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Low Cost Electrification for Branch Lines

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Executive Summary

This report has been prepared as a result of work undertaken for the Department for Transport (DfT) Research Project: Low-Cost Electrification.

The objective of the research is to establish if it can be economically feasible to electrify low-usage branch lines on the National Rail Network. Such lines are currently operated using diesel multiple unit (DMU) type rolling stock and it is considered that replacing these with modern tram-type electric vehicles can offer the following benefits:

- Reduced operating costs, particularly with regard to rolling stock
- Immunity from short-term fluctuations of fuel costs
- A reduction in overall carbon emissions
- Reduced impact on the local environment (air quality and noise levels)
- Improved passenger experience

For the purposes of the study a spur branch line situation is assumed, typical of Community Line or Community Service status, providing low-frequency local services. The electrification scenario assumes services operated by light-rail vehicles to 80 km/h (50 miles/hour) maximum speed.

An assessment of electrification options, which considered various operating voltages and methods of current collection, concluded that a 750VDC OLE system would provide the most economic solution for branch line spurs remote from existing electrification. Primary factors for this conclusion are comparative ease of installation/integration of low voltage OLE with existing infrastructure, and relative ease of grid supply connections.

The study found a number of factors that would substantially reduce electrification costs for a rural branch line scheme compared to the high-usage situations where electrification schemes are normally applied. Those factors include:

- Comparatively low service speeds, requiring limited dynamic current collection performance, that allow the use of lower cost tram-style OLE and lighter weight support structures
- Low service frequency enabling operation from comparatively widely spaced (few in number) 750VDC substations - aided by increasing nominal system voltage to 850VDC as permitted by existing standards
- Lower power substations and reduced OLE copper due to inherently reduced power requirement of energy efficient light-rail vehicles.
- Generally less neighbouring infrastructure in rural locations so that, for example, there will be reduced requirement to relocate/modify buried services for electrical reasons.

In addition to these inherent cost reduction factors, the study also considered how new technologies and innovative designs/solutions may be applied to achieve further cost reductions. Viable options considered include:

- Alternative support mast materials and methods of installation
- Alternative low cost design of OLE
- On-train and trackside traction energy recovery/storage solutions
- Low-power (low cost) substations
- Wireless monitoring and control (SCADA)

The study has also considered other fundamental technical issues that can have significant financial impact on any envisaged electrification scheme such as compatibility with existing signalling, electrical safety (touch, step potential) requirements and measures, including track modifications, that may be required to control traction return leakage currents.

Industry sources have been consulted where possible to derive indicative equipment costings; however estimation of overall project delivery costs is hampered by the lack of available information in the public domain regarding the cost breakdown of relevant schemes. Reasonable assumptions are made to determine likely costs; however actual costs will be subject to substantial variation dependent on local route conditions and circumstances.

With the above proviso, two branch line electrification conversion scenarios, based on real routes, have been assessed to provide an understanding of notional costs. The cases considered are:

- Case 1 – a nine mile long single-track Community Line operating an hourly (approximately) service at low speed (30 miles/hour). Estimated cost for provision of low-cost electrification infrastructure £4.0 million (excluding vehicle costs including servicing facilities)
- Case 2 – a twenty five mile length route operating a Community Service over a twenty mile mixed-traffic branch line, and an additional five mile section of main line. Estimated cost for provision of low-cost electrification infrastructure £9.8 million (excluding vehicle costs including servicing facilities)

In conclusion the study has focused on the technical and financial challenges associated with electrifying a lightly used branch line, giving consideration to the major costs areas and the means by which these may be reduced.

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1 INTRODUCTION

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- Reduced operating costs, particularly with regard to rolling stock
- Immunity from short-term fluctuations of fuel costs
- A reduction in overall carbon emissions
- Reduced impact on the local environment (air quality and noise levels)
- Improved passenger experience

These aims are consistent with strategies presented in the 2007 White Paper ‘Delivering a Sustainable Railway’, and with several key themes encompassed within the Rail Industry Research Strategy (*Reducing the specific cost of reliable infrastructure; The environment, energy and the railway; Traction & rolling stock: reducing cost and improving reliability*).

2 RESEARCH SCOPE

The study is concerned with assessing:

- The minimum technical requirements for low-cost electrification
- The likely costs of route electrification
- Any technical issues requiring further investigation

The assessment is undertaken in the context of rural and suburban branch lines that operate a relatively low-frequency train service (one or two trains an hour) and that operate substantially independent of the main line. Services in these cases are typically operated by single or two car DMU rolling stock such as the Class 14x series 'Pacer' or Class 153 'Super Sprinter'.

2.1 KEY ASSUMPTIONS

The following key assumptions are made to characterise the scope of the study:

- The branch lines are single or double track, remote from existing electrification schemes: i.e. the electrification will not be an extension of an existing system
- The branch lines will link small to medium size communities in a rural or semi-rural setting where constraints on the geographical location and power rating of grid supply connections are likely
- Services will be operated with modern light rail or tram-train type vehicles, on the basis that this class of vehicle would operate efficiently and with low overall running costs
- The maximum line speed will be 80km/h (typical of many modern tramway/light rail schemes [NB longer branch lines with less frequent stops may warrant a higher line speed such as 100km/h])
- For a 'low usage' scenario electrification infrastructure would be required to support a service frequency of 1 train per hour
- For a 'medium usage' scenario electrification infrastructure would be required to support a service frequency of 1 train per half hour

3 ELECTRIFICATION SYSTEMS

3.1 MAINLINE ELECTRIFICATION

3.1.1 General

At present approximately 39% of the UK national rail network is electrified, comprising either 600/750V DC conductor rail (14%) or 25kV AC overhead line (25%) electrification systems. These two systems reflect the two predominant conductor configurations for railway electrification. Conductor rail systems offer a robust and unobtrusive means of power delivery; however overhead line electrification (OLE) is standard for new mainline electrification schemes due to more efficient power delivery and superior dynamic current collection characteristics that allow higher operating speeds. Safety standards also favour keeping live conductors out of harms way.

All new UK main line electrification is of 25kV OLE design, the only exceptions at present being where there is an economic case for extension of an existing 750V DC electrified system. 25kV OLE is the preferred form for new electrification in many parts of the world even where existing electrification infrastructure operates at a different voltage.

Other standards of railway electrification currently in use include:

- 1500V DC OLE (e.g.UK Tyne & Wear Metro, Ireland (DART), The Netherlands and France)
- 3000V DC (e.g. Belgium, Italy, Spain, Poland, Czech Republic, South Africa)
- 15kV AC (e.g. Germany, Austria, Switzerland, Sweden, Norway)

Table 1 Common Railway Electrification Systems

Electrification System	Configuration (Conductor rail or OLE)	Permitted Voltage Range[1]	
		Lowest	Highest
600V DC	Conductor rail	400	800
750V DC	Conductor rail	500	900
1500V DC	OLE	1000	1800
3000V DC	OLE	2000	3600
15kV AC (16 2/3 Hz)	OLE	12kV	17.25kV
25kV AC	OLE	19kV	27.5kV

1. Allowed permanent voltages as defined in BSEN 50163 and IEC 60850

3.1.2 Overhead Line Equipment

The general form of the overhead conductors is similar for most types of railway OLE, typically comprising a copper contact wire suspended from a copper catenary wire by means of droppers; the arrangement being designed to give a nominally level dynamic contact wire profile. Design improvements have tended to simplify the arrangement, moving from the earlier compound or stitched types of OLE, which featured auxiliary conductors to the present day simple arrangement. At the same time increased understanding of current collection dynamics has led to improved designs of OLE and pantograph.

The OLE conductors are suspended from trackside steel masts or portal structures mounted upon concrete foundations; supporting structures are spaced at 40m – 70m along-track intervals. These arrangements will vary according to the complexity of the railway, such that single or double track railways will typically utilise cantilever masts adjacent to each track, whereas portal or headspan structures will be installed where three or more tracks exist. The 'live' parts of the equipment are insulated from the structures by means of porcelain or polymeric insulators.

OLE tension lengths are typically terminated with balance weights to auto-tension the conductors, these provide consistent wire tension and therefore current collection performance over a wide range of operating temperatures.

25kV AC substations are located at intervals of up to 50 km, due to their high power rating (typically 15 MVA) these draw power via dedicated bulk power connections from the National Grid high voltage (i.e. 400 kV, 275 kV or 132 kV) transmission network.

3.1.3 Conductor Rail System

The main line conductor rail system in the UK comprises a steel or aluminium/steel composite rail supported by sleepers via insulators; typically this is at an interval of six sleepers, but this does vary in accordance with the local track layout. To collect current contact is made between collector shoes and the top of the conductor rail.

For the 600/750V system DC substations feed power to the conductor rail, these may be located at intervals of 6 to 8km, but spacing does vary in accordance with local requirements such that 3km spacing may be the arrangement for locations with intense traffic densities. In the UK individual substations are usually fed via a dedicated network of buried high voltage cables, with a single bulk supply point providing a link with the National Grid network.

3.1.4 Traction Current Return

Trains usually return current via the running rails and a network of cables that connect back to the respective substation(s). Correct design and maintenance of this system is essential because it controls local touch voltages and provides an efficient return path, thus optimising efficiency.

3.1.5 SCADA

A SCADA (i.e. Supervisory Control and Data Acquisition) system is essential for the electrification system to provide a means by which the Control Centre can operate and monitor the condition of circuit breakers and other essential equipment. Any such system employs a telecommunications system to carry the command and status feedback messages.

3.1.6 Other Considerations

The electrification of a non-electrified route invariably requires modification to the signalling system (e.g. conversion of track circuits to traction current immune types) and other works to ensure electrical/EMI compatibility with existing trackside systems, neighbouring infrastructure and interfaces to other railway systems.

As well as the civil works associated with installing trackside support structures other substantial civil works may be required to accommodate the OLE. Due to the presence of numerous bridges and tunnels that were built in accordance with an historic gauge, provision of electrical clearances may require the re-building of the infrastructure around tunnels and overbridges; common measures include the lowering of the trackbed and/or raising of soffit heights.

3.1.7 Typical Costs

Provision of a main line electrified railway, particularly when undertaken as a conversion of an existing route, is a complex and hence comparatively costly undertaking. An estimate of the major cost elements is presented below.

Reference [1] cites the capital cost of electrifying an existing route to be in the region of £550k - £650k per single track km (STK) based on the analysis of costs for a number of previous electrification schemes.

Appendix A presents cost breakdown information derived from [1], as an indication of the main cost factors for a main line electrification scheme.

The largest cost contributor is the provision/installation of the OLE support structures at approximately £124k per STK inclusive of cantilevers and insulators; also the additional structures/anchoring arrangements required at overlaps. The supply and installation of the overhead conductors (catenary, contact wire, droppers, and return conductor) is approximately £60k per STK. Other costs including installation of any booster transformers, mid point anchors, neutral sections, section isolators, and provision for signal re-sighting amount to a further £30k per STK for a total of approximately £214k per STK.

Provision of the power feed arrangements (Feeder Stations, Grid Connections, Mid-point TSC) amount to a cost equivalent of approximately £86k per STK, including the provision of SCADA systems for the monitoring and control of the distribution system. The cost of a 25kV AC single/double track feeder station is in the region of £1,000,000, with the additional cost of connecting the feeder station to the grid transmission/distribution system being in the region of £2,000,000; this latter cost will vary according to circumstances such as the proximity of the grid and other factors.

Other significant (route dependent) costs include civil works at overbridges as necessary to accommodate the OLE by bridge raising for example, also in tunnels where track lowering and/or track slewing may be required to provide adequate electrical and mechanical clearances for the OLE equipment.

Another cost element is signalling/telecommunications equipment immunisation where, for example, modification/replacement of existing track circuit equipment to traction immune types will typically be necessary.

The provision of a new electrification depot, or conversion of an existing depot, will typically incur the highest single capital cost for a main line electrification scheme. Other costs that add to the final electrification bill include:

- Project mobilisation and management
- Survey and design work, approvals processes
- Interface arrangements with existing electrification systems
- Test and commissioning activities.

A typical budget figure cited for mainline electrification schemes is £1million per single track km which would be inclusive of the costs identified above.

3.2 TRAMWAY/LIGHT RAIL ELECTRIFICATION SCHEMES

Tram and Light Rail systems use lightweight vehicles that operate at lower speeds than conventional rail vehicles but with characteristics of faster acceleration rates and shorter stopping distances. These systems typically serve relatively short routes in urban areas, operating frequent services between closely spaced stations.

Tramways are inclusive of sections of on-street running, where safety considerations mandate the use of low voltage conductors to deliver traction power, usually in the form of an overhead contact system. A typical modern tramway electrification system will comprise 750V DC (nominal) OLE of relatively simple construction, the low voltage allowing simplified insulation and electrical clearance arrangements. With regard to the need to maintain good current collection low running speeds allow the use of a trolley wire configuration rather than the catenary wire arrangement necessary for higher speeds.

Simplification of the support arrangements enables a ‘lightweight’ design of support mast (traction pole) which will typically be of tapered round cross section for reduced visual impact. Use of support poles in street running areas is minimised where possible by using existing buildings to provide anchor points for ‘cross-span’ support wires. In twin track areas with a suitably wide trackbed the number of support poles can reduced by between-track pole installations, where a single pole can support the OLE of both tracks.

Power is typically provided by substations connected to the 33kV electricity supply distribution system, with substation power ratings of typically 1MW rating and along track substation spacing of around 2 km. The trolley wire arrangement will typically comprise twin copper contact wire (e.g. 2 x 120mm^2 cross section) to provide sufficient live-side conductivity for traction currents in excess of 1000A. Return current will be via the running rails.

Figure 1 Tramway OLE Support Structure

There are many examples of modern tram systems throughout the world, particularly in Europe. Tram systems currently in UK operation are Croydon, Birmingham, Manchester, Sheffield, Nottingham and Blackpool, with more systems planned or under construction.

Light Rail (Metro) systems operate entirely on segregated rail alignments, the two examples in the UK being Tyne and Wear Metro that is operated on former British Rail tracks, and Docklands Light Railway (DLR) built on disused railway rights of way and concrete viaducts. This segregation allows a greater choice of design of electrification system.

DLR electrification is a 750V bottom contact conductor rail system, whereas Tyne and Wear is 1500V DC catenary type overhead. 25kV AC electrification was originally considered for the Tyne and Wear system however 1500V DC was selected primarily for ease of electrification of the tunnel sections.

The Tyne and Wear system provides the most extensive example to date of light rail conversion in the UK. Of an overall route length of 77.5 km, 45 km is converted BR lines with a further 15 km of track sharing with local trains operated by Northern Rail. The maximum operating speed of the system is 80 km/h (50 miles/hour).

3.2.1 Typical Costs

UK rail industry sources suggest a budget price for installing tram/light rail 750V DC overhead electrification of between £150k - £200k per Single Track km. This is inclusive of design, materials and installation costs for the essential sub-systems (i.e. support structures and their foundations, overhead conductors, isolation switches, return conductors and traction return components).

Additional to this cost is the provision of feeder substations (including fault protection and control systems) and electrical grid connections which may amount to £250K or more per route km. This gives an indicative cost of around £600k per route km to electrify a double track route with tram-style electrification.

Comparing the above figures to a European scheme, a recent industry press release cited a contract value of €16.4 million (around £15.8 million) for the electrification of Granada's tramway system of route length 15.9 km, with €9.8 million (around £8.8 million) to cover the installation of 35 km of catenary and 7 traction substations. This latter figure equates to approximately £250k per track km for the provision of the electrification infrastructure including substations, although it is presumed this excludes grid connection costs. The overall contract value puts the cost at close to £1 million per route km; clearly there are other major costs to be taken into consideration which will include provision for project management and the funding of the various stages to implement the electrification scheme (e.g. planning, permissions, approvals, installation, testing and commissioning).

The issue of project organisation costs is considered below.

3.2.2 Project Organisation Costs

The way in which costs for project management and system design are allocated to any branch line electrification project can have a significant impact on the aggregated per-kilometre cost. An estimate is presented below for a hypothetical dedicated 'Project Office'. It has been assumed that two people plus basic support would be employed four-days per week, with other personnel being required for only a percentage of the working week.
It has been assumed that the following resource would be required [N.B. all estimates of costs are inclusive of salary and office support, but exclude accommodation]:

Project Director @ £700k
Legal/Commercial Manager @ £450k
Design Team Leaders
Power Supply & EMC@ £200k
Track & Civil Engineering (part time) @ £200k
Train Control (Signalling, Signage etc) @ £200k
Environment @ £100k
Other engineering functions @ £200k

Total: £2.1M

It has been assumed that other tasks would be undertaken by Contractors and Contract companies, the cost of which would be covered by specific budgets for the survey, design, component procurement sourcing, installation and commissioning.

4 BRANCH LINE ELECTRIFICATION

4.1 OPERATIONAL SCENARIOS

There are essentially two modes of operation for an electrified branch line running light-rail vehicles:

- Exclusively light rail operation with the line closed to all heavy rail vehicles
- Mixed traffic operation where the line remained open to heavy rail vehicles, for example to enable freight services to be run.

These two scenarios are discussed briefly below, although for the purpose of this study the former scenario is assumed to apply.

In either scenario the electric tram or tram-train vehicles will be captive to the route (the main line not being electrified) and provision for local vehicle servicing/maintenance arrangements, including carriage cleaning, would therefore be required. Similarly heavy maintenance arrangements would need to be addressed, possibly being undertaken at an existing rail depot or other centralised facility.

Train servicing and maintenance arrangements fall outside the scope of this study, however the infrastructure cost of provisioning a service shed would have to be factored into the overall cost of a branch line electrification scheme.

4.1.1 Light Rail Conversion

In a light rail conversion scheme the route is designated for light rail use only and is no longer part of the national rail network. In these circumstances strict compliance with National Rail standards is not required. Tramway type operation might then be implemented with line-of-sight operation for driving and tram style trackside 'locally controlled' signal indicators eradicating the need for existing signalling arrangements such as track circuit or token block operation.

Decommissioning existing track circuits on the branch line would eliminate the need to upgrade to traction immune types. [N.B. but as discussed elsewhere track circuits on adjacent main lines would need to be considered].

A disadvantage of full light rail conversion is reduced operational flexibility, where it would not be possible to run standard rail vehicles as temporary replacements should vehicle outages degrade the service available from a small dedicated fleet. Also, the flexible operation of special excursion and/or summer services may be precluded.

4.1.2 Track/Time sharing

In this scenario the line remains a part of the national network. Passenger services are operated using modern electric tram-train type vehicles but other rail services (e.g. diesel freight) are also permitted to run. The route would therefore remain in compliance with national rail standards and would retain an approved railway standard signalling system/methodology.

In this case the route could be operated on either a time-share or track-share basis. For the former scenario the line is designated for light rail/tramway operations at certain times of the day and at other times the line is operated as a conventional railway.

The track sharing scenario is reliant on railway type signalling to separate ‘light’ and ‘heavy’ rail operations and typically requires the provision of a train protection system (e.g. TPWS solution as applied on the Tyne and Wear system at Sunderland) to adequately mitigate the risk of collision between ‘light’ and ‘heavy’ rail vehicles.

4.1.3 Rolling Stock

A detailed study of rolling stock is outside the scope of this study, however for the purpose of this study an appreciation of the possible characteristics of such vehicles has been gained and this is briefly discussed below.

The developing market for Light Rail systems has led to manufacturers offering a spectrum of rolling stock solutions. The lightest categories of vehicle include ‘ultralight’ single car vehicles (e.g. Parry People Mover), ‘tram’ and ‘tram-train’ designs that range in size and performance in accordance with the requirements of the specific Operator. Heavier vehicle types include high performance light-rail and ‘light-heavy rail’ train designs, such as the Stadler GTW that can operate at main line speeds whilst having the ability to operate on light rail systems.

For the purpose of this study operation of a modern electric tram or tram-train type light-rail vehicle is assumed. Such a train would typically comprise a single articulation (i.e. ‘two car’) formation of length 30 to 35 metres, with a tare weight in the region of 35 to 40 Tonnes. The maximum operating speed would typically be 80 km/h. An installed traction power of several hundred kilowatts is generally sufficient to meet acceleration/speed performance characteristics over a normal range of conditions. Vehicles of this type typically operate from an overhead 750V DC supply, although traction power configurations are offered with operation from any of the standard OLE voltages. Dual voltage designs (e.g. 750V DC/25kV AC) can also be engineered. It must be assumed however that there is a cost penalty associated with dual voltage operation; such a configuration may also require a longer/heavier train formation than is required for 750V DC operation.

For the low usage branch line scenario a power demand limit of 500kW per train is assumed as the basis to assess power supply requirements and options for a ‘low cost’ scheme. It is further assumed that the operating regime would be tolerant to short periods of degraded train performance where, for example, two trains in the same electrical section coincidentally demand maximum power. To ensure continued operation modern traction control systems automatically reduce power demand when line voltage is low, a capability that enables ‘power sharing’ under peak demand conditions [N.B. older designs may not possess such a degree of tolerance].

The above assumptions provide for a range of scenarios commensurate with the concept of low cost/usage electrification but would be adjusted according to the specific requirements of a branch line. For example longer branch lines with more widely spaced stops may warrant a higher maximum line speed.

With regard to rolling stock an additional consideration must be the choice of floor height, either to match traditional '915mm' station platforms [9] or a lower (i.e. 300/380mm) platform. This has no direct impact on the electrification system; however it may affect vehicle weight and therefore performance, and might affect the volume of space available for traction equipment.

4.2 ELECTRIFICATION SYSTEM OPTIONS

The options for a branch line electrification system are:

- An overhead line system operating at low voltage DC or high voltage AC, or
- A conductor rail system operating at low voltage DC.

4.2.1 Overhead Line

Light Rail/Tram type electrification systems typically operate at 600V DC or 750V DC although for a fully segregated railway any of the higher standard electrification voltages (1500V DC, 3000V DC, 25kV AC) might be specified.

Higher system voltages enable wider substation spacings and potentially lower electrification costs due to:

- Reduced number of substations and electrical connection points
- Along-track feed positions less critical, allowing more control over connection costs with regard to proximity to suitable bulk electricity supply points, land availability and access provision
- Reduced return current magnitude

The main disadvantage of higher system voltage is the requirement for increased electrical clearances (Table 2) which can entail costly civil works to existing infrastructure, as well as requiring the installation of physically bigger, and therefore more costly, insulating components. Issues with regard to public safety may also increase costs.

A route electrified at 600V DC or 750V DC might be 'opened up' as a tram system, thus substantially relaxing infrastructure segregation requirements compared to traditional 'railway' operation. Such a system should incur lower infrastructure and operating costs, and offers increased adaptability to local transport needs. If appropriate, flexible operation with elements of street running may also be feasible.

Table 2 Electrical Clearances Common Railway Electrification Systems*

	750V DC	1500V DC	25kV AC
Static Clearance (mm)	75	150 (100)**	200 (150)**
Passing Clearance (mm)	25	100 (80)**	150 (125)**

* HSE Publication: Railway Safety Principles and Guidance, part 2, Section 2 Guidance on electric traction systems
** Special Reduced clearance, requiring HSE approval

4.2.2 Conductor Rail

A ground level conductor rail system energised at 600VDC or 750VDC could provide a cost effective solution since the expense of erecting overhead line masts is avoided; additional savings could be achieved by employing lightweight composite aluminium/ stainless steel conductor rail rather than the conventional steel conductor rail.

Conductor rail has significantly lower per unit length resistance compared to a typical OLE conductor arrangement (Table 3). Therefore railways supplied with power at low voltage would feature lower voltage drop and energy losses if equipped with a conductor rail system than with an OLE system. This may enable wider substation spacing, subject to the constraints of running rail ‘touch potential’ limits [6].

Table 3 Comparison of Weight and per Unit Length Resistance of Conductor Rails and Overhead Line Conductors

Conductor Type	Weight (kg/m)	DC Resistance (mΩ/km)
Aluminium Conductor Rail	15kg/m	12
Aluminium Conductor Rail	18kg/m	7
Steel Conductor Rail	74kg/m	11.7
OLE (2 x 120mm^2 Cu)	-	75

Other advantages compared to an OLE system include:

- For a bottom contact system, robust current collection relatively unaffected by weather conditions including snow and ice [N.B. a top contact system would be affected by ice]
- Physically compact arrangement for ease of integration with existing infrastructure and which can be readily ‘gapped’ to reduce installation costs in problem areas such as tight track clearance locations
- Visually unobtrusive

Ground level ‘live’ conductor rail systems do have several significant disadvantages however, including:

- Electric shock hazard due to the accessibility of the live conductor
- Increased risk of short circuit outages

These problems can be mitigated to a degree using modern shrouded designs of conductor rail system, although tram-style operation on public roads would be ruled out due to the residual risks posed by live collector shoes and conductor rails. For such operation it would be necessary to install OLE above the public roads and to equip rolling stock with both collector shoe and pantograph equipments; interlocking would then be required to prevent the collector shoes being energised when the pantograph was raised.

For aesthetic reasons a modern street-safe ground power supply system (known as APS) is used on the Bordeaux tramway system. A 12km section of APS is installed, comprising a trackbed embedded conductor rail between the running rails that is divided into 8m electrically sectioned segments. The segments are energised by a radio control signal as the tram passes over them so that only sections under the tram are live. The APS system is complex, considerably more expensive than an overhead line system and not suited to sleepered track installation. It is therefore not viable for a low cost electrification scheme.

Bombardier offers their own version of catenary-free technology, known as Primove. This is a contact-less system that provides power by induction from a buried conductor. Again this is expensive technology intended for application in historic or environmentally protected areas of a city where OLE installations would not be permitted.

Consideration is given primarily to overhead type systems for the remainder of this study.

4.2.3 Power Supply

Power supply requirements will be relatively low for a light/medium use branch line. A 32km line operating a half hour service in both directions would have, at most, four tram-trains operating at the same time. Assuming a peak power of demand of 0.5MW per train, this being sufficient to give the performance levels envisaged, peak power demand will not exceed 2MW over the entire system and would be unlikely to exceed more than 1MW within any given electrical section.

The system described above could be powered by a single 2MW rated 25kV AC feeder substation located virtually anywhere along the route, or by a number of 1MW rated 750VDC substations appropriately spaced along the route (Section 5.6).

1 to 2 MW power ratings correspond to industrial strength electrical supplies that would typically be fed from the 11kV/33kV three phase local distribution network.

Unlike corresponding normal AC supply points which load only pairs of phases, when working normally the substations of a DC electrified railway present a nominally balanced three phase load to the electrical supply network therefore phase imbalance is not a major concern. The availability of connection points to the local HV distribution network will be dependent on the physical layout of that system and the availability of spare capacity. Factors such as harmonic content limitations are specified by the Distribution Network Operator (DNO), which will be dependent on factors such as existing loads.

Each 25kV AC substation transformer loads a pair of phases, thus local imbalance may be an issue. Considering a whole main line route however, imbalance is essentially mitigated by having a substation topology that employs the 132kV/400kV high voltage transmission network and a distribution of polarity-coordinated connection points that essentially ensures each of the three phases is loaded equally across the network.

In the branch line scenario connection of a 2MW rated 25kV feeder to the distribution network should be achieved at significantly lower cost compared to the main line example. The issue of phase imbalance however may require ‘strengthening’ of the distribution network or provision of other measures (e.g. installation of a power converter at the feeder) which might add significantly to the base cost. This issue will depend on local circumstances where any required measures and additional costs would be determined in consultation with the DNO.

5 OVERHEAD CONDUCTOR SYSTEM

5.1 OVERVIEW

The Overhead Contact System (OLE) comprises the support structures and conductors including various component parts such as jumper/feeder cables, insulators, support arms and tensioning equipment.

5.2 OVERHEAD CONDUCTORS

5.3 CURRENT COLLECTION PERFORMANCE REQUIREMENTS

A maximum speed of 80 km/h (50 mile/hour) allows consideration of tram-style OLE and corresponding economising of support infrastructure compared to typical main line arrangements.

Operating experience on modern tram systems has demonstrated that an auto-tensioned trolley wire arrangement provides adequate current collection performance to speeds of 80 km/h and this in effect represents the minimum specification OLE configuration.

5.3.1 Conductor Material and Size

Copper has long been established as the best material for contact wire with various forms in use (e.g. copper-cadmium, copper-tin and copper-silver alloys, and hard-drawn copper) to provide the desired characteristics of corrosion resistance, strength and conductivity. Despite trials with other materials (i.e. aluminium) no realistic ‘low cost’ alternative currently exists.

Traction current magnitude is dependent on system voltage; a 1 MW load is equivalent to 1333A at 750V and 40A at 25kV (unity power factor). Conductor cross sectional area is therefore less critical for a low power 25kV system.

For a 750V DC system voltage drop in the overhead conductors is a significant factor requiring that substations be relatively closely spaced. Increased conductor size will enable wider substation spacing, at the expense of additional copper and the heavier structures required to support it. Conductor size and configuration may therefore be optimized to reduce overall system cost.

Standard sizes for contact wire [10] are 107 mm^2, 120mm^2 and 150mm^2. As a ‘rule of thumb’ a typical OLE system will comprise a conductor arrangement equivalent to 240mm^2 copper cross section (approximating to contact wire + catenary or twin contact trolley wire configurations).

Calculations undertaken to establish the relationship between substation spacing and overhead conductor size (Appendix B and Table 4) for a ‘low use’ system found the following:

- 75% increase in substation spacing for a doubling (from 120mm^2 to 240mm^2) of OLE conductor size.
- 33% increase in substation spacing for a 50% increase (from 240mm^2 to 360mm^2) of OLE conductor size.

The calculations assume traction current return through the running rails, with the relationship applicable to both single track and double track systems

Table 4 Maximum Substation Spacings, Low Use 750V DC OLE System, 0.5MW load				
OLE Equivalent Copper Cross Section mm^2	Single Track km		Double Track km (tram-style parallel fed)	
	Single End Fed (Stub end)	Double End Fed (Spacing)	Single End Fed (Stub end)	Double End Fed (Spacing)
120	1.7	7.4	3.4	14.9
150	2.1	9.0	4.1	18.0
240	3.0	13.0	6.0	26.2
360	4.0	17.5	8.0	35.4

(for provision of a minimum of 0.5MW power to a single load – see Appendix B for assumptions)

5.3.2 Overhead Wire Configuration

5.3.2.1 Catenary

The standard configuration for main line systems is the catenary wire/contact wire arrangement which has been simplified over the years and which is easily adapted to a wide range of system voltages and performance requirement, including high speed rail operation.

5.3.2.2 Trolley Wire

As discussed above, tram systems typically utilise a trolley wire type arrangement which is suitable only for lower operating speeds. This is favoured for both aesthetic (reduced visual impact) and cost reasons. Elimination of the catenary wire and droppers reduces the component count and installation complexity. Mast height may be reduced as there is no need to support a catenary wire, therefore enabling a degree of reduction in mast/foundation dimensions and costs.

Elimination of the catenary wire may however require augmentation of OLE conductivity by introducing a second contact wire, such twin contact trolley wire arrangements are commonly utilised in UK tram schemes.

A drawback of the twin contact wire arrangement is the relative difficulty of setting up and maintaining perfectly level contact wires, particularly on curved sections of track. This can cause rapid wear of the higher (out of contact) wire due to electrical erosion thus necessitating premature replacement of that contact wire. The problem is compounded by the possibility of alternating out-of-contact wires in the same tension length, resulting in premature wear to both wires. In the branch line scenario this form of contact wire erosion would however develop at a comparatively slow rate because of the relatively few pantograph passes.

It should be noted that twin contact wire is used extensively on European main line DC OLE without apparent problem since the catenary arrangement enables more consistent levelling of the two contact wires.

Conductivity augmentation may alternatively, or additionally, be provided by parallel ‘live’ conductor cables that are periodically bonded to the contact wire; those supplementary conductors may be aerial (i.e. supported by the masts) or buried cable installations. The additional cost of this configuration would need to be judged against the benefits of having a single rather than twin contact wire arrangement.

Operating experience on modern tram systems has demonstrated that an auto-tensioned trolley wire provides adequate current collection performance for speeds up to 80 km/h; this configuration of OLE would therefore be adequate for the branch line electrification scenario considered in this report.

A 'low-cost' trolley wire OLE has been devised by Tram Power Ltd, as demonstrated at Carnforth Railway Centre. The design is based around a single 150mm^2 contact wire and incorporates several design features aimed at reducing costs, including a novel auto-tensioning system and simplified mast installation utilising wooden support poles (Section 5.4.3.1).

5.3.2.3 Hybrid

The hybrid configuration is a 'low-cost' concept developed by Atlas Rail Components Ltd with the aid of a UK government grant (Smart Award Ref. GONW7130TER). The design is essentially a development of the contenary OLE arrangement used in UK 25kV main line electrification schemes where tight clearances need to be overcome at overbridges and tunnels. The arrangement uses two contact wires, one above the other, the higher contact wire effectively acting as a catenary wire.

It is a fixed termination (variable tension) design which therefore eliminates the requirement for mid point anchors and balance weights. The design is intended to provide superior current collection performance compared to auto-tensioned trolley wire systems at comparable cost, with an anticipated maximum operating speed in the region of 95 to145 km/h (60 to 90 miles/hour).

The system is a 'low profile' catenary design that utilises the simplified supporting cantilever arrangement used in trolley wire systems. Cost savings are achieved through the simplified installation using a small number of standard components, this being easier to set up than a twin contact arrangement.

The current design is based on a 57m support spacing although this might be extended to achieve spacings comparable to standard catenary systems.

The characteristics of fixed termination OLE are variation of wire height/tension with temperature, and a drop off in current collection performance at the temperature extremes. At present there are no hybrid OLE installations and a practical evaluation is yet to be carried out. The current collection performance of such a system over the full operating temperature change could however be evaluated by means of computer simulations of OLE/pantograph dynamic behaviour.

The concept appears to be suited for application to the branch line scenario in terms of cost and performance, and with the benefit of superior current collection dynamic performance over the trolley wire configuration; this may enable application to a wider range of situations as a common design, for example longer branch lines operating to speeds of 110 km/h (70 miles/hour) or more.

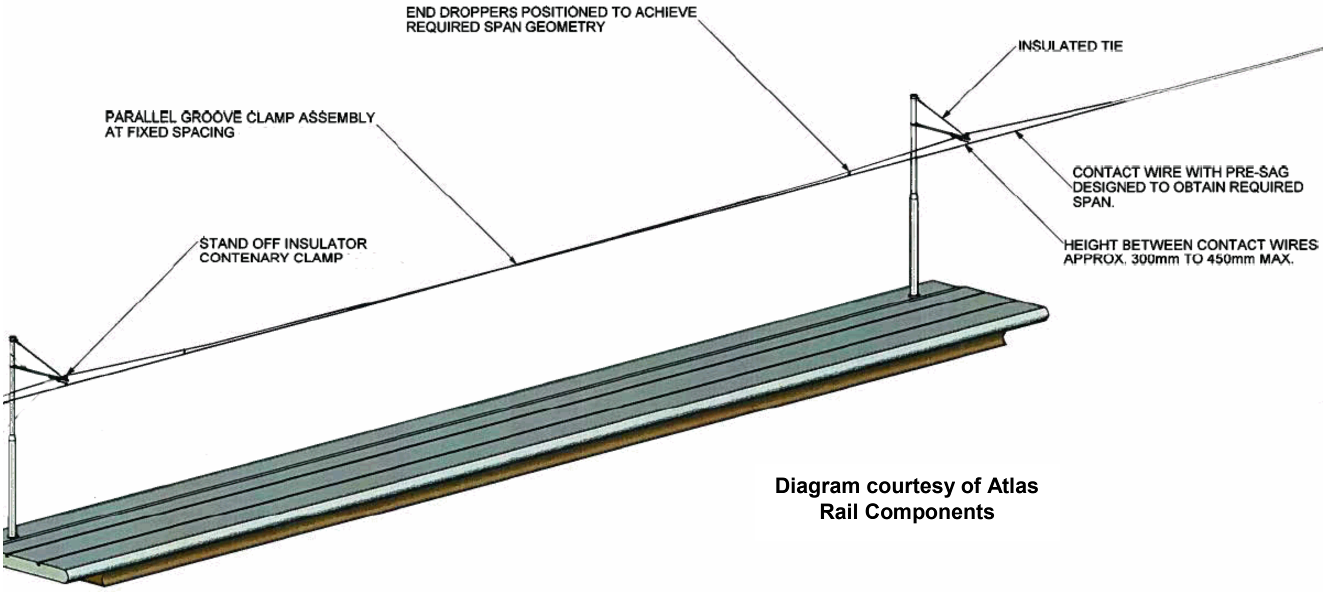

Figure 2 Hybrid OLE Configuration

5.4 SUPPORT STRUCTURES

OLE mast must support the dead weight of the conductors and must withstand any overturning moment applied by such dead weight suspended, for example, upon a cantilever. They also require sufficient lateral stability and stiffness to maintain long term positioning of the contact wire over the track and limited deflection under windy conditions and when ice has accumulated on the conductors [2]. Several methods and materials are available to achieve an array of stable masts; several of these are discussed below.

5.4.1 Typical Design and Installation Practice

Present day OLE systems utilise painted or galvanised steel structures to support the overhead wiring, these structures generally being mounted to either a concrete foundation or metal (vibration) pile. Piled foundations have been favoured in more recent electrification schemes due to their relative ease and speed of installation, the increased productivity of this method reducing both construction time and cost.

For street running tram schemes there is often the option of stringing span wires between existing buildings to support the OLE as a cheaper, and less obtrusive, alternative to using traction poles.

Maximum support spacing for catenary systems on tangent track is in the region of 60 - 70m. For a trolley wire system maximum support spacing is limited to 50m due to contact wire sag. The requirement for additional trolley wire masts (and structure foundations) might therefore offset the cost savings of a trolley wire installation compared to catenary.

On a main-line double track electrified railway single cantilever support masts are typically installed in the cess of each track. Tram systems will typically utilise a single mast to support the OLE to both tracks; this will incorporate an extended boom where installed to the cess of one of the tracks, or else a symmetric boom where the mast can be installed between track pairs. This practice economises the number of support structures/ foundations required and is therefore an effective cost-reduction measure that could be applied to a double-track branch OLE design.

5.4.2 Alternative Foundation Methods

5.4.2.1 Screw Piles

Screw (helical) piles were popular in Victorian times but were superseded by hammer piling with the advent of steam hammer piling techniques. The use of screw piles has been revived more recently with the development of compact hydraulic equipment that enables screw pile installations to be undertaken with greater ease and at lower cost.

Substantial structures can be supported by an array of screw piles where a metal grid (transfer frame) is attached to the head of the piles to provide the foundation base. Screw piles have been used in a number of roadside applications, for example to provide the foundations for large motorway electronic display signs that are mounted to roadside mast/cantilever structures. Railway applications include provision of foundations for railway signal posts and a screw pile array installed at a difficult site to support a large temporary OLE cantilever structure required to undertake remodelling works.

Use of screw piles provides a number of advantages over the use of conventional vibration piles. Features of screw pile technology include:

- Minimal ground disturbance
- Quiet installation – can be installed in noise sensitive urban locations and during night shifts when the use of vibration or hammer driven piles is generally unacceptable
- Long lasting, but can also be unscrewed where a temporary installation is required
- Effective in both compression and tension
- Design life of 60 years

The UK company ScrewFast Foundations Limited has been active in developing and applying screw pile technology with innovations such as ‘angel wings’ to increase lateral stability. The Grip Pile is another development designed for installation into hard ground and solid rock.

The cost of screw pile hardware suitable for supporting an OLE mast is cited as being in the region of £1500 to £2000 and this is similar in hardware costs to the equivalent vibration pile. An installation team at a cost of £3000 per shift could typically install 20 screw piles per shift and 40 vibration piles per shift. Screw piles therefore tend to be the more expensive option under standard conditions but can provide for the more cost-effective solution in restrictive situations.

5.4.3 Buried Masts

The simplest method of installing a support structure is by direct burial in the ground, a technique that is in common use by utility companies to install wooden utility poles (see section 5.4.3.1).

Installation is achieved by boring an oversized hole to the required depth, which is backfilled with the spoil following insertion of the pole. The technique is reliant on stable ground conditions and requires adequate compaction of the backfill. A stabilising mix might be added to the backfill or a poured concrete in-fill used to enhance long term stability.

Substantial mass can be supported (e.g. distribution system cabling and transformers), and steel cable guys may be installed to provide additional lateral support. Methods have been developed to install utility poles into difficult ground including solid rock.

A disadvantage of this method is susceptibility to degradation of the buried portion of the pole, steel products being subject to corrosion and wood to decay. There are however effective solutions to this problem due to advances in coatings and with the development of advanced composite polymer materials.

Applying this method to the installation of OLE support poles could result in considerable construction cost savings compared to the conventional approach of preparing concrete or piled foundations, providing the method is suited to withstanding the overturning moment imposed by OLE wiring geometries.

5.4.3.1 Wood Poles

Wood poles are commonly used in the utilities sector to provide for robust, cost-effective support structures. In the UK much of the rural electricity distribution system is provided by 11kV and 33 kV conductors carried by wooden utility poles.

Poles are graded according to dimensions (‘Light’, ‘Medium’ and ‘Stout’) with diameters ranging from 150mm to 350mm, and supplied in lengths ranging 7.5m to 22m.The poles are pressure treated with preservative and installed by burying in the ground, typically to a depth of 2m although this is dependent on pole length. Advantages of timber poles include relative cheapness, with the insulating properties of wood providing a degree of secondary insulation with no requirement for structure bonding.

A drawback of wooden poles is a perceived limited service life of 30 - 40 years, although replacement rates indicate that average service life is considerably longer. Early replacement of a small percentage of the population can be required due to natural variations in the quality of wood products. Degradation rates depend on local climate and conditions with faster decay occurring in hot, humid climates and with significantly longer life obtained in temperate climates.

Maintenance requirements typically entail 5 or 10 yearly inspections to test for deterioration at/below ground level. Re-application of preservative may be required several times over the life of the pole due to leaching of the preservative into the ground, which may be cause for environmental concern. Pole inspection and servicing can be provided by specialist firms.

North America is the largest market for utility structures with a strong market in the use of wood poles. A number of US suppliers have developed techniques to improve the performance and life of wood poles with the development of polymer barrier coatings (e.g. the ’21 Poly’ coating system) that reduce or eliminate the problem of preservative leaching and are claimed to increase pole life to well in excess of 60 years. Reference [3] reports on recent UK research into timber protection methods.

Disposal costs have become a more recent concern as preservative soaked wood may be classed as hazardous waste (similarly wooden railway sleepers).

The cost of a wooden pole with dimensions suited to OLE support duties (i.e. 9m ‘stout’ grade) is in the region of £200 per pole (£168 recently quoted), or around £400 each including installation to ground.

The use of wooden traction poles in the UK has been demonstrated at Carnforth Railway Centre where 9m length utility poles have been incorporated into a 1.2 km length of prototype ‘low cost’ tram trolley wire system designed by Tram Power Ltd. Twenty-four poles were erected in two days in November 2004 by a single team using an auger and mini-JCB. Only the end-of-tension poles are guyed and the installation has successfully withstood severe winter storm conditions.

Wooden poles are not widely used around the world in railway electrification applications. Anecdotally, such poles are employed in specific areas of Scandanavian countries to minimise the effect of heat conduction between the atmosphere and the permafrost stratum. Timber is employed in support masts in Arizona, USA on the Black Mesa & Lake Powell (BM&LP) railway; in this application a guy wire is used to help balance some of the overturning moment (Figure 3).

Figure 3 Wooden Poles Supporting Catenary on the BM&LP Railway

5.4.3.2 Composite Poles

Composite Fibre Reinforced Plastic (FRP) utility poles have been developed by several North American companies (e.g. RStandard ® Composite Utility Pole, Powertrusion PRFC pole, Ameron uPole®) as an alternative to wood or steel poles. Earlier problems of UV degradation have been overcome by advances in polymer chemistry that have enabled the development of UV resistant resins. The material is inherently rot proof and is not subject to corrosion or degradation either above or below ground.

Composite poles are designed to be direct replacement for wooden poles using the same installation methods. Unit cost is at present around three times the cost of the equivalent wooden pole but do offer the following advantages:

- Approximately a third of the weight of the equivalent wood pole, and therefore subject to lower transport, handling and installation costs
- Easily worked for efficient installation, for example fixing holes for componentry can be readily drilled in situ
- Minimal maintenance requirements
- Environmentally benign, being rot-proof with no concerns over leaching of chemical preservatives or disposal concerns
- Engineered product with consistent performance

Other characteristics include good electrical insulation, high strength and excellent fatigue resistance (e.g. to cyclic wind loading) that is claimed to out perform steel products (Reference [4]).

Material stiffness is considerably lower than steel, requiring larger diameter structures (e.g. a 200mm diameter composite pole would replace a 160mm diameter steel pole) to provide equivalent stiffness.

Uptake by utilities companies has been inhibited by the earlier, now resolved, performance problems and the higher initial cost of the poles. Reduced manufacturing cost has enabled composite poles to become more competitively priced, with whole life costs now claimed to be lower than wood products. Manufacturers are actively seeking to increase market share and more widespread acceptance in the utilities sector is likely.

Composite poles might be utilised as support structures in a low-cost electrification scheme provided low cost installation techniques such as the utilities ‘buried pole’ method can be successfully applied. This may require poles that are specially shaped for railway application, for example incorporating a wide diameter buried section for enhanced ‘foundation-free’ performance to reliably resist the lateral loading of the OLE.

The potential benefits of a buried composite pole system are:

- Speed of installation
- Ease of handling and low installation cost
- Minimal maintenance requirement
- Long life
- Inherently insulating for simplification of OLE design (e.g. by enabling removal of secondary insulation components at the catenary)

5.5 SYSTEM VOLTAGE

Table 5 compares the technical factors that affect the comparative cost of 750VDC and 25kV AC OLE schemes.

Table 5 Comparison of Electrification Infrastructure Cost Factors, 750V DC and 25kV AC

Factor	750V DC	25kV AC	Comments
OLE Conductors	1000+ Amps traction current requires heavier gauge conductors	<100A traction current allows lighter conductor wires	Less copper required for 25kV system
Support Insulators	Simplified insulation arrangements and greater design choice (insulating rope. GRP poles, low profile post insulators etc)	Substantially larger, insulators required, although modern polymeric materials have enabled development of lighter, more compact 25kV designs	Simpler, cheaper support arrangements for 750V OLE
Support Structures	Simple support arrangements at over bridges and tunnels.	More complex support arrangements at bridges and tunnels (bridge arms etc)	
Electrical Clearance	Small electrical clearance more easily accommodated by existing infrastructure	Larger electrical clearance requirements can require expensive civil works to bridges and tunnels	25kV scheme may be subject to substantial additional costs where tight clearance structures feature on the route
Feeder Stations	Close feeder station spacing (~5km) requires more feeder stations and electrical supply connections	Fewer feeders required	Significant factor that would make 25kV electrification the more economic option for longer routes.
Power supply imbalance	Rectifiers operate from three phase supply for equal loading in all phases	25kV transformers operate off phase pairs with potential to cause supply imbalance. May increase substation and/or grid connection costs.	25kV feed would require additional consultation with the Distribution Network Operator (DNO) to establish most economical means of supply provision for specific situations.
Power Supply Harmonics	Substation harmonics may affect supply	Problems from harmonics less likely	May affect connection costings or necessitate the installation of harmonic filters
Signalling Immunisation	Immunisation of track circuits to traction currents required (where fitted)	Immunisation of track circuits to traction currents required (where fitted)	Costs will depend on existing/planned branch line signalling requirements
Traction Return	Running rails required to have good isolation from earth to reduce DC leakage current. Cathodic protection of buried services may be required	AC leakage current less of an issue and standard of rail/earth insulation not as high. Booster transformer return may be required to comply with mandated EMC emission limits	Would be a major cost (£0.5M per STK) if re-railing were required. Significant cost even if only additional insulation at chairs required.

Other issues that may be considered while selecting the operating voltage are factors associated with protecting staff and public against electrocution, such as fencing and the design of bridge parapets.

5.6 DC SUPPLY ARRANGEMENTS

Section 6 provides a detailed analysis of DC substation feeder topologies. It is concluded that a tramway feeding system with its economy of circuit breakers would be appropriate for the branch line scenario, with in-section paralleling on a double track system to maximise substation spacing.

Appendix B establishes the relationship between OLE conductor size and substation spacing for single track and double track lines, with the maximum theoretical substation spacing calculated for a system able to provide a minimum of 0.5MW of power to a single train positioned anywhere on the system. Those results are summarised Table 6 (also Table 4).

Table 6 Maximum Substation Spacings, Low Use 750VDC OLE System, 0.5MW load

OLE Equivalent Copper Cross Section mm^2	Single Track km		Double Track km (tramway feed, in-section parallel)	
	Single End Fed (Stub end)	Double End Fed (Spacing)	Single End Fed (Stub end)	Double End Fed (Spacing)
120	1.7	7.4	3.4	14.9
150	2.1	9.0	4.1	18.0
240	**3.0**	**13.0**	**6.0**	**26.2**
360	4.0	17.5	8.0	35.4

The number and location of DC substations required to operate the system is heavily dependent on the conductivity of the power line as determined by the equivalent copper cross section of the OLE and whether the line is single track or double track (configured for parallel feed).

For a 750V DC system specified to deliver a minimum of 0.5MW to a single load at any location on the line, a two substation system could power line lengths of up to 25.5 km (single track) and 51.4 km (double track) for the maximum OLE copper cross section considered.

For the 'base case' OLE configuration of 240mm^2 equivalent copper cross section (equivalent to twin contact trolley wire or standard/hybrid catenary OLE) the maximum line lengths that can be supported by a two feeder system is 19 km (single track) and 38.2 km (double track). This is illustrated in Figure 4.

Loss of either feeder would prevent service operation however, and acceptable operation would require close to 100% substation availability during running hours. Substation reliability and maintainability would be key factors, favouring the use of proven railway substation equipment incorporating in-built redundancy as may be deemed appropriate. A comprehensive Reliability, Availability, Maintainability and Serviceability (RAMS) analysis of the proposed power supply scheme would be essential, as would a full understanding of the impact of a line closure. The power supply failure and recovery scenario would need to be fully costed.

Figure 4 also shows the feeder configuration necessary to assure service operation in the event of any one feeder being unavailable, requiring three further feeders to be installed. This provides a robust supply configuration where individual feeder availability is not critical.

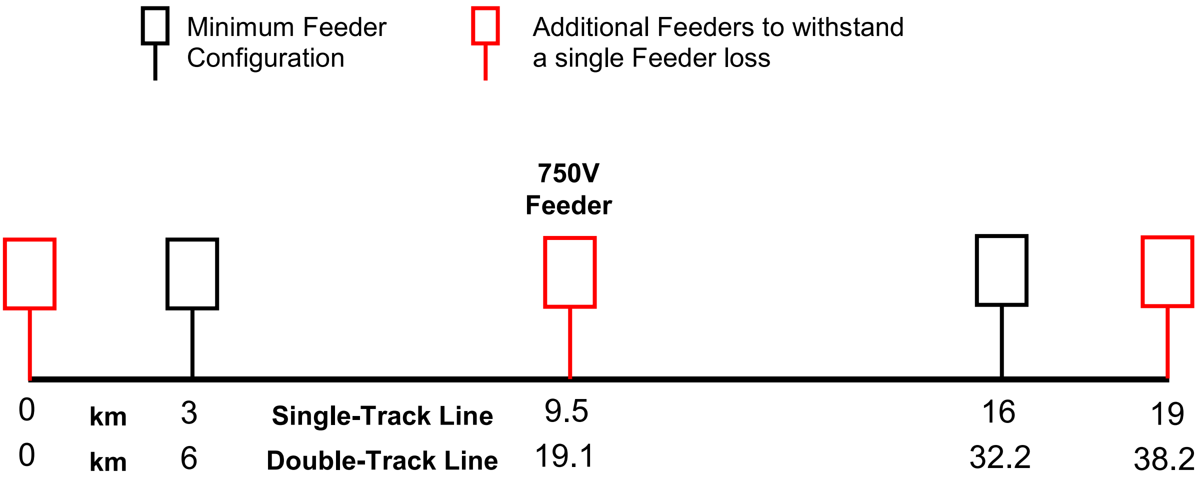

Figure 4 750V DC Branch Line Feeder Configuration (240mm^2 OLE, 0.5 MW power delivery)

With an operating voltage of 25kV AC the same line length would require either one (minimum system) or two (robust system) feeders placed anywhere along the line. The two 25kV transformers could be placed at the same location to share the same electricity supply point, however to achieve maximum reliability this scenario would require independent connections to separate DNO circuits.

5.6.1 Supply Efficiency

The following assumptions were made in the minimum DC power supply configuration calculations (Appendix B):

- Off load Substation voltage of 850VDC
- Supply current of 1000A
- Minimum System voltage (at load) 500VDC

These figures equate to a power supply loading of 0.85 MW to supply 0.5 MW to the load (train) at extreme distance, with a system power loss of 0.35 MW (59% supply efficiency) under those circumstances.

The above calculation demonstrates the principle that increased substation spacing reduces the system energy supply efficiency due to resistive losses in the power line. The whole-life costs associated with power supply inefficiencies therefore need to be factored into the system design.

Considering our example of a 0.85 MW feeder supply. Assuming 20% utilisation (200A average current draw) over a 12 hour operating day equates to an energy usage of around 2 MWhr per day, at a cost of £200 (bulk electricity energy tariff of 10p/kWhr assumed). This corresponds to a £1.44M energy cost over 20 years. Installing additional substations to improve overall energy efficiency would be unlikely to yield more than a 10% (£144,000) energy saving over 20 years which in itself does not justify the cost of additional substations but may justify increasing OLE conductivity.

5.6.2 Energy Storage

Energy storage systems, located either on-board the vehicle or trackside, can potentially reduce electrification system costs by enabling system operation from fewer or lower rated substation installations. Using energy storage to smooth power demand reduces peak energy demand and therefore is relevant to rural electrification schemes where the available electricity distribution system may have limited peak power capacity.

The other major benefit is increased energy efficiency where regenerative braking is used to recover energy for re-use.

Due to budget constraints it may be necessary to incorporate gaps into the supply; such gaps might be necessary for example because certain bridges have insufficient soffit clearance to accommodate live conductors. On-board energy storage may allow limited train ‘wire-free’ running which would enable trains to pass through such gaps. Such a system could also provide a means for the train to reach the next stop in the event of a system power loss and to shunt in unwired locations.

The principle energy storage technologies that have seen use in railway systems are battery, supercapacitor and flywheel systems.

5.6.2.1 Battery Systems

Battery systems have found limited application in some tram systems to provide supplementary traction power.

For example tram-trams in Karlsruhe are fitted with 230 Ahr capacity lead-acid batteries for the purpose of providing power for the tram electrical loads for up to 250m while switching between 750V DC and 15kV AC systems. There have been problems with battery reliability and the lead-acid batteries are likely to be replaced with 200 Ahr NiCd batteries which have better charge/discharge characteristics, more consistent performance and a life expectancy of 15 years compared to 2-3 years for the existing batteries.

Present day battery technologies have limited cycling capability. To provide sufficient capacity for the likely full regenerative storage requirements of a light rail vehicle it is probable that they would take up too much volume and add a prohibitive amount of weight.

Provision of a trackside energy storage system using batteries would have both high capital and maintenance costs. There are no present day examples where battery systems are used for this application.

5.6.2.2 Super Capacitors

Supercapacitors (double-layer capacitors) have limited volumetric energy storage compared to batteries but have excellent power cycling capability and energy efficiencies of 95% compared to 80% or less for batteries. Supercapacitors have no moving parts and are relatively compact devices that can be strung together to form modules of suitable form to fit the available space on board a vehicle. At present there is considerable interest in utilising this technology for traction energy storage purposes, particularly for on-train systems.

For example Alstom, in conjunction with Paris transport operator RATP, are evaluating supercapacitor technology as part of their STEEM (Maximised Energy Efficiency Tramway System) applied research initiative. A bank of 48 supercapacitor modules installed in the roof of a Citadis 402 tram will store energy regenerated during braking, and during station dwell times of 20 seconds will be topped up from specially modified segments of 'rapid-charge' OLE . It is intended that this will allow the vehicle to run between urban stops without using the catenary. Test runs will be conducted under commercial operating conditions over a one-year trial with the vehicle operated with its pantograph lowered on two sections of line T3, viz: Georges Brassens - Porte Brancion and Porte de Choisy - Porte d'Italie. A 'rapid-charging station' has also been installed at Lucotte depot.

'Semi-autonomous' tram operation may avoid the need to install catenary at complex junctions, in front of public buildings and on bridges, also allowing wire-free operation in depot areas. A system to automatically lower and raise pantographs using GPS technology is also to be evaluated as part of the trial to assist transitions between wired and wire-free areas.

Fully-autonomous (wire free) operation may be achieved by the boost-charging mechanism at stops. The STEEM partners believe this technology could reduce investment costs since lines could be built largely without catenary in urban areas where stations/quick-charging points are sufficiently close together.

Another application saw Mannheim tram operator MVV complete four years of trials in 2008 of a 1 kWhr Bombardier MITRAC Energy Saver supercapacitor system (fitted to a tram roof) to store regenerated braking energy. Long-term reliability of the technology was demonstrated with overall power savings of 20% achieved. With the pantograph lowered the MITRAC system was capable of running the vehicle for 500m inclusive of multiple stop/starts.

As a result of these trials, Rhein-Neckar-Verkehr (RNV) has opted to include the system on 19 Bombardier 'Variobahn' trams, thus meeting the aspiration of the city of Heidelberg to avoid erecting wires through a university campus; the additional cost is €270 000 per vehicle. The first six vehicles were due to be commissioned in December 2009 with full fleet commissioning by the end of 2010. The MITRAC equipment will reduce tram power demand by 40% during start-up and acceleration, with anticipated savings for urban usage of 93 MWhr of electrical energy per vehicle each year, the system will also allow trams to operate through two 400m catenary free sections built into the route.

Technical specifications for the MITRAC Energy Saver Unit indicate that two modules would typically be fitted to a 30m Light Rail Vehicle to provide a total of 2 kWhr energy storage capacity and 600 kW maximum output.

The STEEM and MITRAC examples demonstrate how supercapacitor energy storage may be applied to a tram system to reduce infrastructure and running costs, although at significant additional vehicle cost which must be weighed against the potential benefits.

5.6.2.3 Flywheel

The use of flywheel Kinetic or Trackside Energy Storage Systems (KESS or TESS) for trackside energy storage has been demonstrated on a number of urban railways including in London, New York, Cologne, Lyon and Tokyo.

London Underground undertook a series of trials in 2000 to 2001 using three 100 kW KESS units, connected in parallel, installed at Northfields substation. The trials were conducted using three 1996 Jubilee Line cars with regenerative braking running on a 2·8 km test track between South Ealing and Northfields. The tests successfully proved the concept with results matching predictions from computer simulations.

Similar tests were conducted on the Cologne local transportation network using a DC substation installed 600 kW flywheel capable of absorbing 450A regenerated current and storing 6.6kWhr of energy. The tests demonstrated 24% overall energy saving: other benefits noted were the boost in available substation power and stabilisation of catenary voltage. The tests indicated that such an energy storage system could replace a substation in some circumstances. Comparative tests were also undertaken at a second substation using a supercapacitor energy storage system.

In 2002 New York Mass Transit Authority evaluated a 1 MW flywheel (10 x 100 kW array), an ultracapacitor and a battery trackside energy storage systems on the Far Rockaway line. As a result of those tests a lineside flywheel energy storage system was selected in August 2009 for a $5·2m pilot project on Long Island Railroad's (LIRR) West Hempstead line. The system will comprise an array of carbon fibre flywheels capable of providing 2.5 MW for 30 seconds and full recharge in a similar time. The purpose of the scheme is to enable LIRR to evaluate flywheel technology to meet demand from a new, more powerful, fleet of trains that will otherwise require expensive upgrade of the substations.

Present day flywheel technology essentially comprises two types:

- Low speed flywheel systems operate at 1800 – 3600 rpm, they consist of a high mass (steel) flywheel with power electronics for conversion between AC and DC voltages
- High speed flywheels operate up to 30,000 rpm, they consist of a composite (carbon fibre) flywheel running on frictionless magnetic bearings in vacuum chamber housing, coupled to a permanent magnet motor/generator

Low speed flywheels are typically 90% efficient and require regular maintenance.

High speed flywheels represent the current state-of-the-art, being 95% efficient and of lighter weight than equivalent power low speed systems, and designed for low maintenance. Power and cycling capabilities exceed those of supercapacitor systems, factors that favour flywheel over supercapacitor technology for trackside storage systems. Conversely present designs of high speed flywheel are less well suited train vehicle installation compared to supercapacitors, which offer a more compact and vibration resistant on-board energy storage solution.

At the time of writing commercial flywheel TESS systems were being marketed by US companies Pentadyne Power Corporation and VYCON.

The Pentadyne TracBlock™ system is based on the use of 200 kW high speed flywheel modules that operate in arrays to provide systems of 1 MW to 4 MW rating. The corresponding usable 'per cycle' energy storage cycle capability is 2.8 kWhr to 11.1 kWhr [N.B. 2.8 kWhr equates to the kinetic energy of a 30 Tonne rail vehicle at 80 km/h]. Electrical characteristics include a discharge duration (at 50% rated load) of 20 seconds, and a typical idling consumption ranging from 3 kW to 24 kW.

Complete systems are provided in a relocatable outdoors container (shipping container sized) that includes all necessary subsystems including AC and DC Panel Boards, DC circuit breaker and internal lighting and climate control.

The VYCON 'rail regen' system comprises a 500 kW/1.6 kWhr flywheel housed in a 2m x 2m x 0.9m (approx) size cabinet that also contains the control subsystems, vacuum pump and bi-directional power controller.

In the branch line electrification scenario a TESS would typically be installed as a stand-alone 'secondary' power supply placed halfway between the substations to support the system voltage and enable the substations to be placed further apart (Figure 5). The TESS would typically be charged from the 750V OLE during off-load/braking periods in the traction demand cycle.

The operating mode of a TESS can be set to either Energy Saving mode (low charge level quiescent state, ready to receive regenerated energy) or Voltage Support mode (high charge level quiescent state, ready to deliver power). The system could be set to revert to Energy Saving or 'sleep' mode during out of hours running to reduce standby losses.

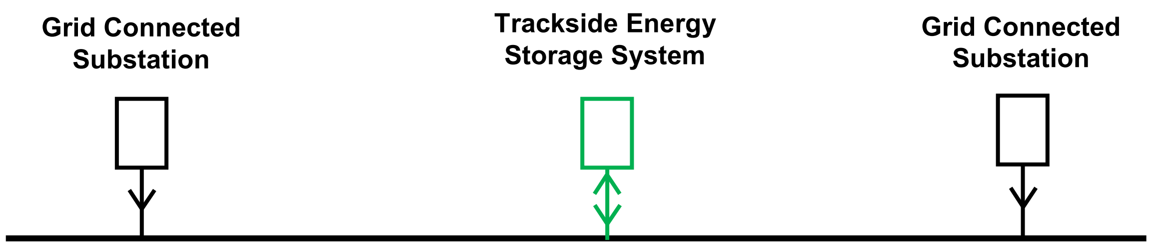

Figure 5 Branch Line Traction Supply Configuration utilising Trackside Energy Storage

Capital cost for a high speed flywheel system is presently in the region of $1000 per kW installed peak power, or $1 million (£670k) for a 1 MW system. Industry opinion is that the cost can be brought down to around $750 per installed kW (equivalent to £500k for a 1 MW installation) with increased take-up of TESS technology in railway/power applications.

Again it would be necessary to assess the economic advantage of this arrangement on a case-by-case basis, also in comparison to the option of on-vehicle energy storage/ regenerative braking system which may provide for greater operational flexibility and least infrastructure capital cost.

6 SUBSTATION EQUIPMENT OPTIONS AND COSTS

6.1 OVERVIEW

Traction substations have evolved over the years to suit the type of load being supplied. There has been an ongoing focus to reduce the equipment count and costs of substations by LUL, BR, Railtrack and Network Rail over the years, but they remain an expensive component in an electrification system.

When considering the electrification of a minor line, potentially in an area that is not connected to main line electrification, and using light weight rolling stock, then it is reasonable to assess whether substations should continue to be configured and built in the way that they always have been.

In this section of the report, we have investigated means by which the substation equipment count and ratings could reasonably be economised and means by which the distance between substations could be maximised, thus reducing the number of substations needed to electrify a particular line.

6.2 DC FEEDING TOPOLOGIES

6.2.1 Operational Considerations

Key to reducing the cost of the substation element of a particular electrification scheme is to reduce the numbers of substations needed, by maximising the distance between them. As has already been discussed in this report, the main factors which influence the substation spacing are the conductivity of the overhead lines and the return rails and the amount of traffic to be supported.

Electric rolling stock has a range of line voltage over which it can exert its maximum performance. If the voltage received by the train falls below the minimum value, the train's drive reduces the tractive effort that it can develop, normally in proportion to the available voltage. Below another minimum value, the drive will shut down and the train will then revert to coasting. This is demonstrated in Figure 6.

As a result of these characteristics, the electrification system as a whole should aim to achieve an average line voltage at each train that enables it to use maximum performance.

As has already been discussed, the voltage available at the train will vary as a result of the resistance of the overhead line that feeds the train with power and the resistance of the rails that are used to return the current to the substations. The voltage will also vary as a result of the load imposed upon the system by other trains and other factors such as variations in the high voltage network supplying the substation.

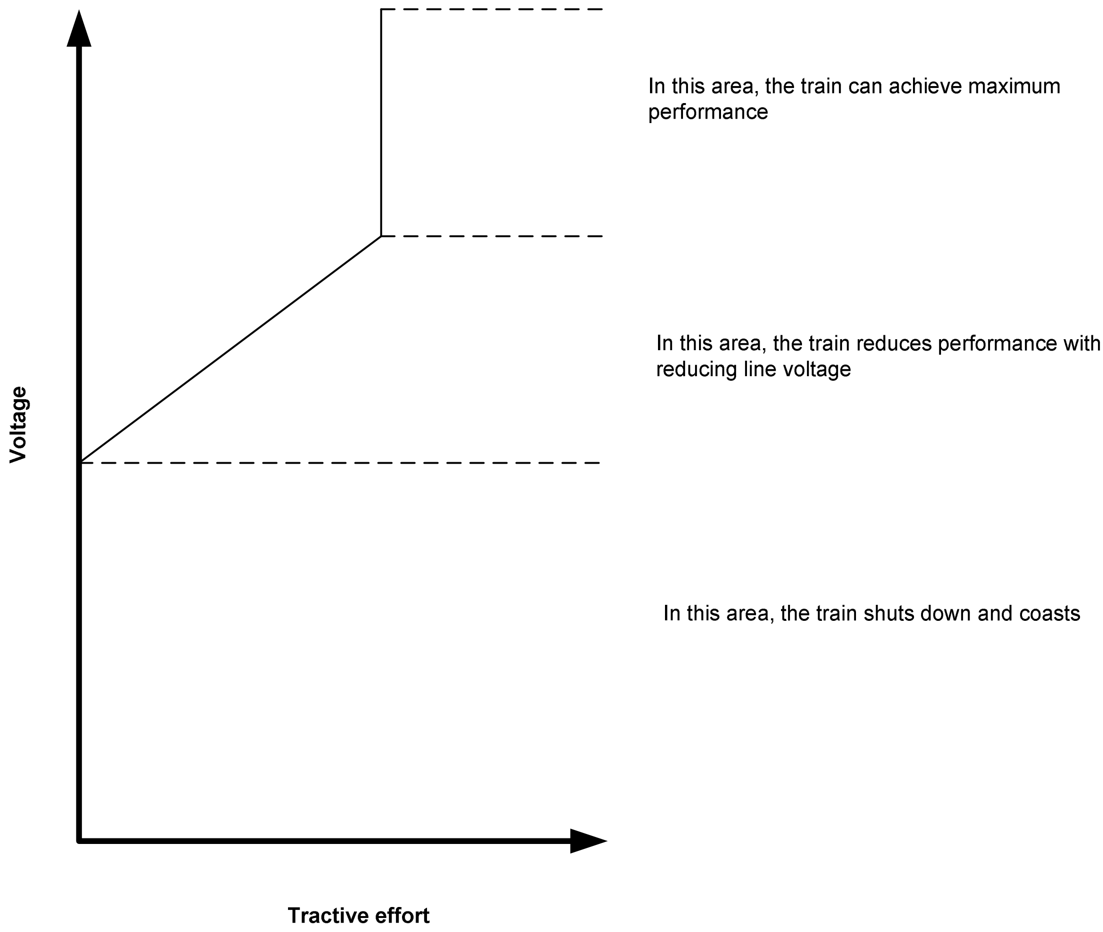

Figure 6 Tractive effort versus voltage of a typical electric train

The means by which the power is distributed to the overhead line system and that network's interconnectivity affects the overall resistance of the overhead line and running rails. Improving the interconnectivity between tracks of the overhead line system and the number of crossbonds between running rails and between tracks will have the effect of reducing the overall resistance of the system and improving the voltage seen at the train. For a given allowable voltage drop (over which the train can still exert maximum performance), the reduction in overall resistance means that the substations can be spaced out further and the overall number of substations can be reduced for a given length of line.

Mathematical models of each feeding topology have been created in a commercially available electrical simulation tool called "PSpice".

For the purposes of comparison a double track section with 5km spacing between substations is used, with the OLE consisting of conductors with the equivalent resistivity of 240mm^2 hard drawn copper and using 49kg/m running rails as the return path.

These variables have been chosen as being representative of the configuration of segregated running sections of UK and continental tramways.

The train is assumed to draw a constant current of 2000A. The voltage at the train is measured at the mid point between substations and at ten locations along the section.

This current has been chosen as it is considered representative of those found in modern light rail vehicles.

The following sections examine four common feeding topologies and compare their merits in terms of the maximum spacing that can be achieved between substations for a single train in section, compared to equipment count and cost, using the outputs from the models described above.

6.2.2 "Conventional" Feeding

This configuration is widely used in DC traction substations feeding both heavy and light rail systems and is in widespread use in the UK in places such as LUL, Manchester Metrolink and in certain areas of Network Rail's DC electrified lines.

The layout consists of a substation at each end of the section feeding "up" and "down" lines. Each line is fed at 750V DC through individual circuit breakers and there are no interconnections between the "up" and "down" lines, except at substations. The configuration is shown in Figure 7.

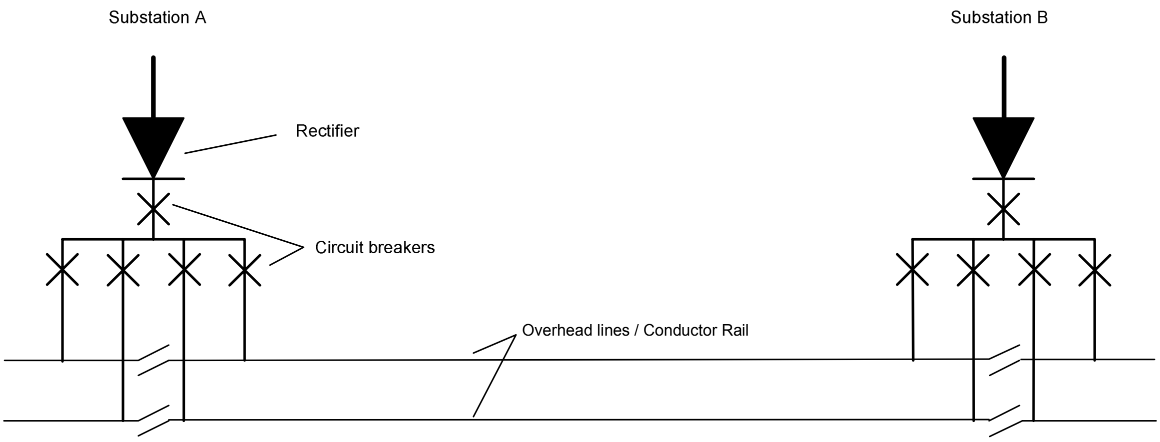

Figure 7 Diagram of "Conventional" DC Feeding

If the above topology is modelled in the manner discussed in section 6.2.1, the minimum voltage seen by our train at the mid point is: 712.5V and the average voltage experienced by the train is: 727.5V. The plot of voltage at the train versus distance is shown in Figure 8.

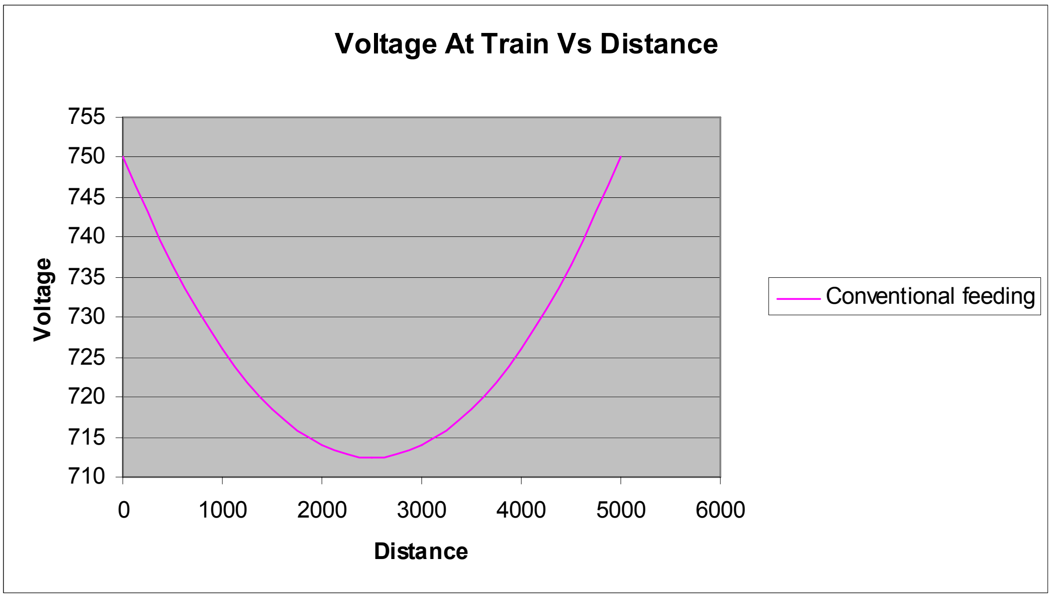

Figure 8 Voltage versus distance for conventional feeding

As shown in Figure 7, each of the "up" and "down" lines is fed from a separate circuit breaker. Thus a fault affecting one line would be detected and cleared by the circuit breakers feeding that line, without affecting supplies to the other line. Similarly, each line can be isolated independently from each other, meaning that traffic can be maintained on one line whilst the other is isolated.

This feature of feeding each line independently from the other means that the system is resilient against faults and offers operational flexibility, which is important for those lines which carry frequent traffic.

6.2.3 "Conventional" Feeding With Mid-point Paralleling

This configuration is a development of conventional feeding which has been described in section 6.2.2.

It was developed primarily to increase the distance that could be fed, by introducing a parallel path for currents that was located at or about the electrical mid point of a section. By paralleling the conductors (in our case the overhead lines), their effective resistance is reduced, thus reducing the voltage drop along the system. For a given train service, it allowed the distance between substations to be increased. Mid point paralleling can also be added to a system that has conventional feeding to allow for a greater train service to be supported by increasing the average voltage along the line and hence allowing the average currents to increase for a given voltage drop.

The configuration is shown in Figure 9.

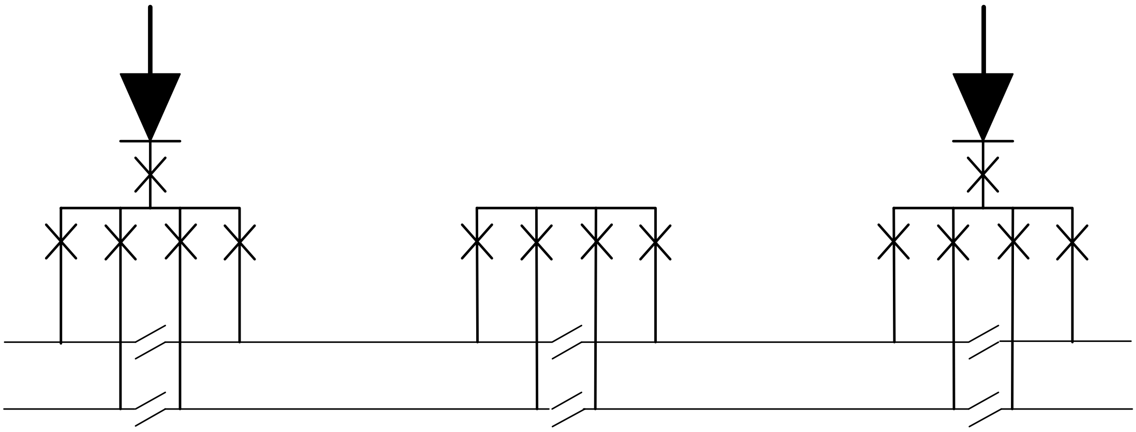

Figure 9 Conventional feeding with mid point paralleling

The mid point paralleling equipment takes the form of a DC busbar being connected to each track in each direction, requiring the addition of 4 circuit breakers. It is commonly called a "Track Paralleling Hut", or TPH.

This method of feeding is in widespread use on Network Rail's southern DC system, where it is considered the norm.

Using the model discussed in section 6.2.1, the voltage profile is shown in Figure 10.

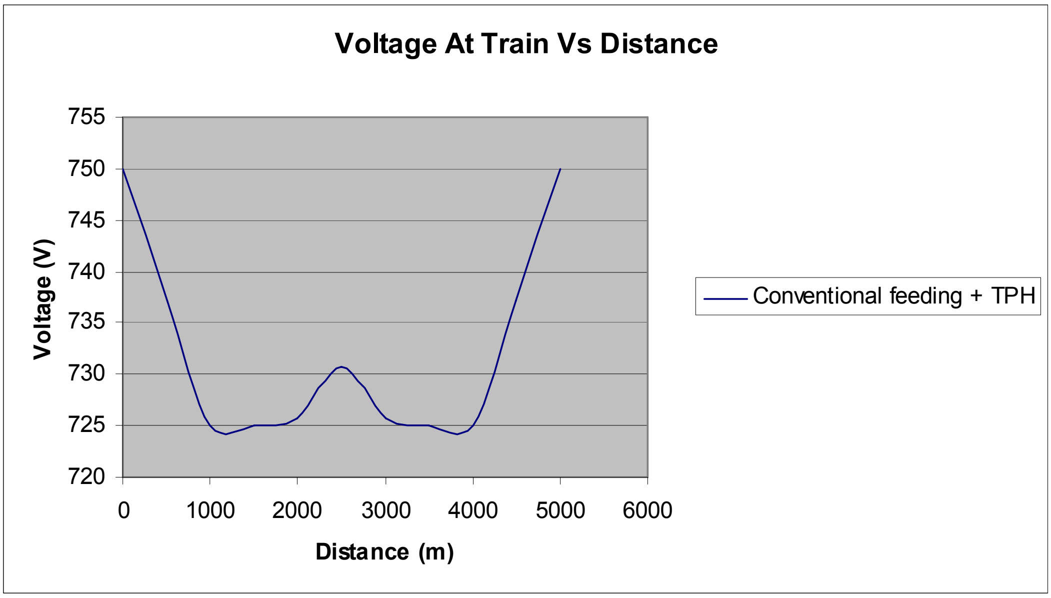

Figure 10 Voltage versus distance for conventional feeding

As can be seen from the plot, instead of the voltage profile descending to a minimum at the mid point, the voltage actually recovers in the vicinity of the TPH. The mid point voltage is 730.8 and the average voltage seen by the train is 732.5V, or 5V higher than for conventional feeding.

Although the difference in average voltage is small, the resistance of the network seen from the train is reduced by 61%. For a given train service, the distance between substations can be increased by a corresponding amount, although in practice, increases of 50% are usual.

The benefits of independency by feeding each line from dedicated circuit breakers at each substation and the TPH are the same as those offered by conventional feeding, although at the expense of a higher equipment count and the need for another installation and building.

6.2.4 "Tramway" Feeding

Tramway feeding obtains its name from the fact that this feeding topology is in widespread use on tramways. In many respects, it is similar to "conventional" feeding in that the section is fed at each end by a substation and it has no intermediate paralleling of the overhead line conductors within the section. Where it departs from "conventional" feeding is that the "up" and "down" lines are fed from the same circuit breaker (Figure11).

Figure 11 "Tramway" feeding

The voltage profile along the section is identical to "conventional" feeding.

This feeding topology has the advantage of requiring fewer circuit breakers, but at the expense of loosing operational flexibility as a fault on one line will cause loss of power to both lines. It is in widespread use within European tramway systems, where the operators do not believe that the loss of operational flexibility is too severe and that persistent faults on overhead lines are rare.

6.2.5 "Tramway" Feeding With In Section Paralleling

This is a minor variation of tramway feeding, whereby paralleling cables are installed at the mid point of the section and at the quarter and three quarter points in the section (Figure 12).

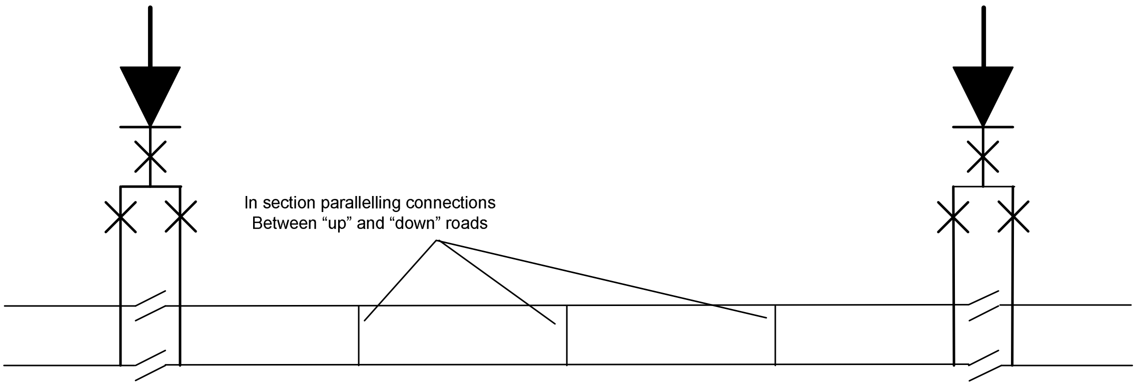

Figure 12 "Tramway" feeding with in section paralleling

This has a similar effect to the addition of a TPH within the conventional feeding scenario that has been previously discussed. Each of the paralleling points acts as a TPH and has the effect of further reducing the resistance between the train and the substations; the voltage profile of this feeding configuration is in Figure 13.

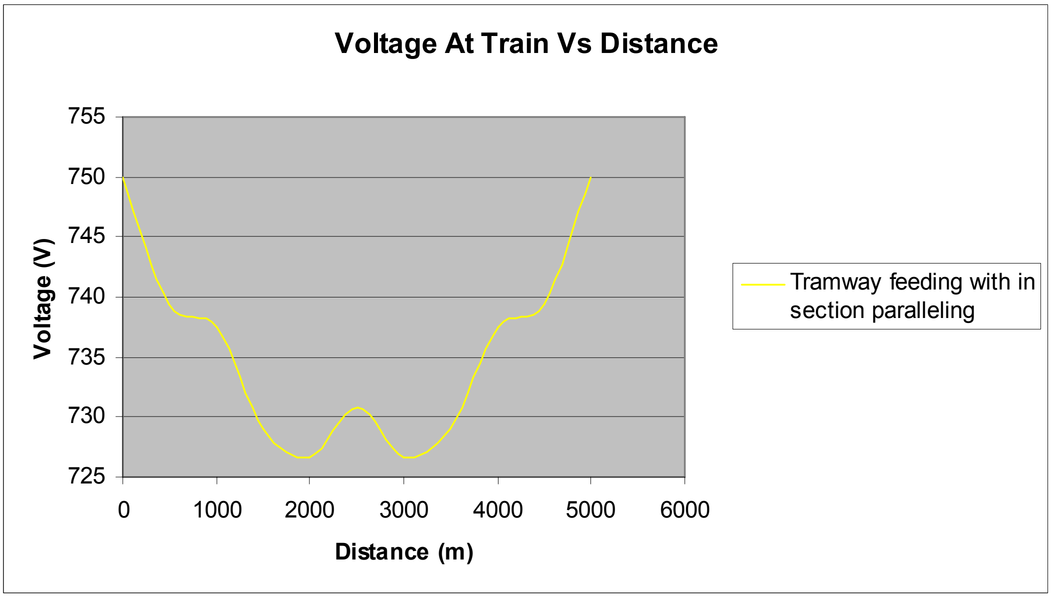

Figure 13 Line Voltage Profile for Tramway Feeding With In-section Paralleling

The average line voltage for this feeding topology is 736V, compared to an average of 727.5V for both conventional and tramway feeding options and 732.5V for conventional feeding with track paralleling hut. Again, although these improvements in average voltage appear small, they belie larger reductions in resistance from the train to the substations. The reduction in resistance using tramway feeding with in section paralleling is 69% when compared to conventional or tramway feeding, in practice allowing the distance between substations to be increased by 60%.

This feeding topology is in widespread use in tramway and trolleybus systems in Europe and on the London Tramlink system in Croydon.

6.3 DISCUSSION OF THE ADVANTAGES AND DISADVANTAGES OF FEEDING TOPOLOGIES

Four of the most common DC feeding topologies have been presented in this paper; each has their advantages and disadvantages, although these must be viewed in the context of the light weight rail vehicles and service pattern that is being considered in this study.

The advantages and disadvantages of each configuration for the type of train service this study is considering, is summarised below.

6.3.1 Conventional Feeding

Advantage	Disadvantage
Separation of "up" and "down" lines provides higher reliability and flexibility	Requires additional circuit breakers to implement independent feeding of each line
Independent feeding of each line can be justified on a conductor rail system which has a potentially high fault frequency	Overhead line systems have a lower fault rate than conductor rail systems, making independent feeding more difficult to justify
Independent feeding has to be implemented where trains draw heavy currents for sustained periods due to circuit breaker rating	Light weight vehicles do not have such heavy current demands, making independent feeding more difficult to justify
Simple topology of one circuit breaker per line, per direction makes the system easy to understand for non technical staff	
	Because no additional paralleling is installed in the section, the sub station spacing is short, requiring more substations

6.3.2 Conventional Feeding with TPH

Advantage	Disadvantage
Separation of “up” and “down” lines provides higher reliability and flexibility	Requires additional circuit breakers to implement independent feeding of each line
Independent feeding of each line can be justified on a conductor rail system which has a potentially high fault frequency	Overhead line systems have a lower fault rate than conductor rail systems, making independent feeding more difficult to justify
Independent feeding has to be implemented where trains draw heavy currents for sustained periods due to circuit breaker rating	Light weight vehicles do not have such heavy current demands, making independent feeding more difficult to justify
Simple topology of one circuit breaker per line, per direction makes the system easy to understand for non technical staff	
TPH reduces apparent resistance seen by train and allows for substation spacing to be increased by typically 50%	Each TPH usually requires an additional building, 4 circuit breakers and ancillary services. Typically only 25% to 33% the cost of a substation though

6.3.3 Tramway Feeding

Advantage	Disadvantage
Feeding of both of “up” and “down” lines from a single circuit breaker reduces equipment count and cost	Loss of independence of feeding means both “up” and “down” roads loose power for a fault
Overhead line systems have a lower fault rate than conductor rail systems, making tramway feeding more justifiable	Conductor rail systems have a higher fault frequency than overhead lines, making independent feeding more desirable
Light weight vehicles do not have such heavy current demands, which means that both roads can usually be fed from a single circuit breaker	Heavy rail vehicles usually have higher sustained currents which could overload a single circuit breaker, making tramway feeding unviable
	Staff need to remember that both “up” and “down” roads are fed from a single circuit breaker – easy to forget this and inadvertently disconnect both lines
	Because no additional paralleling is installed in the section, the sub station spacing is short, requiring more substations
In section paralleling offers trains equipped with regenerative brakes the highest opportunity to return regenerated energy to the system	

6.3.4 Tramway feeding with in section paralleling

Advantage	Disadvantage
Feeding of both of "up" and "down" lines from a single circuit breaker reduces equipment count and cost	Loss of independence of feeding means both "up" and "down" roads loose power for a fault
Overhead line systems have a lower fault rate than conductor rail systems, making tramway feeding more justifiable	Conductor rail systems have a higher fault frequency than overhead lines, making independent feeding more desirable
Light weight vehicles do not have such heavy current demands, which means that both roads can usually be fed from a single circuit breaker	Heavy rail vehicles usually have higher sustained currents which could overload a single circuit breaker, making tramway feeding unviable
	Staff need to remember that both "up" and "down" roads are fed from a single circuit breaker – easy to forget this and inadvertently disconnect both lines
An infinite number of paralleling points can be installed (although more than 4 shows a diminishing return). This topology offers the lowest apparent resistance from train to substations	
In section paralleling offers trains equipped with regenerative brakes the highest opportunity to return regenerated energy to the system	

6.4 CONCLUSIONS

Each of the four feeding topologies has developed over the years and each has been adopted by various organisations for various reasons. There is no single superior topology, each having its advantages and disadvantages. The key issue at stake is the selection of the most appropriate topology for the line and train service being considered.

Network Rail uses both conventional feeding and conventional feeding with TPH on its DC electrified routes and there are good reasons for this; traffic is often heavy and frequent, using heavy rail trains with high sustained currents. In this scenario, tramway type feeding would not necessarily be appropriate or in some cases technically feasible (due to the amount of current being passed through a single circuit breaker). Similarly, in a dense and interconnected network, the independent feeding of "up" and "down" lines is entirely understandable.

Tramways and light rail systems have also used conventional feeding both in Europe and in the UK, although the reasons for this are more diffuse. In some instances, the feeding topology appears to have been significantly influenced by their electrification systems being designed by engineers versed in heavy rail practice, or being used because of the desire to retain maximum operational flexibility. Only a very few tramway systems could justify independent feeding on the basis of exceeding the circuit breaker rating.

The vast majority of tramways in Europe use tramway feeding or a variant of it because of its economy, even in areas of high traffic. In these cases, the system has been less influenced by heavy rail experience and it is known that in suburban and semi rural areas, the frequency of faults affecting the overhead line (and thus causing loss of power to both lines) is rare and usually caused by foreign objects contacting the line. Thus conventional feeding cannot be easily justified except around some critical junction areas.

This report is considering the use of light weight rail vehicles on a segregated right of way with (by tramway standards) sparse traffic. Economical provision of the electrification for such a line would drive the decision towards having the greatest possible substation spacing and the substations themselves having the lowest possible equipment count. Under such circumstances the use of conventional feeding (with or without a TPH) would be difficult to justify.

The use of tramway feeding with its economy of circuit breakers would be recommended, as would the use of in section paralleling, to maximise the distance between substations and to extract the maximum amount of recuperated energy from regeneratively braked trains.

6.5 SUBSTATION EQUIPMENT

6.5.1 Overview

Power supply costs are reduced both by choosing a DC feeding topology that increases the spacing between substations and by a reduction in cost of the substation itself.

The reduction is substation costs has received considerable attention from electrification engineers over the years and the scope for further reductions on the equipment alone is considered to be small.

This report considers how electrification costs can be reduced in order to support light rail vehicles operating on a typical branch line. The report has considered how the design of the overhead line and the topology of how those lines are fed can be optimised to reduce costs. This section of the report will now concentrate on the design of the substations and how they can contribute to lowering the cost of the whole electrification system.

6.5.2 Factors Influencing Equipment Count and Rating

Before we commence the discussion of substation design, it is important to understand the factors that influence the numbers of equipment required and how their ratings are determined, as changes to any of these factors will determine what will be required in the proposed substation design. The number and rating of each of the major items of equipment will to a large extent be determined by the following factors:

6.5.2.1 DC Switchgear

Numbers will be largely determined by the DC feeding topology used. Ratings will be determined by traction characteristics of the trains, the number of trains in a section and the timetable and whether a substation is designed to carry part of the load of the adjacent substation if it should fail.

6.5.2.2 Rectifiers

Usually there will be a single rectifier in a substation. Larger numbers of rectifiers are provided when there is a need to supply loads in excess of the rating of a single unit or where there are special considerations of ensuring the reliability of the supply, such as at depots or those substations feeding underground sections of line. Rectifier ratings are determined by the train characteristics, numbers of trains in section, the timetable and whether a substation is designed to carry part of the load of the adjacent substation if it should fail.

Rectifiers are usually made in a number of standard ratings from which the choice is made. The rating takes the form of a time dependent curve or duty cycle.

6.5.2.3 HV Switchgear

The number of HV circuit breakers is dependent upon the number of rectifiers that are provided at the substation and the number of incoming feeds (whether direct from the electricity Distribution Network Operator or from feeder cables owned and operated by the railway administration). Additional sectioning facilities are usually provided when there is a need to keep at least one part of the HV busbar live to maintain supplies such as at depots or at substations feeding multiple lines or underground lines.

The rating of the switchgear is dependent upon the system voltage and the currents that have to be handled, with the choice being made from a number of standardised ratings.

6.5.3 Proposed Substation Design

In proposing the substations design to support the train service considered in this report, we have taken the view that we should aim to minimise the numbers and ratings of equipment that are provided to the minimum possible levels and have based our design philosophy on tramway, as opposed to heavy rail, design practice.

We believe that this would show what a “bare minimum” design could achieve and we then compare this against typical heavy rail practice to show where the differences lie. Our proposed design is, we believe, robust enough to form the basis of designs that could be used in real life, although we would caution that the design may not be suitable for every situation.

Real world examples should be designed on the basis of the business specification for the train service to be provided and there may be many valid reasons for adopting an enhanced equipment count and greater measures of reliability.

6.5.3.1 DC Switchgear

On the basis that tramway feeding with in-section paralleling is adopted, then a typical traction substation would require one circuit breaker to feed in each direction. Normally this would equate to two circuit breakers per substation (one in each direction).

In order to minimise the let through current in the event of a fault and to disconnect the fault from the source of supply before the short circuit current rises to its steady state value, it is usual to adopt a High Speed Circuit Breaker (HSCB) which has very high speed current extinction characteristics.

Several light rail systems have used Medium Speed Circuit Breakers (MSCB) in the past because the fault currents which can be generated by their small rectifier plant are modest and the time taken for the current to reach its maximum steady state value is long in comparison to heavy rail systems. MSCBs have historically been cheaper to purchase than HSCBs, making their adoption for light rail systems, that do not require very short tripping times, attractive.

Recent developments in circuit breaker design and the small market for MSCB’s have meant that most manufacturers have discontinued their MSCB product lines.

Accordingly, our design uses HSCBs on the basis of availability, choice of manufacturers and the benefits gained from quick fault clearance.

Our modelling of the typical system undertaken in this study indicates that a circuit breaker rating of 2000A in accordance with BS EN 50123-2, is sufficient for the traffic envisaged. This also accords to the ratings used in the London Tramlink system that uses the same DC feeding topology, but operates a more intensive service. HSCBs with ratings lower than 2000A are feasible (one manufacturer offers 1500A devices), but they are not common and adopting a lower rating would restrict choice. The HSCB would be mounted on a withdrawable truck inside a sheet metal enclosure as is the normal practice for this equipment. Protective relays would be fitted to the enclosure to detect any faults in the section being fed and to initiate tripping of the circuit breaker.

In line with the practice being adopted in both light and heavy rail spheres at single rectifier substations, the rectifier output would be connected to the DC busbar by means of a motor operated DC disconnector, as per BS EN 50123-3. This disconnector allows for isolation of the rectifier for maintenance and if it developed a fault, but at lower cost than using a circuit breaker.

6.5.4 Protective Relays

Protective relays would be fitted to each DC feeder circuit breaker in the substation. Their purpose is to detect a fault on the section being fed and to initiate tripping of the DC circuit breaker to clear the fault.

Historically, the type of relay fitted and how it functioned were chosen as part of an overall protection philosophy. If an operator changed his philosophy, the hardware had to change too. Similarly if an additional protection element was required, an additional relay would be fitted.

Modern protection relays are tending towards the relay hardware offering programmable protection functions, where the relay characteristics and function are defined in software. Thus the protection philosophy and which elements are fitted to which circuit breaker can be defined almost at will and can evolve as required over the equipment’s lifetime.

As choices of protection philosophy are no longer constrained by the hardware fitted, we have not confined ourselves to any one philosophy and believe that all of those used in the light rail sphere have their merits and detractions. Which combination of elements to apply is best chosen at a more detailed design stage.

Irrespective of which philosophy is chosen, we have assumed that a programmable digital relay capable of implementing several elements and combinations of elements is fitted to each DC feeder circuit breaker.

6.5.5 Rectifier Plant

Our modelling of the line and the train service envisaged identifies that a rectifier rating of 600kW duty class IV as per BS EN 50238 will be adequate to support the service with all substations feeding the line and to cover the increase in load if the rectifier in the adjacent substation is out of service.

This choice of rectifier rating is again supported when examining the rectifiers used on UK and European light rail systems, where this rating is used on systems which support higher levels of traffic.

It may be possible to reduce the rating of the rectifiers further given more detailed modelling and when the traction characteristics of the trains are known in better detail. This may be worthy of further study in a real world example.

Our design proposal assumes that the rectifier will be of 12 pulse series bridge design on the basis that the harmonic currents injected into the HV supply will be more acceptable to the DNO. It may be possible to adopt a 6 pulse series bridge design, which is cheaper than the 12 pulse design as the transformer has fewer LV windings.

Six pulse designs may be more difficult to accommodate on weak rural HV networks where harmonic distortion may already be approaching compatibility limits, although this could be worth further design effort in a “real world” case.

Our design proposal envisages that the rectifier diodes would be encased with other ancillary equipment in a suitably partitioned steel cubicle within the substation building.

The rectifier transformer could equally be a liquid filled, dry or cast resin type, as at this rating size, there is little to separate them in terms of price or advantage. Dry and cast resin types would need to be accommodated inside of the substation building, making its floor area larger.

Liquid filled types could be installed inside or outside, but environmental legislation could require that they be fitted with a bund to prevent escape of the liquid within the transformer in the event of a leak. Outdoor bund construction can cause the liquid transformer overall costs to exceed those of an indoor dry or cast resin transformer.

6.5.6 HV Switchgear

In our proposed design, we are assuming that the high voltage supply for the substations is derived from a DNO network, as opposed to a railway operated high voltage distribution network.

It is likely that where secondary and branch lines are electrified to serve lightweight vehicles and that there is no existing railway high voltage network, the costs of installing such a dedicated network would be too high.

To minimise the amount of HV switchgear required, we would propose that the high voltage switchgear should be owned and maintained by the DNO, with operation of the HV circuit breaker feeding the rectifier being vested in the railway administration. The same methodology has been adopted on the London Tramlink system and so sets a precedent.

Other UK light rail systems have not always been able to profit from such an approach and cases where the DNO and tram operator have duplicated equipment are to be found.

Our proposal is that the HV switchgear should consist of a ring main unit with two ring switches and a single circuit breaker, in line with the arrangement used on London Tramlink. The ring main unit would be specified by the DNO.

6.5.7 Ancillary Services

The substation would need a range of ancillary services such as:

- Batteries and charging system to support switchgear operation and SCADA equipment
- Negative busbar for return current connections
- An earthing system
- Low voltage services such as heating and lighting

All of these services relatively are standardised and easy to obtain. None give rise to major cost concerns.

6.5.8 Substation Building

The last 20 years or so have seen an increasing tendency to prefabricate substations into metal buildings that can be constructed and integrated in a factory environment and shipped to site in one or more “blocks” that are then assembled into the complete building on site.

We would advocate that prefabrication is likely to lead to the lowest overall costs for the construction of substations.

Concerns have been raised over the visual aspects of steel buildings in various landscape settings. These can be ameliorated by cladding the steel skin of the building with a suitable finish (such as brick or stone) to match the neighbourhood. Other strategies may include the use of paint schemes to camouflage the building’s outline.

6.6 PROPOSED DESIGN - SUMMARY

The proposed design of the traction substation is shown in Figure 14.

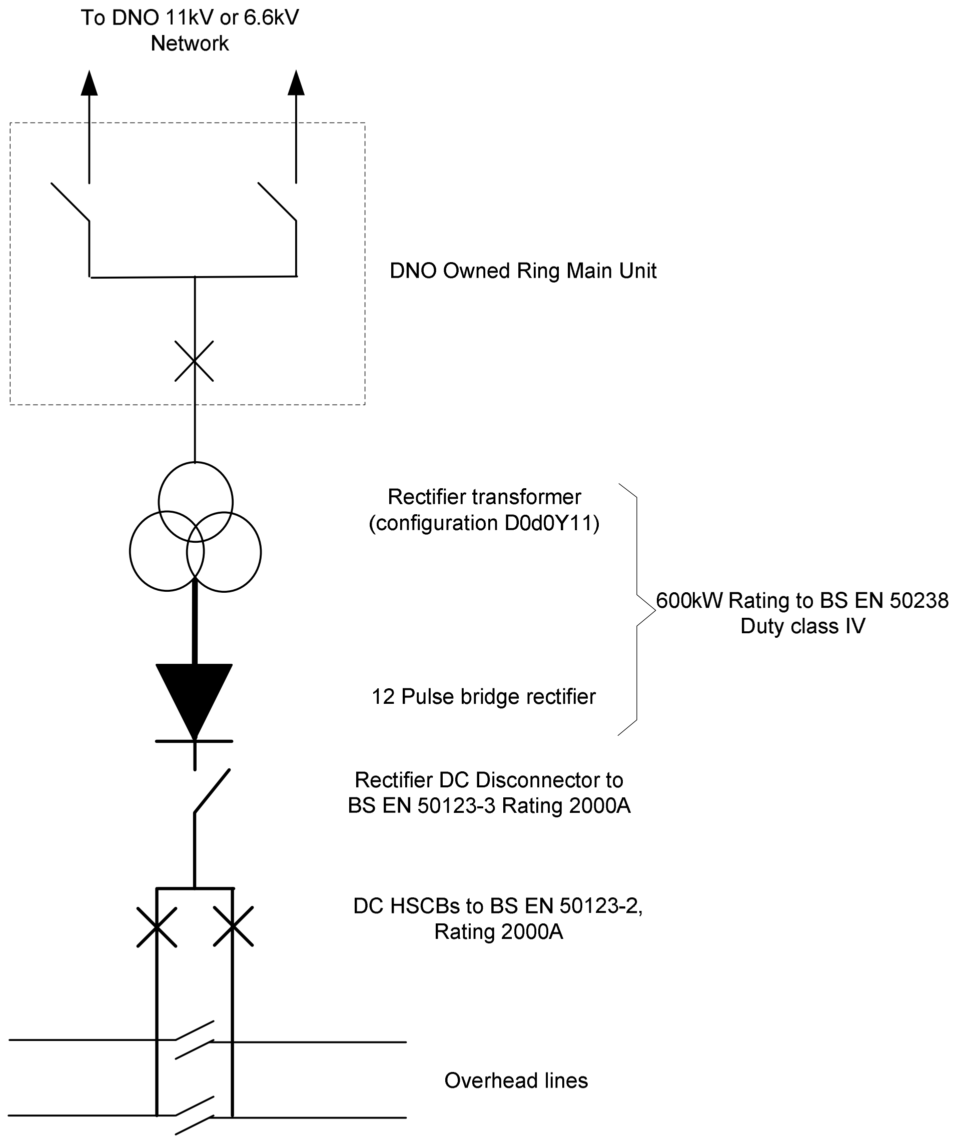

Figure 14 Proposed Traction Substation Configuration

6.7 COSTING

Competition between suppliers of substation equipment and the volatility of raw material costs has lead to a reluctance for companies to quote budget prices without a specific application being known. The costs below therefore are presented in broad ranges, with the caveat that a structured request for quotation against a confirmed specification might yield a higher price: also a recovering world economy may cause prices to inflate as the demand for materials increases:

- 600kW rectifier set (transformer, rectifier and enclosure for the rectifier itself, with ancillaries) ex works costs of £180k to £250k
- 1200kW rectifier set (transformer, rectifier and enclosure for the rectifier itself, with ancillaries) ex works costs of £320k to £400k
- ESI standard SF6 insulated circuit breaker ring main unit ex-works costs from £18k to £27k
- DC circuit breaker: £28k to £55k per panel
- DC enclosure (with space for up to 4 DC High Speed Circuit Breakers) £80k to £100k installed on site
- Foundations / civils work (except for DC module, which includes these costs): £120k (assumed good ground with no need for significant earthworks etc) to £250k, (requires piling, structural works etc)

Connection charges to the 11kV network cannot be estimated without specific knowledge of the local DNO networks and loading. It may be assumed however that the cost of connecting to a robust urban network with no capacity issues would be considerably lower than connecting to a weaker rural network that requires some degree of reinforcement. A target cost of £500k per connection may be used for budgetary calculations until specific local conditions can be formally assessed. In many cases, moving the traction substation a kilometre or so in each direction may enable the connection to be made to a better 11kV location.

6.8 LOW POWER SUBSTATION

The analysis presented above considers ‘conventional‘ DC traction substations with power ratings ranging from 0.6 MW to several MW, this being the range typically employed in tram/light rail electrification schemes. Those power ratings require a medium/high voltage (11 or 33kV) electrical grid connection.

Low voltage (400V AC) connection is a feasible proposition for loads rated below 0.5 MW which can significantly reduce costs where reduced power substations can be accommodated in the system design.

For example Reference [5] discusses the power supply arrangements for Portland (Oregon) 750V DC Streetcar/tram system where the decision was made to keep substation power ratings below 500 kVA in order to make use of the 480V AC distribution system. All substations utilised on the system have an output power rating of 300 kW, with substation spacing reduced to 0.8 km in order to meet service load requirements.

This configuration allows the use of a single 150 mm^2 trolley wire overhead without requiring parallel feed conductors. The overall power supply arrangement is designed to accommodate the operation of 360 kW rated trams (20m, 29 Tonne vehicle) capable of drawing a maximum acceleration current approaching 1000 A, operating on track grades to 8.5%.

Reference [5] cites a reduction in the price of the primary power equipment by a factor of three since the 480V AC (US 400V AC equivalent standard 3-phase supply voltage) connection allows the use of a standard industrial switchboard for the incoming supply rather than requiring an incoming AC cubicle and 15 kV AC breaker.

Significant construction cost savings are realised by the simpler incoming feed arrangement that enables a reduction in substation building footprint from 60 m^2 (typical for a 1 MW substation) to less than 40 m^2. Furthermore a simplified grounding arrangement is permissible with a low voltage connection. A medium voltage connection requires a buried ground mat (of area 116 m^2 for a 1 MW substation) to comply with step/touch potential limits in the event of a fault on the AC supply, whereas a low voltage connection requires only a perimeter ground.

The perimeter ground for the Portland streetcar substations consists of four 5m long rods electrically tied together, each being driven into the ground at 1 m from the corners of the substation building. The utility supply neutral is tied to the substation structure and to the perimeter ground. Considerable cost saving is thus achieved through the elimination of a full ground mat and corresponding excavation works that would otherwise be required.

The use of a compact design also simplifies substation pre-fabrication (containerisation) for reduced installation and on-site commissioning costs.

Specific costing information is not available, however it should not be unreasonable to assume an installed cost of a ’low power’ substation in the region of a third to half the cost of a ‘standard’ 1.0 MW tram/light rail substation which typically costs up to £1 million per installation.

6.8.1 Application to Branch Line Scenario

For the low-use branch line scenario the power feed system will comprise a small number of widely spaced substations, as discussed in Section 5.6. Because of the separation between substations there will be minimal power sharing where a train is close to any one substation; hence train (peak) power demand cannot exceed individual substation rating.

Low-cost low-power substations are relevant to a branch line electrification scheme where performance requirements are limited, for example where the line speed is particularly low or where smaller and/or lighter light-rail/tram vehicles (350kW power rating or less) can provide the required level of service.

Low-power substations might also be employed in place of ‘standard’ substations where effective energy storage/recovery systems (Section 5.6) are able to provide a significant proportion of the peak power delivery at lower cost than is presently the case.

7 ISSUES REGARDING TRACTION RETURN CURRENT

As with most railways the running rails must be used to carry return current back to the substations. This presents several challenges, the most serious being safety concerns due to the potential difference with respect to ground, and the effect that stray current that leaks from the rails has on railway and third party infrastructures.

7.1 TOUCH AND ACCESSIBLE VOLTAGE

EN50122-1 (Reference [6]) defines Touch Voltage as a condition that exists for a period of time less than 0.6 seconds, whereas Accessible Voltage is a term applied to a condition that may be considered as long-term (up to 5-minutes) or even permanent. Several publications use Touch Voltage as the generic term for both Accessible and Touch Voltage, therefore this term is used herein.

For a most sections of a DC railway the maximum steady-state value for touch voltage is 120V, however for workshop conditions a limit of 60V is applied; that lower limit is also applied to tramways (Reference [7]) due to the assumption that for a high proportion of time passengers will be in contact with both the ground and the traction return network (i.e. as they climb on and off trams). For a railway with less frequent station stops this restriction should not apply, but the legal framework under which any electrified branch line operates must be explored.

For an emergency feeding scenario (i.e. one substation out of service) and given a 750kW tram operating at full power along a section of railway with a return path resistance of 10mΩ/km (i.e. one track, dual rail return), the limit for touch potential would be reached at a distance of some 12km from a substation with an adjacent rail-to-earth fault. In practice rail touch voltages at locations along the line which are located between substations would be limited by the second substation.

Should additional protection be required at stations, rail earthing circuit breakers could be provided which are actuated by voltage sensitive relays. The rails could therefore be earthed when the touch potential exceeded 60V; provision of a train detection device might inhibit operation of the earthing relay when a tram was not in the station platform. Clearly the period that any earthing relay causes the running rails to be earthed causes additional current to flow into the ground, therefore the number of such events should be limited.
It should be noted that high rail-to-earth voltages will encourage the flow of current into the ground, therefore according to ground conditions and the nature of the surrounding third party infrastructure, additional intermediate substations may be required to limit the tendency for galvanic erosion and other return current-induced effects to occur.

7.2 TRAIN DETECTION SYSTEMS

It is probable that lines with low traffic density will not require provision of train detection and signalling systems, except possibly at certain passing loops and junctions. If tramway rules can be adopted line-of-site protection may be used for much of the line. Permission to enter a section of the line may need to be controlled by a token block, ERTMS or another system providing the same degree of protection from conflicting movements. Any such system would not require provision of track circuits, or other train detection systems for the whole length of a section of line. If required an axle counter could be installed at each end of a long block section.

These systems are out of the scope of this report, however it must be appreciated that immunity to the effects of traction current must be a pre-requisite for such systems.

In addition to consideration of train detection systems on the branch line, those systems for any main line railway that may be affected by the operation of electric traction must be considered. It is probable that track circuits on main line railways that are operated exclusively by diesel traction will be DC-types; also each track circuit section may be relatively long outside the confines of the main line/branch line junction and associated station. A case-by-case analysis of stray currents and their effects would be required to determine how many track circuits would need to be converted to traction-immune types. For the purpose of this study it has been assumed that the following costs would be associated with that process:

- Study £250k
- Design £150k
- Physical conversion £300k

7.3 QUALITY OF TRACK AND BALLAST

Assuming the rail, chairs, sleepers and ballast are in good physical condition and track circuits are not required, a diesel railway service can be operated whatever the resistance between the running rails and ground. However, an electrified railway requires there to be relatively little electrical leakage into the ground, otherwise stray current can flow via undesirable routes and therefore potentially through structures and systems that would be damaged by such flows. Also, leakage between the running rail and chair will lead to electrolytic erosion of these components.

While any line is being electrified any remedial works to the running rails etc should be undertaken. If the running rails, sleepers etc are of modern type then this might entail simply replacing life-expired components and upgrading support insulation to an agreed standard. However, it is likely that on some branch lines Bullhead rail with sleepers and chairs exist that are not suitable for basic remedial actions.

Special consideration would be required where sleepers are made of steel because leakage of return current to ground would tend to cause degradation due to electrolytic erosion. This effect would be mitigated by choice of chairs and associated insulation; the maintenance of these components would need to be managed with care however.

Where such a condition occurs the probable solution is to replace the rails, rail supports, sleepers and the top layer of ballast. The cost of such an undertaking is approximately £500k/STK.

7.4 RAIL RETURN PATH

To provide a traction current return circuit with low resistance on any line, there must be a continuous path for current to flow through. Many branch lines are still equipped with fishplated running rails, therefore jumpers would be required to shunt current around each joint. Figure 15 shows a typical fish plate jumper arrangement.

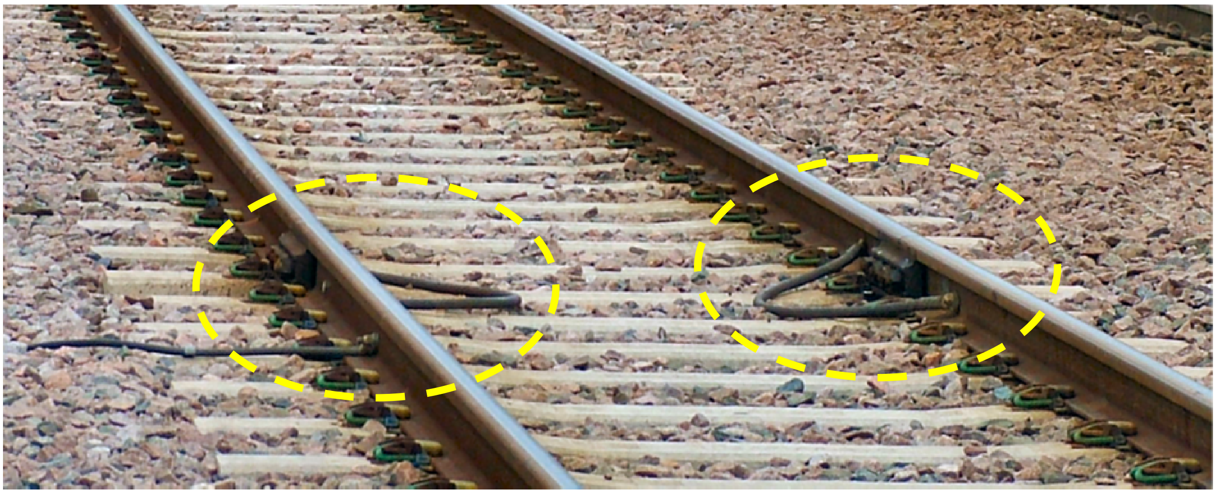

Figure 15 Jumpers Across Fishplated Rail Joints

7.5 ELECTROMAGNETIC COMPATIBILITY

All railways must satisfy requirements set out in the relevant Industry, National and International Standards that refer to Electromagnetic Compatibility (EMC). Part of this requirement involves implementing a railway that does not affect the safe operation of adjacent railways due to the flow of conducted electric current. The flow of such current can disturb the safe operation of vital safety equipment such as track circuits, therefore a study is required to establish the extent of such potential disturbance and mitigation measures must be implemented to reduce the risk to safe operation. This may partly determine the number and location of substations.

In the case of a DC-powered branch line, the extent to which DC track circuits on adjacent railways could be disturbed must be given particular attention. Mitigation measures could include the replacement of DC track circuits with AC and/or 'Traction Immune' types of equipment. It must be noted that track circuits that form part of Absolute Block sections must be considered [7], as well as those which are included in (for example) Track Circuit Block schemes.

8 CONTROL ROOM

Tramways are normally characterised by a high density of passengers in urban and suburban locations, thus costs associated with a dedicated Electrical Control Room cum Operations Control Centre, may be justified by moneys collected via the fare box and subsidies from Local Government. A lightly used tramway also requires an Electrical Control Room (ECR) function which rules mandate must be able to communicate reliably with those undertaking Operations Control duties. The economies of providing a dedicated ECR for any one low-cost electrification scheme are questionable.

A more economical system for providing ECR function would be to extend the scope of an existing ECR, or to group such functions for several branch lines onto a single control centre. This would require suitably reliable communications, but is technically feasible.

9 SCADA

A Supervisory Control and Data Acquisition (SCADA) system is required for system monitoring and substation control functions. Such systems have typically utilised lineside cables rather than relying on RF technologies.

Radio-based SCADA systems are now in widespread use, even for the control of signals and switches (i.e. Automatic Train Control System (ATCS) in the USA). For safe operation the system controllers would need to communicate with substations via a digitally encoded and encrypted data stream. The appropriate Safety Integrity Level (SIL) would need to be chosen for each component; it is possible that substations would need a high degree of autonomy so that, for example, the loss of the radio link to the ECR could be handled intelligently [N.B. it is possible that loss of the data link would trigger a system shut-down].

With the need to run physical 'pilot' wires for the remote detection function of the protection relays provision of a troughing route would be required to carry the cables associated with this function. The cost of such provision has been estimated to be £100k per route km.

10 INSTALLATION

One factor that can influence the cost of upgrading railway infrastructure and installing systems such as electrification is track access. Utilisation of manpower is generally poor when railway projects require work to be completed in a series of individual possessions and other disjointed track access regimes, often due to the need to repeatedly place and lift protection arrangements and the short period (often only 00:01 to 05:00) that is available for physical work to be undertaken.

Better use of manpower and other resources is achieved by closing a line for an agreed period using Blockade arrangements, with passengers being transported using buses and/or taxies. Other advantages to this method of working are that a wider pool of manpower and plant is available, which may reduce costs and make the operations yet more efficient. With certain lines the timetabling of a blockade may need to take into account seasonal factors, for example if a line serves a community dependant upon summer tourists then spring or autumn would be the periods less likely to adversely affect the local economy.

The degree to which preparatory work could be undertaken while maintaining the existing train service is very much dependant upon local conditions. For a route with only light traffic and relatively low speeds, much of the preparation can be undertaken by provision of fenced and separated Green Zones.

Construction and installation of substations and most of the associated equipment should be a task that can be undertaken without the need to disrupt normal rail traffic, unless access to certain sites can only be achieved via the railway.

11 SURVEYS

It is probable that route survey work and design could be undertaken without disrupting operation of a line, best use of resources such as Omnicom surveying should be encouraged rather than manual surveys on foot [11]. Ideally surveys should be a ‘single pass’ operation, but inevitably specialised survey work must also be undertaken.

Important elements of the railway that would need to be known early would be rail condition and ground resistivity. Such parameters are obtained only by carrying out surveys and topographical studies.

12 LEGAL FRAMEWORK

It has been assumed that one or more specific Transport and Works Act would be required prior to electrification of any branch line. Those acts would grant powers for the work, land purchases and other related actions.

The costs associated with preparing and submitting an application to Parliament for such an Act cannot be estimated at this stage because manpower and consequential costs would be driven by the scope of the project and the amount of ground work required to complete the electrification process.

13 LAND FOR SUBSTATIONS

The location and electrical feeding arrangements for substations must be determined by specific local conditions and the availability of suitable power supplies. Although free land may be available adjacent to a station, it is unlikely that a suitable power supply is also available, thus dedicated cables would need to be installed either buried under the public roads or laid in troughing at trackside. The cost of agricultural land is relatively low, £5,000 per acre being quoted on the *Farmers’ Weekly* website (from *Savill’s Farmland Price Model*). Provision of an average of £10,000 per substation may be required to allow for land purchase; this includes some allowance for an access roadway.

While planning the electrification consideration may be given to the need to locate substations immediately adjacent to the railway line. This conventional arrangement may not always be appropriate especially if local aesthetics must be considered.

14 SUMMARY OF COST ESTIMATES

Table 7 Summary of Major Costs Associated With Low Cost Electrification of a Branch or Other Minor Railway Route

Component or Function	Per Route Cost	Per Item Cost	Cost per STK	Comments/Qualifier
Overhead line equipment, supporting structures and basic return path bonding	-	-	£100k	All CuAg catenary type, total 120 + 120 sq mm CSA
Foundations	-	-	£60k	Assumes good subsoil conditions, hence use of conventional foundation techniques
33kV/750V 1MW Substation	-	£1M	£167k	Assumes 6km between substations, connection does not require complex civil engineering and/or buried feeder cables
Electrical Control Room function	-	-	-	Estimated figures based on a 34km branch line
Trackside SCADA and Pilot cables	-	-	£100k	Estimate based on 1metre concrete troughing and single multi-pair cable
Signalling immunisation	£500k	-	£14.7k	Estimated figures based on a single section of main line railway requiring the replacement of existing DC track circuits with a Traction Immune type – 34km branch line
Project office costs	£2.1M	-	£61.7k	Estimated figures based on a 34km branch line, project office is not shared with other branch line electrification schemes
DC Stray Current prevention/protection measures.	-	-	-	Local track conditions may require works to improve rail to ground resistance to limit stray DC traction currents. Buried services may need to be moved or protected from stray currents. An estimate is not given due to the project specific nature of such costs; these may be significant and impact on the viability of a particular scheme.
Survey and subsequent information extraction	-	-	£60k	Estimated figures based on the use of Omnicom single pass survey, with supplemental surveys of specific structures and components
Station Touch Potential protection measures	-	-	£6.25k	Estimate based on one station per 8km, £50k per protection device
Transport & Works Act Fees	?			Unknown

15 CASE STUDIES

Two case studies are discussed for the purpose of establishing base-line costs and issues for electrifying low-use branch lines. The examples assessed (two community rail branch lines in Cornwall) do not constitute any form of recommendation for a viable scheme.

15.1 LOOE VALLEY LINE (LISKEARD TO LOOE)

15.1.1 Route Characteristics

The Looe Valley Line is a 9 mile long single track branch line linking Liskeard (Population 10,000) and Looe (Population 5,000) in Cornwall that carries approximately 80,000 passengers annually. Passenger loading is seasonal with the line being popular with tourists in the summer.

Line speed is limited to 30 miles/hour with an operating a capacity of one passenger train per hour, limited to one train on the line at any time. The steepest line gradient is 1:40 on the section of line between Liskeard and Coombe. A cement freight train operates over this section of the line (Liskeard to Coombe Junction Halt) once per day.

The Spring 2010 timetable shows a daily service of 12 return journeys. The majority of passenger journeys are end-to-end with stops at four intermediate stations available on a request basis. Passenger traffic is seasonal with increased tourist use in the summer months. The service is currently operated by either a two-car Class 150 DMU or single car Class DMU 153 DMU.

The line is supervised from Liskeard signal box, being divided into three sections controlled by tokens/staffs. The line joins the Cornish Main Line at Liskeard station, although the branch line platform is physically separate (at 90 degrees to) the main line.

Although it would be possible to physically separate the branch line from the mainline with the current station arrangement, the connection must be maintained because of freight operations.

15.1.2 Electrification Scenario

15.1.2.1 Rolling Stock

With only one train allowed on the line the service could be operated by a single, dedicated, light rail vehicle.

15.1.2.2 Power Supply

The low speed, low power requirement may enable operation of a 750V DC OLE electrification scheme from two low power (300 - 400 kW) DC substations as discussed in Section 6.8, with one located at each end of the line. A third supply feed located approximately half way along the line (consisting of either an additional low power substation or a stand-alone TESS installation) may however be required to ensure sufficient mid-section power and to limit ground return currents.

15.1.2.3 OLE Equipment

A low cost trolley wire configuration (1 x 150mm^2 copper contact wire) would suffice given the low power requirement. A fixed termination design may give adequate current collection performance to 30 miles/hour although an auto-tensioned design at marginal additional cost would accommodate higher speeds that the track may be capable of supporting for light vehicle operation.

15.1.2.4 Traction Current Return

Track modification would comprise installation of track joint bonds and rail cross bonds. Depending on track condition, rail to track bed electrical isolation may require enhancement to limit DC leakage currents and cathodic protection of local buried services may required.

It is assumed that there would be little need to move buried utilities given the rural situation of the line.

15.1.2.5 Signalling and Electrical Control

No changes to existing signalling arrangements necessary. 'Line of sight' operation could be implemented over much of the line (due to the ability to quickly stop a light rail vehicle) but with a formal method of ensuring safe time/distance separation with freight operations on the Liskeard-Coombe Junction section of the line required. This might be implemented/assisted by a cab radio communication system for driver contact with Liskeard Signal Box.

The Cornish main line at Liskeard is controlled by semaphore signals and it is presumed that there are several DC track circuits in the vicinity of the station that would require conversion to AC (DC traction immune) types.

Monitoring and control of the power systems might be implemented by wireless systems to minimise trackside cabling, with the Electrical Control located remote from the line at any suitable control centre. Likewise a wireless remote substation tripping system might be considered to avoid the need to install trunking to run pilot wires along the length of the track.

15.1.3 Electrification Cost Estimate

For the provision of the basic 750VDC 'light-rail' electrification infrastructure comprising:

- Power supply
- OLE/support masts
- Track works
- Electrical control
- Signalling compatibility

Vehicle capital costs and provision of vehicle servicing facilities are not considered.

Notional Scheme Cost = £4.0 million (excluding contingency), assumptions given below.

15.1.3.1 Power Supply

Two ‘low power’ feed points at £0.5 million each installed cost including grid connections (possibly requiring a third mid-point substation).

Total cost = £1 million to £1.5 million.

15.1.3.2 OLE Masts

45m average mast spacing (trolley wire system) = 22 masts/km

Conventional installation methods comprising metal support poles mounted to a concrete or piled (screw or vibration) base. Assumed to cost £3k per installation (£500 ea mast plus £2500 foundation cost), £66k per track km, £594k route total.

Alternative ‘Buried Pole’ installation comprising of planted composite support poles. Assumed to cost £1.25k per installation (£750 ea mast plus £500 installation cost), £27.5k per track km, £247.5k route total.

15.1.3.3 OLE Support Components and Wiring

Hardware cost (single wire trolley system) estimation £35k per single track km. Installation £10k per single track km.

Cost Installed: £45k per track km, £405k route total.

15.1.3.4 Track Works

Installation of track joint jumpers and rail cross bonding, £5k per single track km, £45k route total.

Significant additional cost may be incurred if improvements to rail/ground electrical isolation were required by, for example, fitting electrically isolating chairs. This need would be determined from an assessment of existing track condition and limits, the proposed power supply arrangement and limits of allowable ground leakage traction current.

15.1.3.5 Signalling and Control

DC track circuits at Liskeard likely to require replacement with DC immune types. Assumed cost £150k.

Provision of SCADA function including provision of secure wireless communications and Control Centre monitoring station - £250k.

15.1.3.6 Project Delivery

Project Office/Main Contractor Fees: £1 million.

15.2 ATLANTIC COAST LINE (PAR TO NEWQUAY)

15.2.1 Route Characteristics

The Atlantic Coast Line is a 20¾ mile length branch line serving 7 stations and comprising of single track with passing loops. Maximum line speed is 50 miles/hour. The steepest track gradient is 1 in 37.

Passenger numbers have increased from around 80,000 in recent years to in excess of 120,000 for 2009.

The Spring 2010 timetable shows seven return services a day, including one through service (HST) to Newquay from London. There is significant china clay freight traffic over the six mile section of line between Par and Goonberrow Junction.

Local passenger services are designated as Community Service although the line itself does not have Community Line status due to the china clay freight train and HST through services to Newquay.

Focal, a local 'friends of the line' group has called for a regular dedicated service between St. Austell and Newquay via Par to provide local rail services more suited to community needs. That proposal would necessitate extending the branch line light-rail electrification system for approximately 5 miles along the main line between St Austell and Par.

For the purpose of this exercise costing of the extended (25 mile length) scheme is considered.

15.2.2 Electrification Scenario

15.2.2.1 Rolling Stock

Current service frequency might be met year round by a single, dedicated, light rail vehicle however two such vehicles would provide for significantly increased service frequency and operational flexibility, with passing loops on the branch line allowing for multiple train operation, assuming this could be successfully integrated with existing freight operations.

The current method of signalling would require the operation of track circuits on parts of the route, for which light rail vehicles must be equipped with TCA (Track Circuit Assistance) equipment. Train protection equipment (e.g. TPWS) may have to be fitted to the vehicles and shared track sections to comply with safety requirements associated with operating a mix of 'light' and 'heavy' rail traffic.

15.2.2.2 Power Supply

A minimum of four 750V DC 'conventional' feeder substations would be required to power a 25 mile length 'low-use' system.

15.2.2.3 OLE Equipment

An auto-tensioned twin trolley wire (2 x 120mm^2 copper contact wire) or fixed termination hybrid OLE system at similar cost would provide sufficient current collection and current carrying performance for 50 miles/hour light-rail operation. The hybrid system would accommodate higher speed operation should the light-rail scenario support increased line speeds.

15.2.2.4 Traction Current Return

Track modification would comprise installation of track joint bonds and rail cross bonds. Rail to track bed electrical isolation may require enhancement to limit DC leakage currents, depending on present track condition and the layout of neighbouring buried services.

15.2.2.5 Signalling and Electrical Control

The Cornish Main Line and at least part of the branch line are controlled by semaphore signals, therefore it must be assumed that there would be a number of DC track circuits requiring conversion to DC traction immune types.

Monitoring and control of the substations might be implemented by wireless systems to minimise trackside cabling requirements, with the Electrical Control located remotely from the line at a suitable control centre.

15.2.3 Electrification Cost Estimate

For the provision of the basic St Austell/Newquay 750VDC 'light-rail' electrification infrastructure comprising:

- Power supply
- OLE/support masts
- Track works
- Electrical control
- Signalling compatibility

Vehicle costs (fleet capital cost and servicing facilities) are not considered.

Notional Scheme Cost = £9.0 million to £9.8 million (excluding contingency), assumptions given below.

15.2.3.1 Power Supply

Power Supply: £4 million
Assumptions: Four feed points at £1 million cost each installed & connected; 'standard' substations.

15.2.3.2 OLE Masts

55m average mast spacing (hybrid OLE) = 18 masts/km.

Standard' installation comprising metal support poles mounted to a concrete or piled (screw or vibration) base is assumed to cost £3k per installation (£500 ea mast plus £2500 foundation cost), £54k per track km, £1350k route total.

'Buried Pole' installation comprising of planted composite support poles. Assumed to cost £1.25k per installation (£750 ea mast plus £500 installation cost), £22.5k per track km, £562.5k route total.

15.2.3.3 OLE Support Components and Wiring

Hardware cost estimate (hybrid OLE) £50k per single track km. Installation labour cost £10k per single track km.

Cost installed: £60k per track km, £1,500k route total.

15.2.3.4 Track Works

Installation of track joint jumpers and rail cross bonding, £5k per single track km, £125k route total.

Significant additional cost may be incurred if improvements to rail/ground electrical isolation were required by, for example, fitting electrically isolating chairs. This need would be determined from an assessment of existing track condition and limits, the proposed power supply arrangement and limits of allowable ground leakage traction current.

15.2.3.5 Signalling and Control

In lieu of more detailed information and in depth study a budget figure of £500k is assumed to undertake any necessary track circuit conversions.

A budget of £350k is assumed for provision of a ‘wireless’ SCADA system/Control Room monitoring station.

15.2.3.6 Project Delivery

Project Office/Main Contractor Fees: £2 million.

16 DISCUSSION/CONCLUSIONS

16.1 OVERVIEW

This study has focused on the technical and financial challenges associated with electrifying a lightly used branch line such that the project budget would not exceed a value which would preclude the project being economically viable. Therefore it has been necessary to explore solutions that would not be acceptable for main line use, but would be acceptable on the grounds of economics, for incorporation into a railway line that had been reassigned to be a tramway, and would have tram-like vehicles running along it.

16.2 SYSTEM VOLTAGE

25kV AC electrification delivers significant advantages over lower voltages due to the efficiency with which power is transmitted along the OLE. However there are significant issues with such a high voltage due to the need to balance electrical load between phases and to make provision for adequate electrical clearances to structures and people; there are also very few tram-like vehicles equipped to operate from such a high voltage.

Adoption of 750V DC significantly reduces the onerous tasks associated with insulation and clearances. It is the standard voltage for tram schemes and in common use for light rail/metro schemes. There is consequently a broad supplier base of 750V DC electrification equipment and this enables the railway operator to choose from rolling stock that is in common use in many countries around the world; the use of refurbished instead of new vehicles also becomes viable.

A disadvantage of employing the lower voltage is the higher current draw required to maintain the power level; voltage drop along the conductors is a significant limiting factor that requires more substations to be installed. Each substation installation represents substantial capital cost, therefore a reduction in overall scheme cost might be achieved by specifying a higher system voltage (1500V DC or 3000V DC). However use of such voltages raises similar issues to the 25kV electrification case in terms of public safety and electrical clearances etc, where the desire is to 'open up' a branch line to tram type operation.

There are many factors to consider in terms of establishing 'the best' system voltage. On balance a 750V DC scheme is considered to be the more viable option for a low cost system.

16.3 POWER SUPPLY

A consequence of installing more substations is the need to make more connections to the Distribution Network Operator transmission lines and in rural sparsely populated locations, such as those often served by branch lines, there may be fewer locations at which suitable connections can be made.

System loading and voltage calculations show that a lightly used branch line can be operated with comparatively few 750VDC substations; for example a lightly used single-track branch line with no more than two trains in operation at a time can be operated from two 750VDC substations for line lengths up to 19km. For a two-track line the two-feeder operating distance may be extended to 38km due to the lower resistivity of parallel OLE and track. A two feeder arrangement is however inoperable with the loss of either feeder, requiring high level of substation equipment reliability and suitable servicing arrangements to achieve acceptable service availability. In-built equipment redundancy (e.g. dual rectifier installation) may provide for sufficient substation reliability/availability to avoid provisioning of ‘back-up’ substations at additional track-side locations.

The use of traction energy storage systems can potentially reduce electrification system costs by reducing peak power demand to enable fewer or lower power, substations to be installed. Most benefit is obtained where regenerative braking is employed to enable energy re-use; even in the absence of regenerative braking capability benefit is obtained through power demand smoothing and line voltage support.

Significant advances have been achieved in supercapacitor and high-speed flywheel energy storage systems over the past 10 years, with commercially available systems resulting from traction-specific trials with both technologies. The capital cost of such systems is typically justified by anticipated energy savings over the life of the equipment, which may be considerable on a high use system. The benefit in terms of reduced infrastructure cost for a low-use scheme is less clear and will depend on the specific circumstances.

A consequence of using direct traction current is that attention must be paid to the possibility that the flow of return current will cause electrolytic erosion of metallic components on and adjacent to the railway. This is a complex subject for which significant information is required with regard to the condition of the civil engineering assets before any judgement can be made as to whether significant expenditure will be required to mitigate against any detrimental effects. For DC electrified railways, the ideal is for the running rails to be well insulated from the sleepers and for ballast and ground resistance to be relatively high. One mitigation measure is to make provision for an increased number of substations, thus minimising rail potential and the distance over which return current must flow.

16.4 OVERHEAD SYSTEM STRUCTURES

OLE supporting structures are traditionally constructed from steel with foundations being concrete or steel piles. Provision of foundations by these traditional methods is the most costly aspect of installing OLE masts since foundation costs exceed the cost of masts by a factor of four or more. Other foundation technologies such as screw piles and grip piles offer the more cost-effective solution in difficult ground conditions, awkward to access sites and in noise sensitive areas with restrictions on the use of vibration piling and heavy plant operation. Screw-piles are attractive for other reasons that include minimal ground disturbance and re-use (removable), but are otherwise not significantly cheaper than traditional piling methods.

Lowest installation cost is achieved simply by burying support structures directly into the ground, as practiced by utility companies to install wooden poles as support structures for 11kV/33kV electricity distribution cables for example. This is a well proven technique that can provide for reliable, all weather support structures at low cost. Treated timber poles are cheaper than the steel or concrete alternative and are available in a variety of standard sizes including those of suitable size and strength to support OLE equipment.

Preservative treated poles have service lives of 30-40 years and require appropriate inspection and treatment regimes, however polymer surface coatings have recently been developed that provide for 60 year service life and reduced maintenance requirement. More costly Composite Fibre Reinforced Plastic (FRP) utilities poles are available as an alternative to timber poles. These provide a long life (60+ years), are maintenance free and are compatible with timber pole low-cost installation methods. The use of composite poles may be an attractive proposition for a branch line electrification scheme due to low installed cost and maintenance free properties.

16.5 OVERHEAD CONDUCTORS

A tram type auto-tensioned trolley wire system will provide adequate current collection performance for a branch line electrification scheme operating to 80 km/h. A 750VDC system will typically require twin contact wires to provide sufficient conductivity to limit the number of substations required, a configuration that would enable a twin track ‘tramway parallel feed’ system to operate off two 750V DC substations is discussed above. A single-track line may require a supplementary ‘live’ conductor for sufficient OLE conductivity in order to optimise substation arrangements for minimised capital cost.

An alternative conductor configuration is the hybrid (contenary) arrangement which provides for a compact arrangement with similar support arrangements to the trolley wire configuration. In this case one contact wire is above the other, rather than side-by-side. The pseudo-catenary arrangement provides for superior current collection performance that may negate the need for auto-tensioned equipment.

Both the above configurations are cheaper than a conventional catenary arrangement by virtue of a simplified, compact support arrangement that is easier to install and with fewer components required.

16.6 TRACTION ENERGY STORAGE

Regenerative braking systems, operated in conjunction with on-board or trackside energy storage systems can significantly reduce system loading demand, the benefit of this being fewer or lower power substations being required for reduced substation/connection capital cost. On-train energy storage enables trains to operate through ‘wire free’ areas, which may provide a cost-effective solution to the problem of electrifying tight clearance infrastructure.

Supercapacitor and high-speed flywheel energy storage systems are becoming well established technologies in the field of traction energy storage applications. Although the high capital cost of these systems limit their general application and use in a low cost electrification system, operational flexibility combined with savings in operating (energy) costs may favour the adoption of this technology for schemes where this could be incorporated at a moderate overall increase of capital cost.

16.7 SYSTEM MONITORING AND CONTROL

There are a number of options for operating a Supervisory Control and Data Acquisition (SCADA) system over private or public communications networks. Wireless SCADA, for example, has been in use in the oil and gas industry for many years to operate remote sites. Monitoring and control of a ‘remote’ branch line electrification system can therefore be effected from any suitable location such as a centralised signalling and electrical control room.

Existing communications infrastructure can be utilised to provide the link between the control room and the system under supervision; SCADA communication may be achieved over cellular systems (e.g. GSMR), private licensed and unlicensed radio networks, and by means of satellite. Local maintenance staff may similarly be alerted by cell phone SMS messages or email.

Internet or Web Based SCADA enables integration of SCADA function with existing Information Technology systems. Effective protection measures must be implemented to ensure security of a Web based SCADA system against 'hacking' and communication intercepts. Those measures would include the use of a Virtual Private Network (VPN) and encryption of transmitted data.

16.8 COST ESTIMATES

The case studies considered in Section 15 yielded the following results:

- Case 1 – a nine mile long single-track Community Line operating an hourly (approximately) service at low speed (30 miles/hour). Estimated cost for provision of low-cost electrification infrastructure £4.0 million (excluding vehicle costs including servicing facilities)

- Case 2 – a twenty five length route operating a Community Service over a twenty mile mixed-traffic branch line, and an additional five mile section of main line. Estimated cost for provision of low-cost electrification infrastructure £9.8 million (excluding vehicle costs including servicing facilities)

These estimates indicate a notional costing of £400k - £450k per route (single track) km for a low-cost branch line scheme compared to approximately £1 million per route km for a typical tram/light rail scheme (Section 3.2.1) and £1 million per track km for main line railway electrification (Section 3.1.1).

Industry sources have been consulted where possible to derive indicative equipment costings although estimation of project delivery costs is hampered by the lack of available information regarding the cost breakdown of relevant schemes. Actual cost will be also be dependent on route specific conditions and circumstances that require more in-depth analyses to fully quantify.

17 RECOMMENDATIONS

The scope of this study is limited to the consideration of costs pertaining to the provision of ‘low-cost’ electrification infrastructure only. A separate study is required to the establish the economic validity of branch line electrification in terms of whole life operating costs and the socio-economic/environmental benefits to local communities, compared to other solutions.

To proceed with the concept of branch line electrification and to produce a set of line-specific and in-depth costings, a focussed pilot study is required. It is appreciated however that such studies may not be cost-effective if not based on a practical application, therefore the study should be undertaken on the assumption that it will lead to the electrification of a specific branch line, or set of branch lines.

That work must begin by carrying out the survey of one or more branch lines, thus obtaining correct data with regard to rails, resistivity and electrical clearances; the location and capacity of DNO supply points should also be obtained.

One possible obstacle to DC electrification is the presence of buried structures such as pipelines that are susceptible to galvanic corrosion. In specific locations certain civil structures may also need to be protected, these include for example suspension bridges and structures that include large amounts of rebar such as viaducts. These need to be identified and risk-assessed.

With regard to rolling stock information is required regarding the whole-life cost of both new and cascaded trains. It was noted that older technologies may not support operation for a sufficiently wide range of supply voltages that would be present on a line that has been electrified within the principles of a low cost scheme; therefore the cost-effectiveness of adaptation should be addressed.

A major cost associated with electrification is the erection of the masts required to support the overhead line conductors. Several novel technologies exist which could be adopted to reduce these costs, however their relative practicability needs to be assessed; this could be achieved by inviting manufacturers and their partners to carry out trial installations.

Another major cost element is the price of substation equipment. The adoption of a standard containerised form-factor for all such equipment should be explored, as should the feasibility of obtaining such equipment from a diverse set of suppliers.

Project management and design office costs are major cost elements that might be optimised by adopting a rolling programme of branch line electrification projects. This aspect must be explored, especially in the context of adopting a hypothetical ‘central office’ that would be able to manage the electrification of lines throughout the UK, while not incurring excessive travel expenses.

With regard to the interface with main line railways the plans of Network Rail to re-equip existing lines should be considered. For example, if a programme of track circuit equipment overhaul and replacement is being planned, the merits of upgrade to traction immune equipment rather than like-for-like replacement should be discussed.

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APPENDIX A MAINLINE ELECTRIFICATION COST BREAKDOWN

Equipment/Installation Costs for Mainline Electrification (Classic 25kV AC Booster Transformer/Return Conductor arrangement)

This information has been derived from RSSB Project T633 Final Report: ‘Study on further electrification of Britain’s railway network’, the costs having been determined by W S Atkins from an analysis of a number of electrification schemes.

TABLE A1 Typical Overhead Line Equipment Costs for Main Line 25kV Electrification

Item	Typical cost per Item £	Equivalent Cost per STK £	Comment/Assumptions Made
Foundation for single track cantilever mast	5,000	85,000	60m average mast spacing
Foundation for twin cantilevers (added cost in place of single cantilever mast at overlap)	4,000	6,700	Two per 1200m tension length
Foundations twin anchor mast	9,000	15,000	Two pairs per 1200m tension length
Cantilever + insulators	1,000	17,000	60m average mast spacing
Supply and installation of catenary, contact, droppers, return conductor	60 (per metre)	60,000	-
Tensioning Equipment	1,200	1,000	1200 m tension length
Mid Point anchor	5,000	4,170	1200 m tension length
Neutral Section	8,000	320	25 km spacing
Switching Equipment (Isolator)	5,000	1,000	5 km spacing (excluding substations)
Booster Transformer	25,000	8,300	3 km spacing
Track Bonds	250	1,000	250m spacing
Structure Bonds	250	5,000	20 per km inc masts
Signal Sighting alterations	4,000 per STK	4,000	-
Miscellaneous (clearance etc)	5,000 per route km	5,000 (2,500)	Single track (Double Track)
	SUB TOTAL	**213,490**	

TABLE A2 Typical Distribution Equipment Costs for Main Line 25kV Electrification			
Item	**Typical cost per Item £**	**Equivalent Cost per STK £**	**Comment/Assumptions Made**
Feeder Station, single or two track (inc isolators and feeder cables)	1,100,000	22,000 (11,000)	50 km spacing, single track (Double track)
ESI Grid Connection	2,000,000	40,000 (20,000)	50 km spacing, single track (Double track)
Mid Point TSC, single or double track (inc isolators and feeder cables)	900,000	18,000 (9,000)	50 km spacing, single track (Double track)
Substation building/compound construction works	30,000	1,200 (600)	25 km spacing, single track (Double track)
SCADA system	4,500 per route km	4,500 (2,250	single track (Double track)
	SUB TOTAL	**85,700**	

TABLE A3 Other Significant Costs for Main Line 25kV Electrification			
Item	**Typical cost per Item £**	**Equivalent Cost per STK £**	**Comment/Assumptions Made**
Signalling equipment Immunisation	5,000 per STK	6,000	-
Telecoms Equipment Immunisation	1,000 per route km	1,200 (600)	single track (Double track)
Civil Works - Over bridges	30,000 per bridge	Variable	-
New Electrification Depot	20,000,000	Variable	As required to service a main-line fleet. For information only (not applicable to branch line scenario)
Existing depot conversion	5,000,000	Variable	

APPENDIX B LOW USE ELECTRIFICATION CALCULATIONS

Effect of OLE Conductor Size on Substation Spacing – 750VDC System

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B1 Introduction

This report details the results from calculations of maximum distance between substations, and from substation to train, for a given configuration of overhead powerline cross section, track impedance, and substation capacity. The scope for the calculations are described in the DeltaRail document "Exercise to Establish Optimal Conductor Size/Substation Spacing for a 750VDC OLE 'Low Use' System".

B2 Model Parameters

Substations

The substations are modelled as a constant voltage source in series with an effective resistance. When the substation is loaded, there is a voltage drop at the busbar which is accounted for by the voltage that is dropped across the series resistance. It should be noted that the substation transformer provides a degree of load regulation, and therefore the resistance should not be used in loss calculations without taking into account the change in power factor of the AC supply. Table 1 shows the values used. The substations are each assumed to have a nominal power output of approximately 1 MW. The load regulation for this type of substation is typical with the assumed values shown in table B1.

Description	Symbol	Value
Substation open circuit voltage	V_s	850 V
Substation effective resistance	R_s	50 mΩ

Table B1: Substation parameters

Powerline

The resistances per unit length for the four power line configurations are shown in Table B2. Brief details of the calculation of these values are in Note 1.

Power line	Cross section [mm^2]	Resistance per unit length [$\mu\Omega m^{-1}$]
Single trolley wire	120	150
Single trolley wire (2)	150	120
Double trolley wire or catenary	240	75
Catenary wire with double contact wire	360	50

Table B2: Power line resistances

Track

The parameters of the track are the most difficult to determine accurately. The rail is 49 kg m^{-1}. The values used in these calculations represent typical working ranges of DC track resistances. Note 2 details the origin of the two values shown in Table B3.

Description	Symbol	Value
Track resistance (1)	R_{track}	15 $\mu\Omega\ m^{-1}$
Track resistance (2)	R_{track}	50 $\mu\Omega\ m^{-1}$
Track resistance to ground	R_g	10 kΩm
Maximum touch potential	$V_{tp,max}$	120 V

Table B3: Track parameters

Train

The train has a current draw of 1000 A at a minimum terminal voltage of 500 V as shown in Table B4. These values were used in the calculation of substation-train distance.

Description	Symbol	Value
Current	I_{train}	1000 A
Minimum terminal voltage	V_{min}	500 V

Table B4: Train parameters

Other assumptions

The substation to the powerline and the track return feeder cables have zero resistance. These are not significant compared to the substation effective resistance, representing only a few metres of track.

B3 Calculations

Case 1: Train fed by a single substation – single-end fed
It is assumed that no current flows outside of the loop path consisting of a substation, powerline, train and return track. The impedance to ground is high enough that the ground current can be ignored. The distance between train and substation has been calculated based on the requirement that the train terminal voltage does not fall below 500 V. The touch potentials have been computed assuming a nominal track-to-ground impedance, but this value is so high as to be essentially the same result as assuming an infinite resistance between track and ground (which gives the highest touch potential possible). Table B5 show the results for different powerline conductor arrangements for the high value of track return resistance. Table B6 shows the results for the low value of track return resistance.

Powerline conductor equivalent cross section	Powerline conductor impedance [μΩ/m]	Distance from substation to train [m]	Touch potential [V]
120	150	1715	42.8
150	120	2070	51.6
240	75	3003	74.8
360	50	4009	99.6

Table B5: Distance from substation to train, single track (50 μΩ m^{-1})

Powerline conductor equivalent cross section	Powerline conductor impedance [μΩ/m]	Distance from substation to train [m]	Touch potential [V]
120	150	1904	14.3
150	120	2353	17.6
240	75	3637	27.2
360	50	5220	39.0

Table B6: Distance from substation to train, single track (15 μΩ m^{-1})

The effect of reducing the track return resistance is most significant when the powerline resistance is less dominant. It is not very significant except in the case of minimum powerline resistance. The danger of assuming the lower track resistance is that during the lifetime of the track the resistance may rise as the connection resistances increase and the rail wears, resulting in reduced capacity for powering the trains.

Case 2: Train between two substations – double-end fed

The total train current is 1000 A, but the worst case train voltage and touch potentials arise when the train is located exactly midway between two identical substations. By symmetry the train takes 500 A from each substation. Current from additional substations further away is ignored. Tables B7 and B8 shows the results for the high and low track resistance cases respectively.

Powerline conductor equivalent cross section	Powerline conductor impedance [μΩ/m]	Distance between substations [m]	Touch potential [V]
120	150	7435	46.2
150	120	8978	55.6
240	75	13057	80.2
360	50	17513	106.1

Table B7: Distance between substations, single track (50 μΩ m^{-1})

Powerline conductor equivalent cross section	Powerline conductor impedance [μΩ/m]	Distance between substations [m]	Touch potential [V]
120	150	8255	15.4
150	120	10198	19.1
240	75	15769	29.3
360	50	22655	41.8

Table B8: Distance between substations, single track (15 μΩ m^{-1})

The touch potentials are higher than in the single substation. This is because the lengths are approximately four times greater than the single substation and train separation. The lower current in each substation's equivalent series resistance results in a higher busbar voltage at the substations, allowing more track and powerline length.

Note that the touch potentials are the absolute potential of the track under the train relative to earth. In the calculations, the substations are floating, and therefore the substation negative busbar will be equal to the touch potential – but will be negative.

Case 3: Double track and full cross-bonding
The tracks are doubled up and the powerlines are doubled up. This essentially halves the powerline impedance and the return impedance while leaving the substation impedance constant. Hence the results are similar if two trains are powered in this configuration. If one train is used, the distances are increased as the out and return impedance are decreased. However, it would be impossible to supply current to two trains in the same section (or even close together). The results are given in the tables B9 and B10.

Distance between one substation and one train

Powerline conductor equivalent cross section	Powerline conductor impedance [μΩ/m]	Distance from substation to train [m]	Touch potential [V]
120 x 2	150/2	3430	42.8
150 x 2	120/2	4140	51.6
240 x 2	75/2	6011	74.6
360 x 2	50/2	8035	99.1

Table B9: Distance from substation to train, twin track (50 μΩ m^{-1} per track)

Distance between two substations

Powerline conductor equivalent cross section	Powerline conductor impedance [μΩ/m]	Distance between substations [m]	Touch potential [V]
120 x 2	150/2	14881	46.0
150 x 2	120/2	17982	55.3
240 x 2	75/2	26225	79.1
360 x 2	50/2	35380	103.9

Table B10: Distance between substations, twin track (50 μΩ m^{-1} per track)

The crossbonding of the tracks and of the powerlines makes them effectively in parallel. The non-paralleled parts are of limited length and the small increase in impedance that this creates has not been accounted for. However, it is assumed to be negligible.

Commentary

The calculations described in this report assume powering a single train at a determined distance from a substation. If a substation were removed from service, then the network would not be able to supply the correct voltage to the train. In between two substations, the effect of removing one substation is to double the distances. This approximately doubles the loop impedance (the substation impedance is a significant contribution, but not overly so). For the loop current of 1000 A the voltage drop of 350 Volts approximately becomes 700 Volts, so the voltage remaining at the train is only 150 Volts.

At the end of the line, if the final substation feeds a stub of track of maximum extent, a failure in this substation results in the stub length effectively becoming approximately five times longer. This results in the loop impedance increasing by a factor of 5, resulting in almost no possibility of delivering suitable power to the trains.

To summarise, the distances calculated are maximum possible distances, with no allowance for substation outage. In order to maintain some level of redundancy the distance must be considerably reduced with special attention paid to the ends of the networks.

Note 1: Power line resistance

The power line conductor resistance is based on the given equivalent copper conductor cross section. The resistivity of copper is approximately 17.2×10^{-9} Ωm at 20°C, with a positive temperature coefficient of 0.0039, so

$$R = 17.2 \times 10^{-9} \times (1 + 0.0039 \times (T - 20)) \quad [\Omega m]$$

Hence, the resistivity of copper at 32°C is about 18 nΩm. This value has been used to create Table 2.

Note 2: Track resistance

The resistance of track is a difficult to determine. Computing the resistance from first principles results in small values that are probably too low given the connection resistances at possible rail joints, expansion joints, switches and crossings, etc. From literature, other values can be obtained.

However, using steel the resistance is 31.27 $\mu\Omega\ m^{-1}$ per rail, giving a parallel resistance of approximately 15.5 $\mu\Omega\ m^{-1}$. This is a typical value used for ideal track.
Using loop resistance measurements taken in the field, a more typical value for track DC resistance is closer to 50 $\mu\Omega\ m^{-1}$. This value has been used in the calculations with additional results for cases 1 and 2 using 15 $\mu\Omega\ m^{-1}$.

Note 3: Touch potentials

With a powerline resistance of 50 $\mu\Omega\ m^{-1}$, a voltage drop of 350 Volts around a loop results in a touch potentials of half of 175 Volts, or roughly 87.5 V. This relies on having floating substations. Note that two trains on opposite sides of a substation will result in increased (negative) touch potential at the substation and may be important, although the current will be split between substations resulting in a reduced touch potential. However, in order to service the current requirements of both trains, the substations will need to be closer together. The fact that the running rail is relatively large gauge but the current demand is modest, the touch potentials are unlikely to be a problem in comparison to the low voltage at the train terminals.