therefore reduces the overall NPS, providing loads are similarly balanced, background NPS is low and winding outages can be reduced or avoided.

A.2 Transformer supply with power electronics

A.2.1 Power factor correction (PFC)/balancer

Figure A2 shows the a basic arrangement for phase balancing as could be applied to traction supply points, provided the controlled elements can be economically designed for direct connection at up to 33 kV.

The Railway Infrastructure Manager would specify, own and operate transformers with power electronics unless otherwise agreed by the Electricity Network Operator

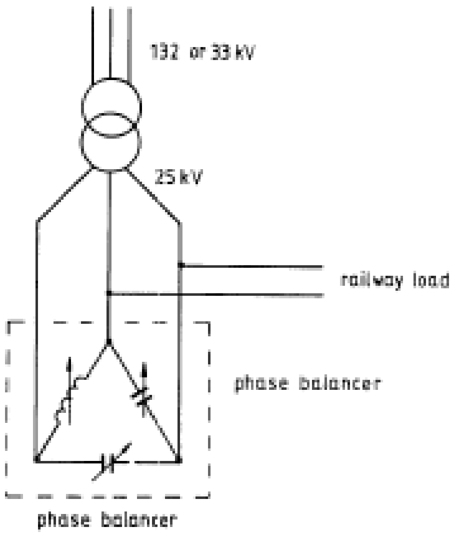

Figure A.2 — Basic phase balancer arrangement

The limiting condition defining the rating of the compensator would be during the outage of a railway supply transformer where two track sections must be fed from the same transformer.

The balancer must limit the unbalance to the specified value which ensures that the level on the local supply system to other consumers does not exceed voltage unbalance limits. If there are two transformers at a supply point, some economy in compensator components is possible if both supplies are taken from the same pair of phases. It is not then necessary to provide both capacitive and inductive controlled reactances in each phase, since the nature of the unbalance load variation restricts the range of compensation required. The control system for the phase balancer can be designed to operate only on the load drawn by the railway with the control signals derived from railway load current measurement. Alternatively, the system can be designed to attempt to minimise the total unbalance on the local supply system. This requires the compensator to react to the net out-of-balance due to the railway and other loads. It should in general provide a better quality of supply for other consumers. The control signals would need to be derived from the voltage at the point of common coupling.

Two main types of compensator have been identified as below.

A.2.1.1 Smooth Control of Unbalance

Where smooth and precise control of unbalance is required, equipment including thyristor control of the reactive elements must be used. Current flow in part of the inductive load is switched by back-to-back connected thyristors operating under phase control. This provides a smooth variation of effective inductive reactance value from open circuit to the actual component value. Only part of the total inductive load need be operated under phase control with some duplication for security. The remainder would be in separate units of about the same size switched in by their own back-to-back connected thyristor as required. This has the merit of reducing the harmonic distortion produced by the compensator. The size of the reactor units would be optimised in terms of thyristor and reactor costs.

The capacitor banks are similarly sub-divided but have to be switched in as units since phase control is not applicable. However the fast response-of the thyristors and the associated control allows the phase controlled reactor unit to effectively smooth out voltage changes which might otherwise cause annoyance.

Where the balancer is only required to deal with the railway unbalance, the arm connected across the railway phases will be capacitive and by inclusion of suitable inductors can provide harmonic filtering. It should be possible for some of the capacitance to be in circuit at all times and additional capacitance will be inserted as the traction load increases. Hence added filtering will be introduced as it is required by the additional harmonic distortion.

The cost of phase balancing equipment will depend on the degree of sophistication and the connection voltage. For a balancer connected at 25 kV or 33 kV the cost is likely to be in the range 2-3 times the cost of a transformer of the same rating. Operating losses are likely to be of the order of 0.75% of MVA rating but would vary with the operating conditions.

A.2.1.2 Step Control of Unbalance

Where a less precise control of the unbalance is permissible, lumped values of capacitance or inductance can be inserted when required. Vacuum switches would probably be used as the controlling element to reduce maintenance requirements. The sub-division of the reactive units provides some measure of added security against failure of individual sections. The degree of sub-division of the active components determines the number of switching operations and precautions would need to be taken to distribute these between the switches. Discrete component switching would also increase the number of voltage steps applied to the system, but suitable selection of component value for the individual steps could limit the step voltage to an acceptable level.

For most railway supply points there can be very considerable and rapid fluctuation of traction. This would necessitate frequent switching and such information should be made available to manufacturers quoting for balancing equipment. While it is possible that the compensator need not respond to load fluctuations of very short duration, it must be able to prevent an excursion of the voltage unbalance limit.

A.2.1.3 Design of power factor correction equipment

Figure A3 shows the circuit for balancing a single-phase line-to-line connected load on a three-phase system, while Figure A4 shows the vector diagrams for the individual branch currents and their summation to effect the required symmetrical loading. It should be noted that the inductive arm is connected between the unused phase and the leading phase of the load.

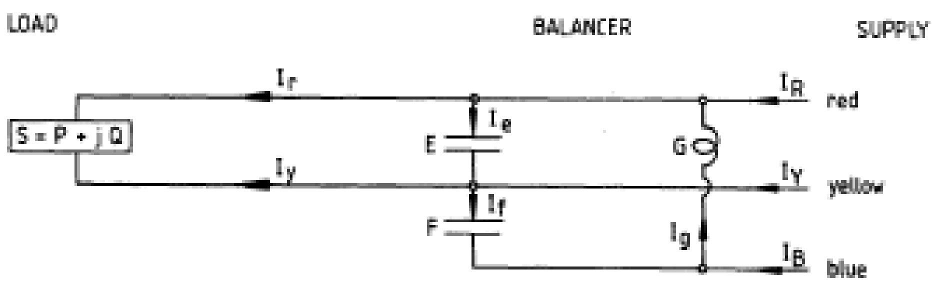

Figure A3 — Balancer for single-phase load

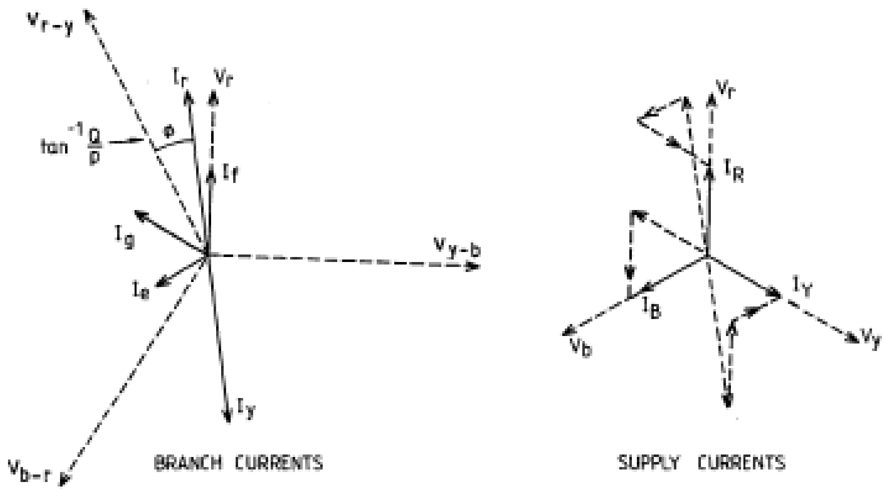

Figure A.4 — Vector diagrams for a single-phase load balancer

The balancer will improve the power factor of the resultant three-phase load and can, depending on the component values chosen, be designed to provide complete or partial balancing. For full balancing of a single line-to-line connected load it can be shown that the resultant power factor of the three-phase load at 50 Hz will also be unity. For a load of S MVA comprising real and reactive components P and Q, the required component values for full balancing would be rated at:

- E= -j S sin Ø = - j Q
- F= -j (S/ √3) cos Ø = -j P/√3
- G= +j (S/ √3) cos Ø = +j P/√3

In practice it may be uneconomic to provide full phase balancing and a criterion may be adopted whereby the traction load at a supply point should not contribute more than x% of negative phase sequence voltage. In this case the part of the maximum railway load S to be balanced would be

- S= xF/100

where F is the minimum plant fault level at the point of common coupling. This assumes no interconnection with other supply points and a somewhat smaller compensation may be possible where a harmonic study of the interconnected system indicates that some of the load is compensated by contributions from other supply points.

Where two line-line loads are connected at the same supply point, as shown in Figure A5 the nature of two arms must be interchangeable and depend on the relative values of the two loads. Provided both loads exist simultaneously it can be shown that there could be some reduction in the MVAr requirement for two of the three arms. However, since it is a planned outage condition that both supplies can be connected to the same phase pair, the reduction in the component rating cannot be realised. Where a balancer is used, it is preferable for both track sections to be fed from the same phase pair as this avoids the need to interchange inductor and capacitor.

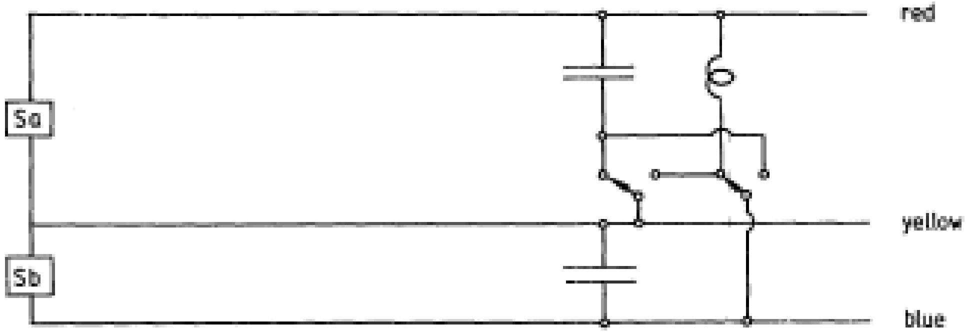

Figure A.5 — Balancer for two line-to-line loads

Annex B
(informative)
Static frequency converter (SFC)

Static frequency converters are in mainstream use in other industries within the United Kingdom, including large scale wind turbine generation. There are examples of other countries in Europe applying this technology to traction and also in Australia there are examples of its use on 3-phase 50 Hz a.c. distribution networks.

An SFC, as used for traction power supplies, converts 3-phase 50 Hz a.c. power from the supply into a single-phase 25 kV 50 Hz a.c., suitable for distribution on the traction electricity network. The name frequency converter is somewhat misleading as the resultant output frequency is matched to the input frequency; it is however ‘converted’ during the process. The input 3-phase power is transformed down to a manageable voltage, rectified to create d.c., fed through an inverter which produces the single-phase a.c. power and then transformed up to a useable voltage.

Power can flow in both directions through an SFC at a variable range of power factors (pf) with the input pf not necessarily matched to the output.

It should be noted that at the time of publishing this document, no SFC traction power supply exists in the United Kingdom.

Due to the nature of SFC connections, whereby the Electricity Network Operator will provide a standard 3-phase connection at a nominal standard system voltage (rather than building a dedicated EHV/25 kV single-phase substation), then the connection/interface arrangements between the Electricity Network Operator and the Railway Infrastructure Manager will be different to those presently defined for a traditional connection within the main body of this document. For an SFC the point of supply and the point of connection would be at the Electricity Network Operator’s metering circuit-breaker.

The Railway Infrastructure Manager will typically own all assets (cables etc) beyond the Electricity Network Operator’s EHV metering circuit-breaker and as such the Railway Infrastructure Manager will also specify, maintain and own all associated protection equipment, compliant with rail industry standards. The Electricity Network Operator can then provide the connection to required standards, as for any other load connection. The Electricity Network Operator will specify, maintain and own all protection equipment on its EHV metering circuit-breaker.

Considerations when planning and designing an SFC connection include the following.

- Earthing.
- Harmonics / quality of supply.
- Protection and control interfaces. Including cross boundary protection settings.
- LV auxiliary supplies.
- The ‘pre-charge’ supply required for the SFC, be it from the auxiliary or main supply, the Railway Infrastructure Manager should make provision for the start-up & shut-down of the equipment without the need for the Electricity Network Operator to open/close circuit-breakers.

The relative distance between the Electricity Network Operator substation and the Railway Infrastructure Manager in-take site may influence the choice of the protection scheme to be employed, for example if the Electricity Network Operator substation is adjacent to the Railway Infrastructure Manager Substation (cable route <~100 m) and the land between the sites is secure (not public) then it is feasible that the Railway Infrastructure Manager interface protection could be achieved without the need for the Railway Infrastructure Manager owned protection relays to be located at the Electricity Network Operator site. Such a solution, for example a circulating current type scheme, whereby the CT connections in the Electricity Network Operator’s metering circuit-breaker are cabled direct to the Railway Infrastructure Manager site (e.g. copper multicore cables), and connected directly to a single protection relay at the customer site.

NOTE 1: Ownership of CTs for any circulating current scheme should be at the discretion of the Electricity Network Operator and Railway Infrastructure Manager.

NOTE 2: Earthing / earth potential rise considerations may preclude the use of copper multicore cable (i.e. transferred potentials and equipment stress voltages).

The Electricity Network Operator may provide an interface cabinet to marshal all multi-core cables (Electricity Network Operator and the Railway Infrastructure Manager) associated with all a.c. and d.c. cross boundary interfaces. This box would be owned by the Electricity Network Operator (typically located in the Electricity Network Operator’s control room) and would contain associated interfacing trip relays and interposing indication/alarm relays.

If the distance between the Electricity Network Operator and the Railway Infrastructure Manager substations is significant (>~100 m), or requires pilot cables to be run on land not owned by either party, then a feeder unit protection (current differential) type scheme may be specified. In such circumstances, a unit protection scheme which employs fibre-optic cables could be used, eliminating the need for copper multi-core cables to be run from the Electricity Network Operator to the Railway Infrastructure Manager site.

Whatever arrangement is provided, as well as the a.c. signals, there will be the need for a trip signal to be passed from the Railway Infrastructure Manager to the Electricity Network Operator (to trip the metering circuit-breaker when the Railway Infrastructure Manager’s interface protection operates) and a trip signal from the Electricity Network Operator to trip the Railway Infrastructure Manager incomer protection in the event of a Electricity Network Operator back-up protection operation.

The Electricity Network Operator is obligated to provide an emergency trip pushbutton which would normally be located in the metering annexe (one per metered feeder). If the Railway Infrastructure Manager requires an additional emergency trip pushbutton (on the Railway Infrastructure Manager site, say adjacent to their incomer circuit-breaker), then an emergency trip repeat arrangement should be made available by the Electricity Network Operator, such that the pressing of the pushbutton on the Railway Infrastructure Manager site results in the tripping of the associated Electricity Network Operator metering circuit-breaker.

At the time of writing, traction loads display a transient of up to 7 MVA per train passing on an Electricity Network Operator’s system.

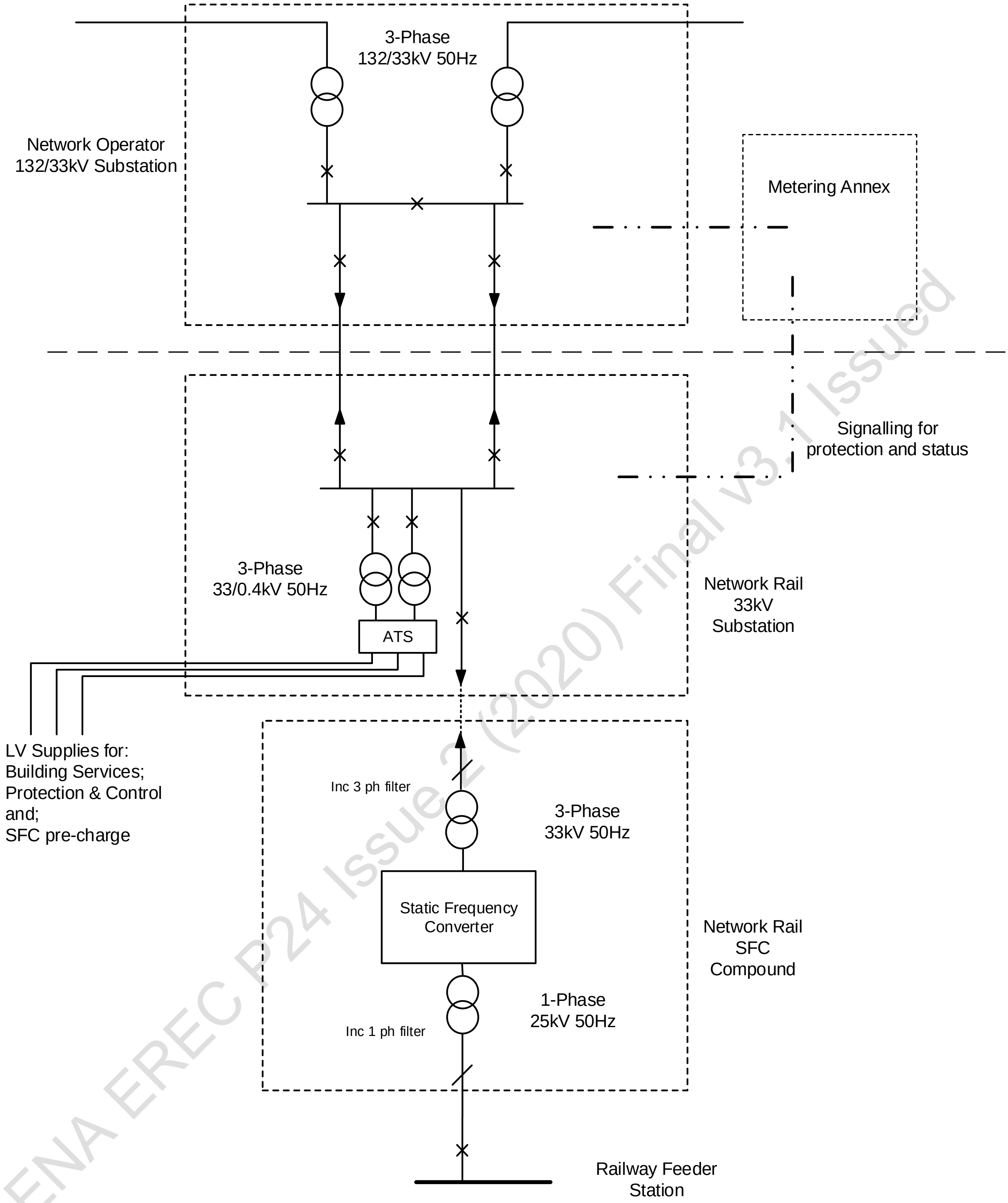

Figure B.1 — Diagram of a typical interface between the Electricity Network Operator and Railway Infrastructure Manager for an SFC 33 kV connection

Bibliography

For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

[1] ENA ETR 116, Report on voltage unbalance due to British Rail AC traction supplies

[2] National Grid UK Electricity Transmission plc, National Safety Instruction Guidance, NSI 26

[3] ENA TS 41-15 Part 9