WPD INNOVATION
Transforming the electricity network

DC Share Closedown Report

Closedown Report

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1. Executive Summary

The DC Share project was a 2019 Network Innovation Competition (NIC) winning project. This project sought to trial a novel network topology that would offer capacity for Electric Vehicle Rapid Charging Clusters. To enable this project to progress, the NIC made a funding award of £4.7M towards the total project cost of £5.28M. The DC Share project was to be hosted by Western Power Distribution (WPD), in conjunction with a Consortium comprising of Ricardo Energy and Environmental, Electricity North West (ENW), Turbo Power Systems, and Vectos.

The novel topology to be trialled was a solidly interconnected Low Voltage Direct Current (LVDC) equalisation network. The LVDC equalisation network would be implemented by installation of devices known as Grid Tied Inverters (GTIs) into existing HV/LV substations. These GTIs would convert Low Voltage Alternating Current (LVAC) to LVDC and control the power flows around the LVDC network, with the goal of ensuring no substations were overloaded. To enable power to be shared between the substations and to connect the Electric Vehicle Charge Points (EVCPs), a continuous ring of DC cables would connect each GTI to form a mesh. In the event that the EVCP demand could not be fed without overloading the existing substations, the EVCP demand would be curtailed.

One of the key features of this trial was to investigate whether an LVDC equalisation network could economically release any spare capacity that was held on existing HV/LV transformers. The motivation for this was to investigate whether this capacity could be used to help the connection of rapid chargers for Electric Vehicles (EVs).

In accordance with WPD governance, we review the anticipated project benefits, based on ongoing or incoming project learning throughout the project and consider the implications for roll out at the end of the project. Towards the end of the DC Share design phase, we reviewed what we had learnt regarding the application of LVDC equalisation networks, including:

- Updates on the cost base that should be expected when constructing the LVDC equalisation network
- Insight into the "firmness" of the capacity that would be offered from LVDC equalisation networks to EVCP customers
- Understanding gained through the detailed design of the proposed trial installation
- Protection system limitations
- Whether there were any specific operational benefits to EVCP customers from adopting a DC point of connection.

In addition to reviewing learning from within the project, we have also reviewed learning with regard to how routes to connection for EVCP have evolved in parallel since the start of this project.

We incorporated this learning into an updated cost benefit analysis, and review of whether LVDC meshed networks were likely to deliver what customers wanted from a connection to a rapid EVCP cluster. This process indicated that the cost benefit balance of LVDC equalisation networks had fallen behind alternative methods. Learning from the DC Share project has also indicated that the physical delivery for this type of network topology was unlikely to deliver on customer expectations for rapid connection delivery.

We explained our learning about LVDC equalisation networks with Ofgem and requested that the DC Share project be terminated. As a result of this early termination, £2.4M of unspent NIC funding is to be returned to customers.

2. Project Background

The DC Share project was a winning project in the 2019 Networks Innovation Competition (NIC). The following sections explain the ideas behind the DC Share project.

2.1. What was the problem DC Share sought to respond to?

At the time of writing the Full Submission Pro-forma (FSP), it was recognised that the prevalence of rapid EV chargers is a key enabler in the decarbonisation of transport. This is because they enable destination charging and the needs of high utilisation commercial vehicles to be met.

It was also recognised that the connection costs for rapid Electric Vehicle (EV) charging facilities are a critical consideration for developers of Rapid EV Charge Points (EVCP). It was considered that if the cost of connecting rapid EV Chargers fell, then the penetration of rapid EVCP across society would increase.

The DC Share project sought to develop a response to the need to deliver capacity in urban centres where there are already existing substations in close proximity.

At the time of writing the FSP, the connections access regime was that developers would have to pay for the cost of the network extension assets, as well as any reinforcement costs at the connection voltage, and a proportion of those at one voltage level above. Since the FSP, the network access arrangements have been altered such that for demand connections, any reinforcement costs are socialised.

2.2. What was the method case?

The DC Share Method will use an LVDC equalisation network to provide an alternative solution for rapid EV charging demands. The purpose of an LVDC equalisation network is to access the unused capacity across neighbouring substations instead of making a larger reinforcement at one location. The equalisation network does this by joining together adjacent substations to take advantage of any unused capacity or differences in daily load cycles.

This cannot be achieved in traditional networks as coupling substations in this manner tends to overload cables and transformers due to unequal load sharing. LVDC equalisation networks overcome this because they are able to control the power flow along transformers and cables. This does mean that the cables which tie the neighbouring substations together need to carry Direct Current (DC) as opposed to Alternating Current (AC). By locating the EVCP on the DC side of the substations, these large point loads could also participate in demand side response to ensure that both the AC and DC assets remain within capacity.

2.2.1. Capacity creation mechanism.

The principle behind LVDC equalisation networks was to join together existing substations which have dissimilar load profiles and to increase loading on the underutilised substations and decrease loading on the highly loaded substations, as shown in Figure 1 and Figure 2.

To be able to apply the capacity creation mechanism, it is axiomatic that the methodology favours existing networks with existing customers, and that the infrastructure can be retrofitted into existing substations. At the FSP stage, it was recognised that the methodology would be unlikely to suit application in green-field developments, as these connection projects have the opportunity to install assets with suitable headroom.

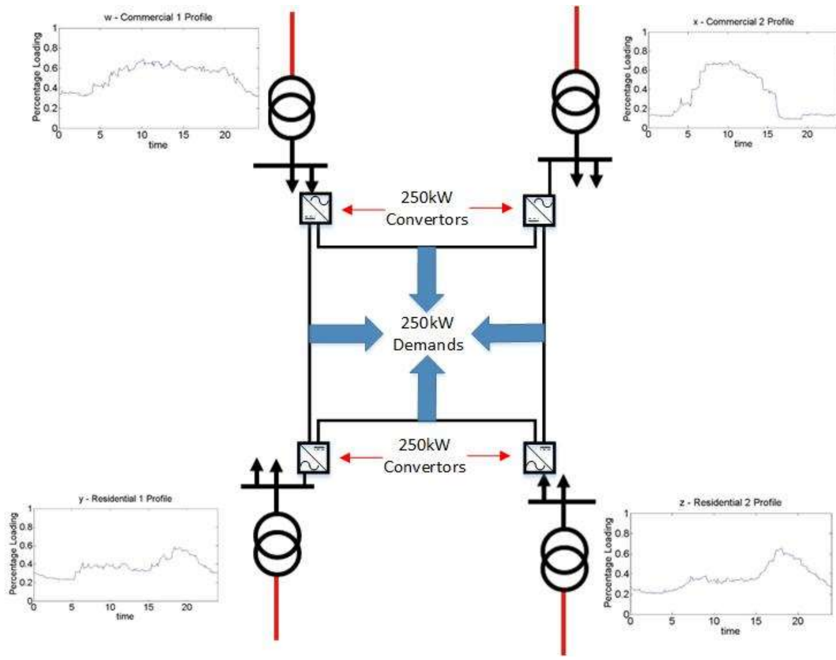
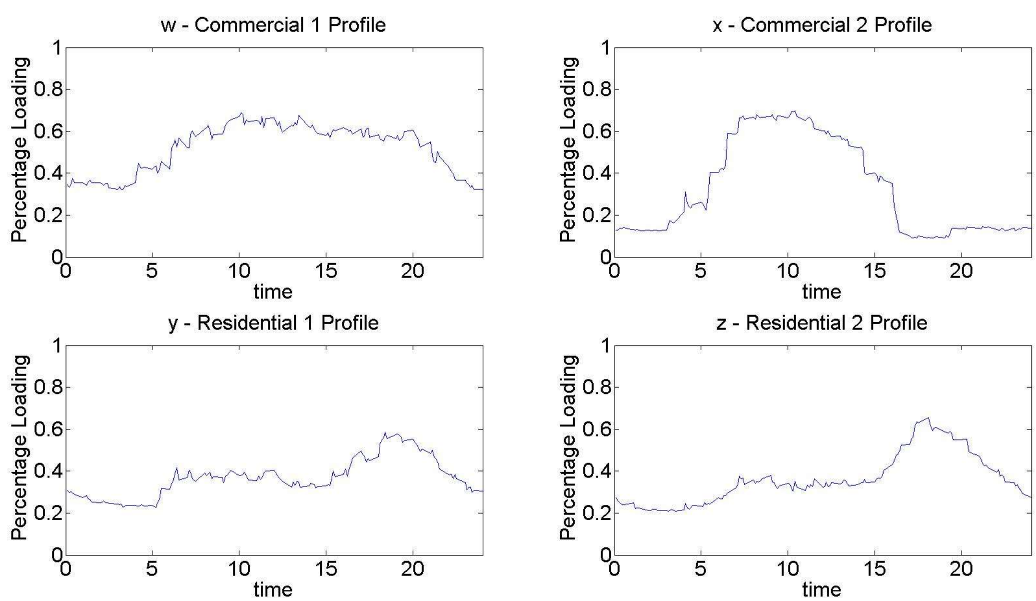


Figure 1: Example of capacity creation through dissimilar load profiles (before equalisation)



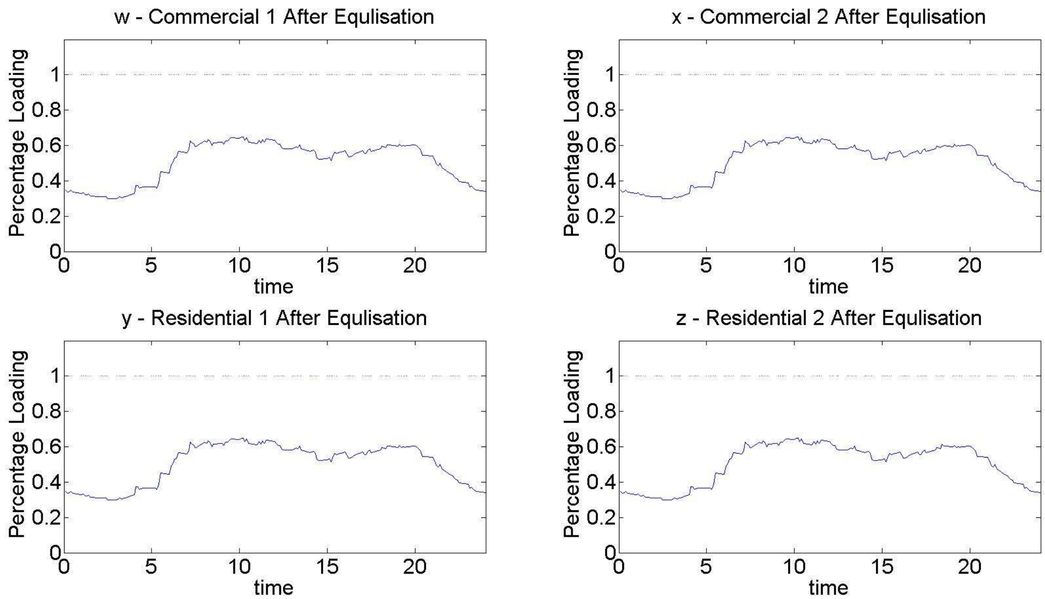


Figure 2: Example of capacity creation through dissimilar load profiles (Pre and post equalisation)

2.3. Components of the LVDC equalisation network

This section provides an overview of the key components that make up the LVDC equalisation network. An annotated visual summary is provided in Figure 3 and an introduction to each of the systems is provided beneath.

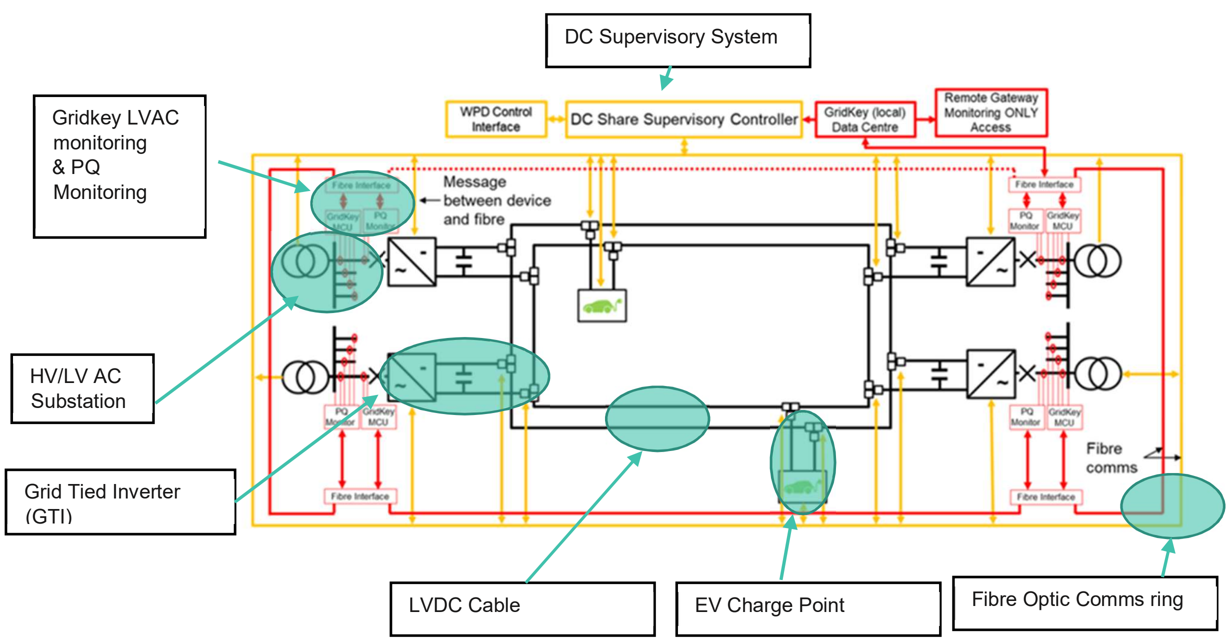


Figure 3: Overview of an LVDC equalisation network

Grid Tied Inverter (GTI)
The GTI converts 415V three phase alternating electricity supply into a ±400V DC system (i.e. the pole to pole voltage is 800V but the potential relative to earth is ±400V DC). The GTI has different control modes: Constant power or a droop control where the power set point is determined by the DC voltage and a pre-set volt-power droop arrangement. On the AC connections of the GTI was an AC circuit breaker and non-load break isolators were located on the outgoing ways of the DC side. The GTI can connect two DC circuits to its terminals via these isolators. The GTI has basic protection functions on its AC side circuit breaker.

In the DC Share project, the set points and control modes of each GTI were to be co-ordinated by the DC Share supervisory system. These messages were to be relayed to each GTI via a fibre optic ring.

There were a total of four GTIs feeding the proposed equalisation network.

DC Share Supervisory System
The role of the DC Share supervisory system was to oversee operation of the LVDC equalisation network. The DC Share Supervisory controller was able to determine how to share the EVCP load across the GTIs and also how to support the load of the existing AC HV/LV substations. These decisions would then be enacted by sending instructions to each of the GTIs and EVCP to operate in different control modes and set points. The DC Share supervisory system could also instruct EVCPs to curtail demand. This system would also oversee energisation or de-energisation of the DC assets.

To resolve loading issues, the DC Share Supervisory System would receive data from each of the Gridkey LVAC monitors, GTIs, and EVCPs via the fibre optic communications ring.

EV Charge Points
Each EV Charging point cluster would have a number of EV charging points. These charging points would accept an incoming supply at ±400V DC and provide an outgoing charging supply direct into the EV. Each EVCP would also have a separately metered auxiliary 230V AC supply for cooling fans etc.

When capacity had ran out on the LVDC equalisation network, the DC Supervisory controller would instruct curtailment of the EVCP's to resolve the capacity issue.

Existing AC Substations
Each GTI would be located within an existing HV to LV substation. At the FSP stage, it was assumed that the GTI would need to be connected from the existing LVAC fuse pillar via a dedicated fuseway and a dedicated cable. The GTI would need to fit within the existing footprint and fabric of the existing substation.

2.4. Project Partners.

The project was comprised of the following partners:

2.4.1. Ricardo

Ricardo is a global strategic, technical and environmental consultancy, and a specialist niche manufacturer of high-performance products. The company employs over 2,000 professional engineers, consultants and scientist who are committed to delivering outstanding projects focused on class-leading innovation.

Ricardo has significant experience of working on NIC projects, including leading workstreams, and it has relevant skills in each of the key project roles. Ricardo has been an active project partner and taken lead roles in the development and implementation of a number of Low Carbon Network Fund and NIC projects. Ricardo was the lead partner responsible for the delivery of the DC Share project.

2.4.2. Western Power Distribution

Western Power Distribution is the DNO responsible for electricity distribution in the Midlands, South West and Wales. Western Power Distribution was to be project sponsors for DC Share and will be responsible for delivering the full benefits to their customers and to Ofgem.

2.4.3. Electricity North West

Electricity North West is the DNO responsible for electricity distribution in the North West England. Electricity North West complementing the knowledge brought by Western Power Distribution to ensure the DC Share solution is applicable across GB.

2.4.4. Turbo Power Systems

Turbo Power Systems (TPS) design and manufacture world class power conversion systems using cutting edge technology. They have had relevant experience in the delivery of power converters for use on public LV distribution networks through their role on the UKPN's FUN-LV and Active Response projects.TPS via Ricardo were responsible for provision of the power converters and charge points for the DC Share trial

2.4.5. Vectos

Vectos is a transport planning, infrastructure design & flood risk, and hydrogeology & sustainable drainage consultancy specialising in assisting the property development industry to maximise the commercial value of land/assets through the planning process. Vectos have gained an enviable reputation for master planning, securing planning contents, and development consent orders for complex and challenging schemes. Vectos were engaged to assist with the practical aspects of the project in respect of locating the charge points

3. Details of the Work Carried Out

3.1. Location and Site Selection

At the time of the FSP, a host town for the DC Share project had not been selected. Therefore, one of the first tasks was to select a town where the trial was likely to be successful. As a result of a selection process, Somerset West and Taunton were identified as being a good partner for the DC Share project, and the DC share project team selected Taunton town centre as a host for the project. In conjunction with Somerset west and Taunton Council, the DC share team sought to select car parks that would host the new DC charging clusters.

A list of options for suitable sites were developed in early 2020.These options were:

- Option 1: Firepool (North of river) and Coal Orchard car parks
- Option 2: Coal Orchard and Canon Street car parks

In May 2020, option 1 was initially selected as the preference for the following reasons:

- The Firepool north development was part of a brownfield development.
- Strong commitment from the local authority to make space available for the EVCP
- There were no EVCPs in the immediate location

Figure 4: DC Share car park locations

The initial design was to place 15 EVCPs across each of the two clusters.

During June 2020 the DC Share project team was made aware that the Firepool North car park was no longer available and that the Coal orchard car park would only be able to accept three EVCP rather than the initial seven chargers that were assumed. Somerset West and Taunton were able to offer use of the Firepool South car park as an alternative to the Firepool North car park. To maintain locations for 15 EVCPs, Somerset West and Taunton offered the project use of the Canon Street car park.

The eventual design intent was to construct three DC charging clusters, namely:

- Coal Orchard, to use 1 x 100kW EVCP and 2 x 50 kW EVCP

- Cannon Street (2 x 100kW and 4 x 50kW)
- Firepool South (2 x 100kW and 4 x 50kW)

3.2. Substation selection

The original intent of DC Share project was that Grid Tied Inverters (GTIs) should be placed into existing HV/LV substations and that this could be done without additional substation remodelling.

To identify the substations that could be used, we applied a process that initially shortlisted substations on the grounds of a desktop selection criteria, which assessed likely viability of installation. This process considered:

- Estimated remaining headroom, based on either Maximum Demand Indications (MDI) or estimates from design tools
- The availability of spare ways in the LV fuse pillar (To accept a GTI connection)
- Likelihood of sufficient existing space to fit the GTI that had been designed for the DC Share project.
- Legal permissions to enable new cable entry into the substation.

We applied this process to 73 HV/LV substations surrounding the selected car parks. The following observations were made across the population of reviewed sites:

- 61% of the sites reviewed had no spare available LV ways. This meant that a GTI could not be connected on site without replacing the LV pillar. It should be noted though that in the case of package substations, the LV pillar cannot be replaced without replacing the entire substation package (i.e. HV switchgear, Transformer and LV pillar) which automatically facilitates uprating of the transformer anyway. This contingency would have applied to 26% of the substations that were reviewed.
- 68% of the sites reviewed had insufficient space or land to be able to accept a GTI.
- 10% of sites supplied HV metered customers and there was no LV pillar. This meant that a GTI could not be connected at that site without addition of a transformer, LV pillar and negotiation of cable access agreements.
- 50% of sites would have required some form of building fabric remodelling. In most cases, this would have meant replacing the existing Glass Reinforced Plastic (GRP) substation enclosure with a new version that could accept a GTI as well as the substation plant, providing that there was sufficient space in the substation compound.

The selection of substations proved to be quite a dynamic process due to the many and varied constraints that were encountered. Eventually, a design decision was taken that accepted there was no such thing as the perfect LVDC substation and instead sought to de-risk the cable route by selecting the substations solely on the criteria of physical space.

By accepting that it was a lesser delivery risk to remodel or reinforce substations than deliver the cable route to substations that had no limitations, the cable route reduced from 1600 m to 1165 m. As a result, some significant, though not all, cable installation obstacles were avoided.

The final substations selected were: Duke Street, Priory, Works, and Canon Street as depicted in Figure 5:

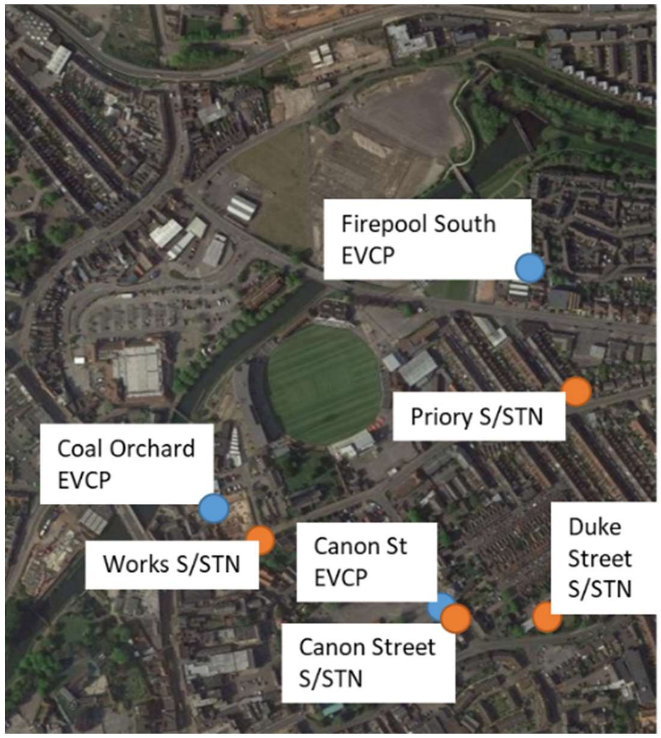


Figure 5: DC Share car park and substation locations

3.3. EVCP operator selection

To ensure that the DC EVCP's could be commercially operated, the DC Share project conducted a competitive selection process to determine who would run the EVCP during the trial and adopt them after the trial.

The winners of this process were SWARCO and they were a key part of the following works:

- Agreement on roles and responsibilities during trial period
- Technical Consultation on EVCP design and fabrication
- Initial discussions on post project takeover of assets
- Initial discussions on post project connection agreement

3.4. Approach to Safety Rules

In order to ensure a safe method of installing, working on, and operating the DC Share projects assets, the project team began developing a suite of DC specific documents, with an overarching Policy Document linking to multiple Standard Techniques.

These would be based on applying the LV live working rules to the DC network, but with adaptations made for DC where needed. Outcomes of this included confirmation that all test equipment could be used on DC Systems and all standard tools/shrouds/PPE could be applied. The existing distribution safety rules do not specifically consider AC networks, so this system of work would have sat within this.

To sit alongside this new suite of documents, it was intended that a number of DC specific training courses would be developed and delivered. Once complete, relevant staff would then be eligible for obtaining authorisations, including LVDC Authorised Person, LVDC Senior Authorised Person, and LVDC Jointer. When carrying out work on the DC share projects system, risk assessments would have been required as designed. All of the roles mentioned would have had to have been trained on the safety mitigations and ways of working on a LVDC network.

In addition to development of the safety rules, all design and construction, planning was delivered in accordance with our own internal procedures for ensuring project delivery in accordance with the Construction, Design and Maintenance regulations.

3.5. DC Cables, Joints and test equipment

A set of requirements for the LV cable system were developed. These requirements needed to be compatible with National Joint Utilities Group (NJUG) and WPD safety rules. In addition to these requirements, the DC Share project team sought to investigate to what extent WPD's existing supply chain and equipment standards could support the application of LVDC networks.

The overall requirements for the cables that were selected are recorded in Table 1. Engagement with WPD's suppliers demonstrated that the requirements expressed in Table 1 would have delivered a cable system that was able to withstand the 400V DC phase to earth or 800V DC phase to phase. Engagement with our suppliers of resin and parts for Wavecon straight joints indicated that those joints were able to withstand the load and voltage that was anticipated. The project team also checked that the standard test equipment carried by WPD jointers was rated for the proposed DC voltages.

A particular challenge for the DC Share project was how to establish connections between the LVDC mains cable and the EVCP. The cable entry box into each EVCP could only accept one incoming LVDC cable. This meant that some form of service tee-off arrangement needed to be created for each EVCP.

Whilst an acceptable work-around was developed for the purpose of the innovation trial, the physical footprint of this jointing solution was unacceptably large. To overcome this barrier to scaling, the DC Share project team formed the opinion that either a 100 kW service joint would need to be developed, or some form of junction box would have been required at each charging cluster to enable connections to be made from the LVDC mains onto each EVCP.

Table 1: DC Cable

Requirement	DC Share requirement	
Standard of Manufacture	The 300mm three core Waveform cable shall be generally manufactured in accordance with BS 7870-3.40:2011 XLPE insulated, copper wire waveform concentric cables with solid aluminium conductors. However, it will have the following variations:	
Procurement Standard	WPD specification EE74/3, with the following clarifications and variations	
	Oversheath Colour	Aqua, subject to NJUG engagement
	Oversheath Markings	DC Cable 400/800V
	Insulation Thickness	As per BS5467 and BS7870-3.4 Minimum average thickness = 1.8mm Minimum thickness at any point = 1.52mm
	DC Core colours	Core colours shall be in accordance with IEC 60502-1, with the following detail in Table 2

Table 2: DC Cable core colours

	DC	DC		
Positive	L+	+		Red
Negative	L-	-		White
Mid-point	M	M		Blue
Earth	Cu waveform	Cu waveform	Bare	Bare

3.6. Cable Installation survey

To provide the cabling requirement for the LVDC equalisation network that DC share needed to deliver, the cable route depicted in Figure 6 was committed to survey to inform whether it could be constructed.

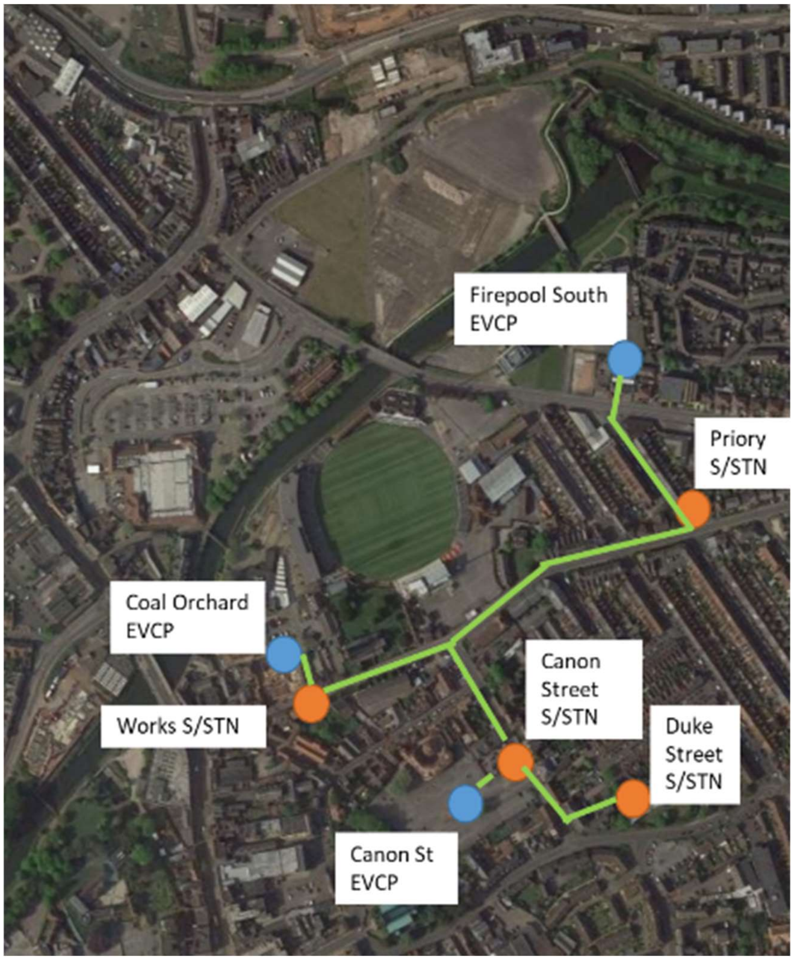


Figure 6: Initial cable route and duct section

This cable route was contingent on the use of the cable duct section shown in Figure 7. Two LVDC cables were required in the trench to interconnect all ends of the equalisation network. The thermal design of this section meant that the LVDC cables were thermally dependant on each other[1]. Delivery of a design where the LVDC cables were be thermally independent would have widened the trench. A wider trench would make the cable route harder and more expensive to deliver. The telecoms duct was required for the fibre optic communications link to enable the control system to manage all four inverters and ensure the protection system could send signals to all infeed's.

[1] Thermal dependency means that the rating of the cables increase if one of the cables is off load, but both cables have a lower rating if they are both on load.

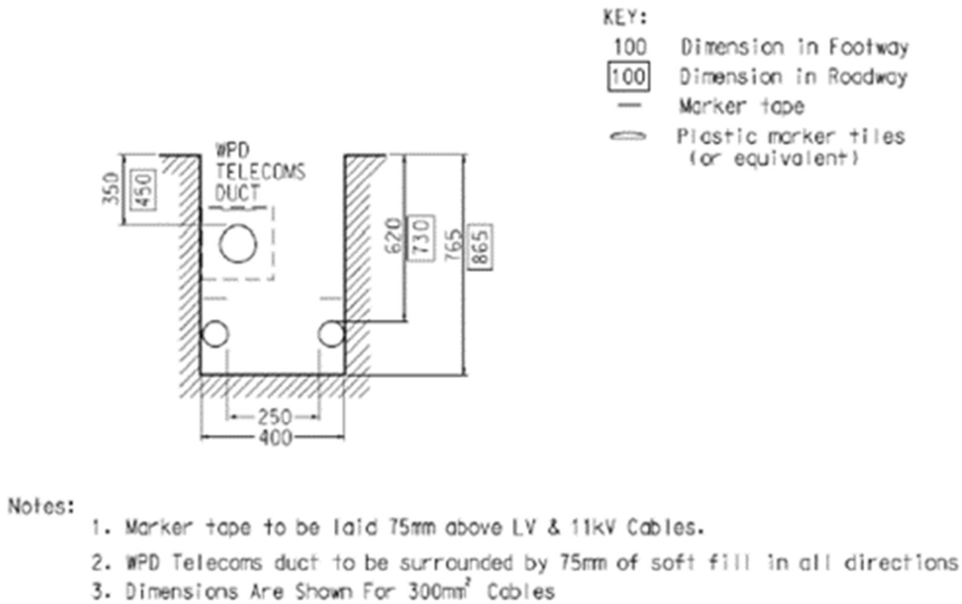


Figure 7: Initial cable route and duct section

Completion of the survey recommended the overall cable route would be comprised of the surface types as summarised in Table 3:

Table 3: Surface composition of cable route

Surface type	Sub-distance (metres)
Carriageway	397
Driveway	84
Field	29
Footway	589
Verge	20
Total	1195

It should be noticed from Table 3 that of the total route length of 1195 m, 397 m (or 31%) needed to be in the public highway because the footways were already full. The cost of installing in the carriageway is significantly more expensive than installing cables in footways and verges.

Because of the significance of the carriageways that we needed to install within, the DC Share project needed to agree road opening permissions, timing, and methodology with Somerset County highways. Having met with Somerset Highways, it was agreed:

- Road opening on the portions of the cable route that encroach St James Street and Priory Avenue would need to be limited to winter periods. This was due to its status as a main road in and out of Taunton.
- Temporary traffic lights would be required to regulate traffic along the remaining highway of St James Street/Priory Avenue and at the top of Canon Street. The requirement for traffic lights at Coal Orchard would be reviewed when the permission to open the road was booked.
- The DC Share project would need to establish an alternative one-way system around the town centre during the period that St James Street/Priory Avenue was open for construction.

- To facilitate construction at the Priory LVDC substation, an additional period of lane rental would be needed outside Priory substation for delivery and equipment laydowns. This would require additional traffic management measures across.

Despite the fact that this cable route significantly reduced the overall length, the cable survey still flagged up a number of engineering obstacles or installation influences, as summarised in Table 4:

Table 4: Surface composition of cable route

Obstacle	
Parking bays	30 parking bays required temporary suspension
Pedestrian Crossings	3 pedestrian crossings required temporary suspension
Section 58 restriction. (Meaning that the carriage way may not be dug up)	67 m section upon Cannon Street carriageway
Areas of concern,	Five pipeline crossings required trial pits to verify that there is enough space

The section 58 restriction along Canon Street, as summarised in Table 4 was particularly problematic. The cable route survey indicated that due to the width of the footway and the proximity to scheduled buildings, it was not feasible to install cables in parts of the footway on Canon Street hence installation in the public carriageway should be considered. However, because of the recent refurbishment of the Canon Street road surface, a section 58 restriction was enacted to stop the road being excavated from June 2020 to June 2023 (which was too late for the DC Share project). This meant that the DC Share project could not navigate the portion of Canon Street from Priory Avenue to the entry to the Canon Street car park. We overcame this by developing an alternative route. This alternative approach would have allowed the LVDC cables to exit the Works substation (on the site of Taunton 33/11 kV), cross Middle street and enter the Canon Street car park from the North West, rather than the road access on Cannon street.

To deliver this new cable route, the bus route and parking on Middle Street would have need to have been temporarily suspended, both of which are deliverable with enough notice and planning. The key issue that would have decided whether this route was feasible was influenced by the fact that the new route encroached on a scheduled ancient monument known as Borough Bank. WPD are not allowed to lay cables within any scheduled ancient monuments unless the government has granted permission.

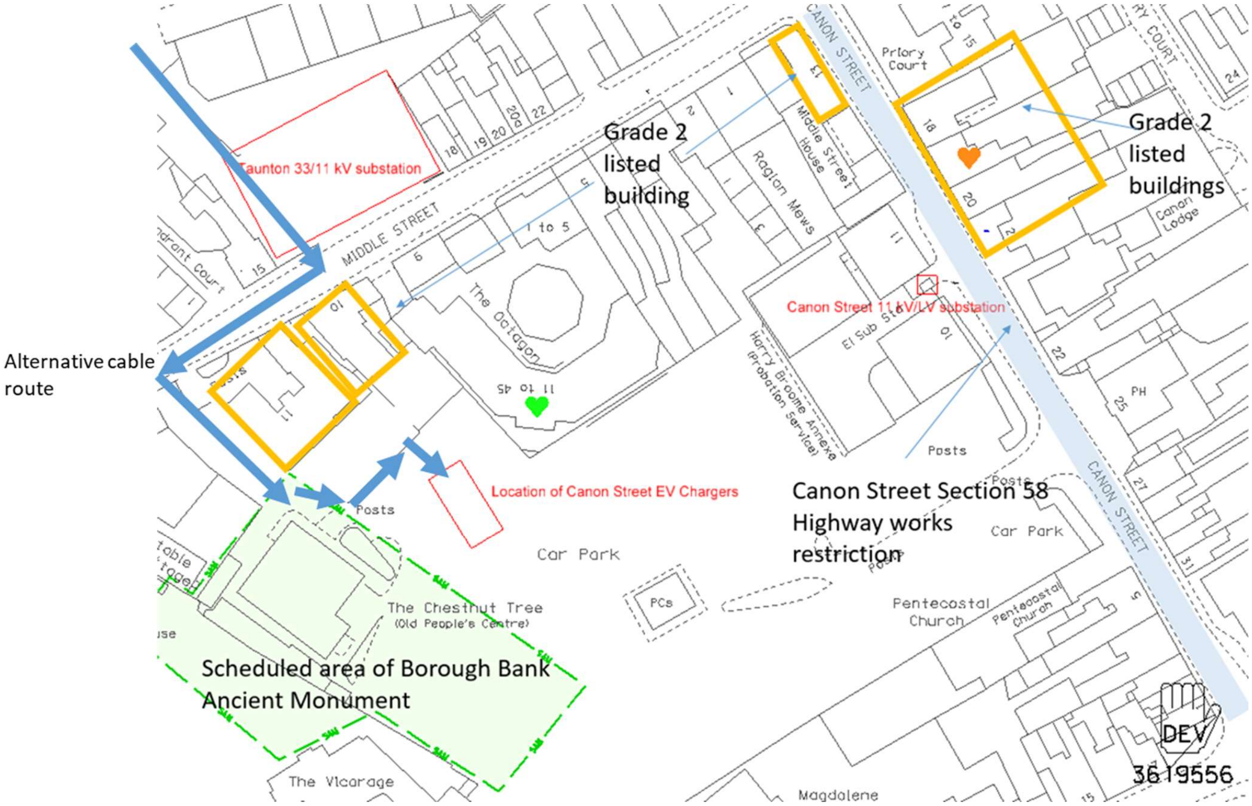


Figure 8: Map of section 58 limitations on Canon Street and alternative route along Middle Street

To understand whether it would be feasible to use the cable route described in Figure 8, WPD approached the local Historic England Inspector with a report explaining the difficulties and justification. Having reviewed the situation, the local inspector was satisfied that there were a grounds to apply to government for Scheduled Ancient Moment Consent (SAMC). As such, WPD were preparing to obtain SAMC prior to request to halt the project was submitted to Ofgem.

3.7. LVDC equalisation system modelling

3.7.1. DC Share Model

Before the designs could be progressed to construction, the DC Share team conducted an exercise to ensure that LVDC assets would be acceptably loaded and the EVCPs would receive acceptable voltage.

Because there were no commercially available packages that could easily replicate the overall LVDC equalisation system, a bespoke package was to be developed..

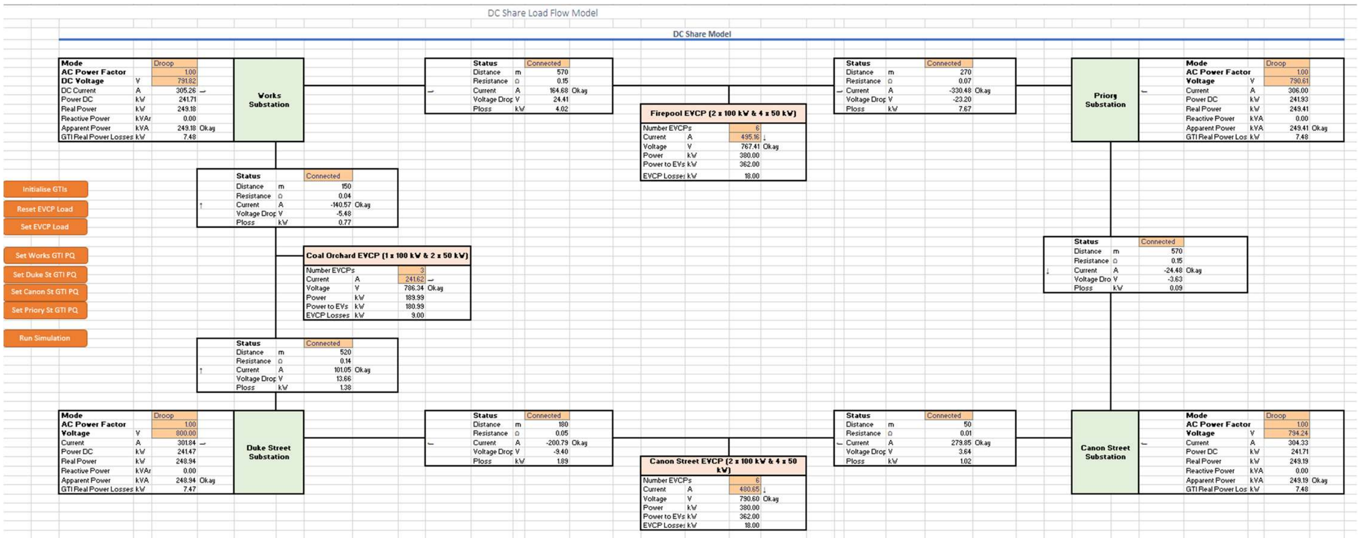


Figure 9: DC Share model interface

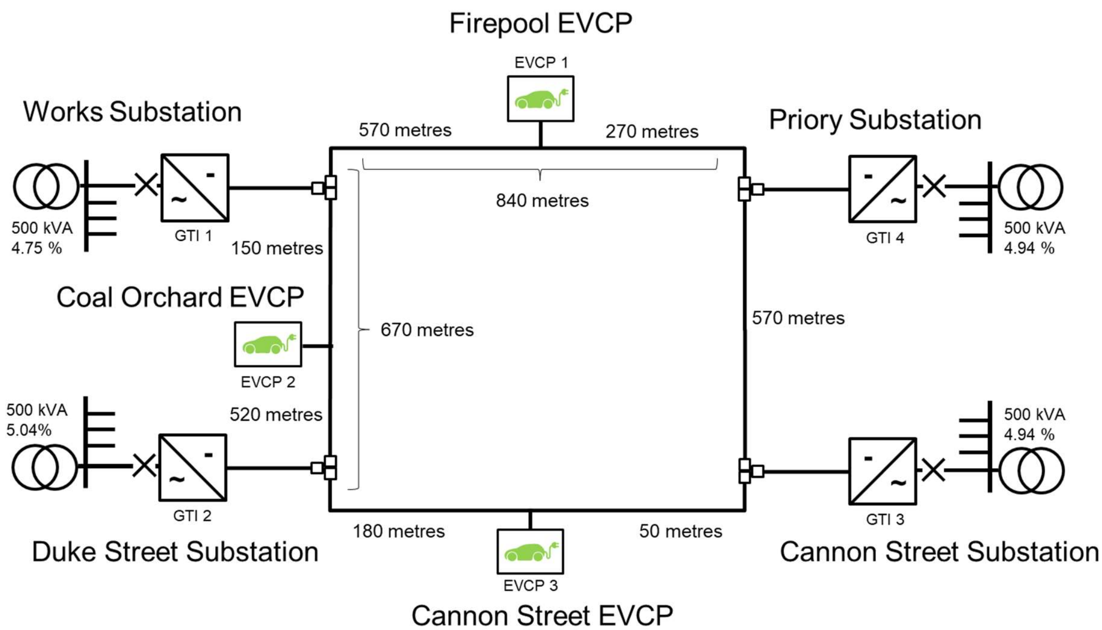


Figure 10: Network schematic of the system that was modelled.

The DC Share model was created to calculate the power flow in the DC cable and the expected DC voltages at the terminals of the GTIs and EVCPs. An example of the user interface is shown in Figure 9, with Figure 10 illustrating the network that was modelled.

The model contains an optimisation algorithm based on the Newton Raphson method to calculate the DC voltages that are required to achieve a particular sharing ratio between the GTIs. The model was be used to demonstrate the system operation and different DC Share use cases.

The model calculates:

1. The real power and reactive power from the GTI
2. The DC node voltages at the terminals of the GTIs and EVCPs

3. The losses in the DC cable, EVCP and GTIs
4. If a GTI or cable section is overloaded
5. If there is an under-voltage at the EVCP
6. The DC voltage required to change how the GTIs share the EVCP load
7. The output when a single GTI is placed in PQ set-point mode

The DC Share model was use to review the expected performance of the equalisation network and some of the results are discussed in 4.7.2.

3.7.2. Modelling results

A modelling campaign was undertaken to review the system performance under intact conditions and also under conditions when one GTI or cable was out of service. This section provides an overview of the analysis (rather than an exhaustive record) to illustrate how we arrived at some of the learning points.

GTI Loading
We used the DC Share model to verify loading on the AC side of the GTIs. Figure 11 shows the real power as measured on the AC side of the GTI when the Supervisory controller is sharing load equally across GTIs.

The simulation results demonstrated that 100 % of EVCP load was not achievable due to losses within the GTIs and DC cables. To connect 1 MW of EVCP load, each GTI is required to supply up to 262 kW of power on the AC side of the GTI. This is 12 kW above the rating of the GTI. This would cause the GTI to trip on overload and the DC Share network to collapse. This meant that the supervisory controller would need to limit the total load of the LVDC equalisation network to 95% of the GTI capacity. Under some LVDC cable outage conditions, the DC loses were greater and the GTIs would need to be temporarily de-rated by a greater magnitude.

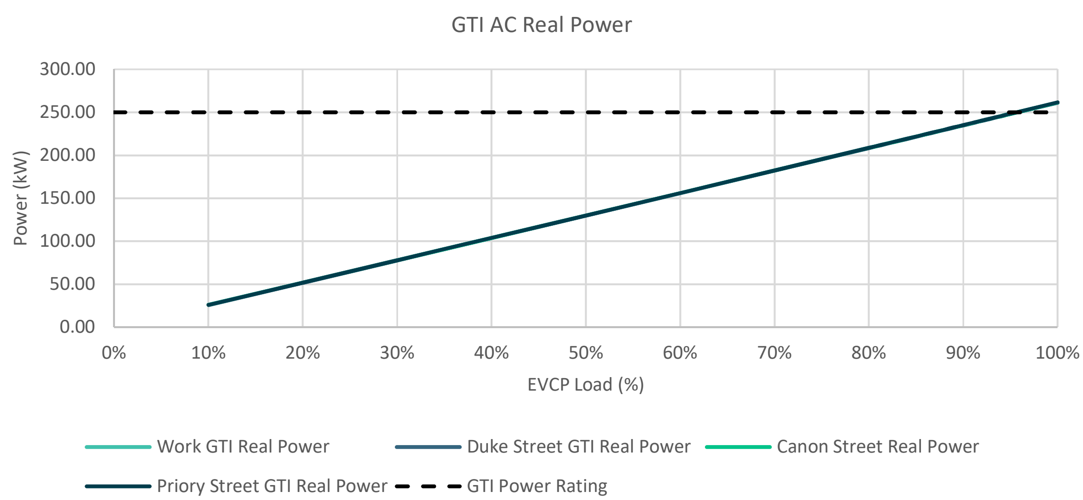


Figure 11: Power flow from the AC side of the GTIs under intact conditions.

LVDC Voltage Profile
To be able to dispatch the power flow to meet a sharing goal, the DC voltages at each of the substations would need to be raised or lowered by the GTI control systems. This meant that every different sharing scenario would have its own voltage profile. To ensure that the DC EVCP's received acceptable voltages, we conducted studies to verify that an acceptable voltage profile could be achieved. An example of one of these studies is shown in Figure 12:

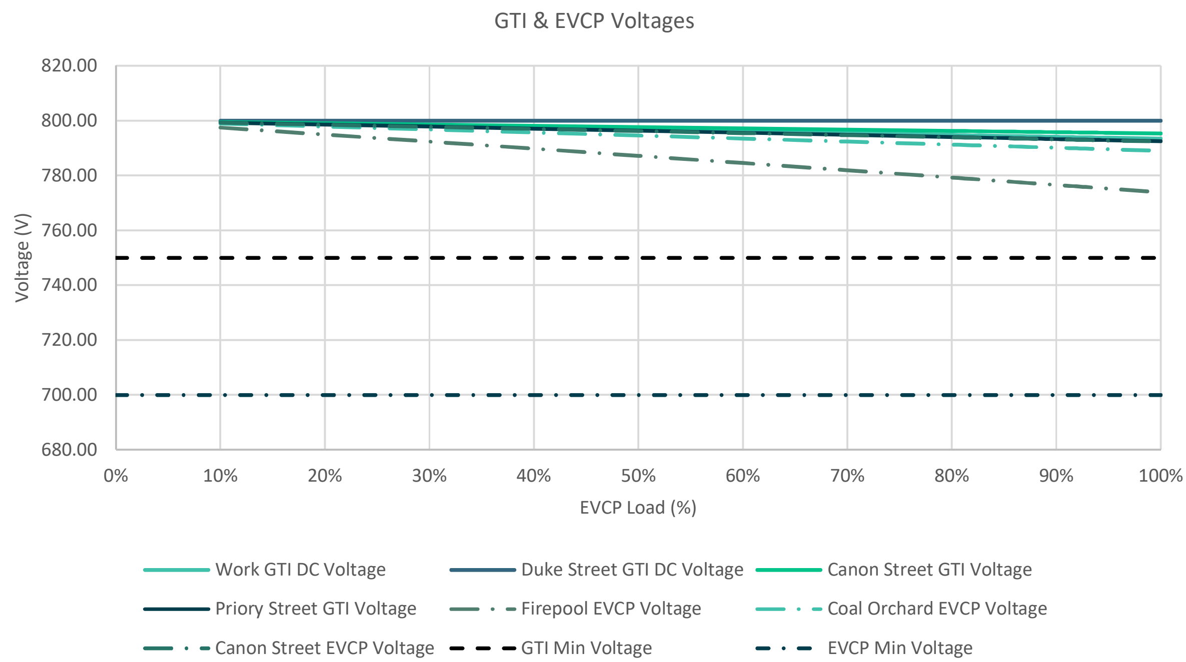


Figure 12: DC voltages required on the DC side of the GTI to share the load equally between the four GTIs and the EVCP voltages

The results in Figure 12 show the DC voltages as calculated from the simulation for sharing the load equally between the four GTIs and three EVCPs. Different terminal DC voltage are required to mitigate the voltage drop across the DC cable. Duke Street is furthest from the EVCP load and maintains the highest voltage. As the load increases in the DC network, the voltage different between the GTIs increases. The minimum GTI voltage as simulated is 793 V. This example shows that under conditions where the GTIs are equally loaded, an acceptable voltage profile could be achieved across the GTIs and the EVCP.

We also conducted voltage profile studies during planned cable outage conditions and GTI conditions. These studies demonstrated that under some cable outage conditions, the EVCPs would not receive acceptable voltage and would therefore need to be disconnected for the period of the cable outage. These conclusions would be worsened if the GTIs were instructed to not share load equally as the voltage profile in some parts of the network would have to be lowered.

LVDC Cable Loading

We conducted exercises to understand the cable loading under different EVCP loading scenarios under intact and outage conditions. Figure 13 provides an example of this for the condition of system intact, summer continuous cable ratings and equal GTI loading.

In this example, the cable section between Priory and Firepool is the most heavily loaded with the current flowing from Priory GTI to Firepool EVCP. The maximum current of 345 A is observed when the EVCPs are operating at 100 %. This is below the specified design rating of 360 A for the DC cable. When operating at 95 % EVCP load, the maximum loading conditions to prevent the GTIs from being overloaded, the maximum DC current is 327 A. The current is positive when flowing in the direction as stated in the legend.

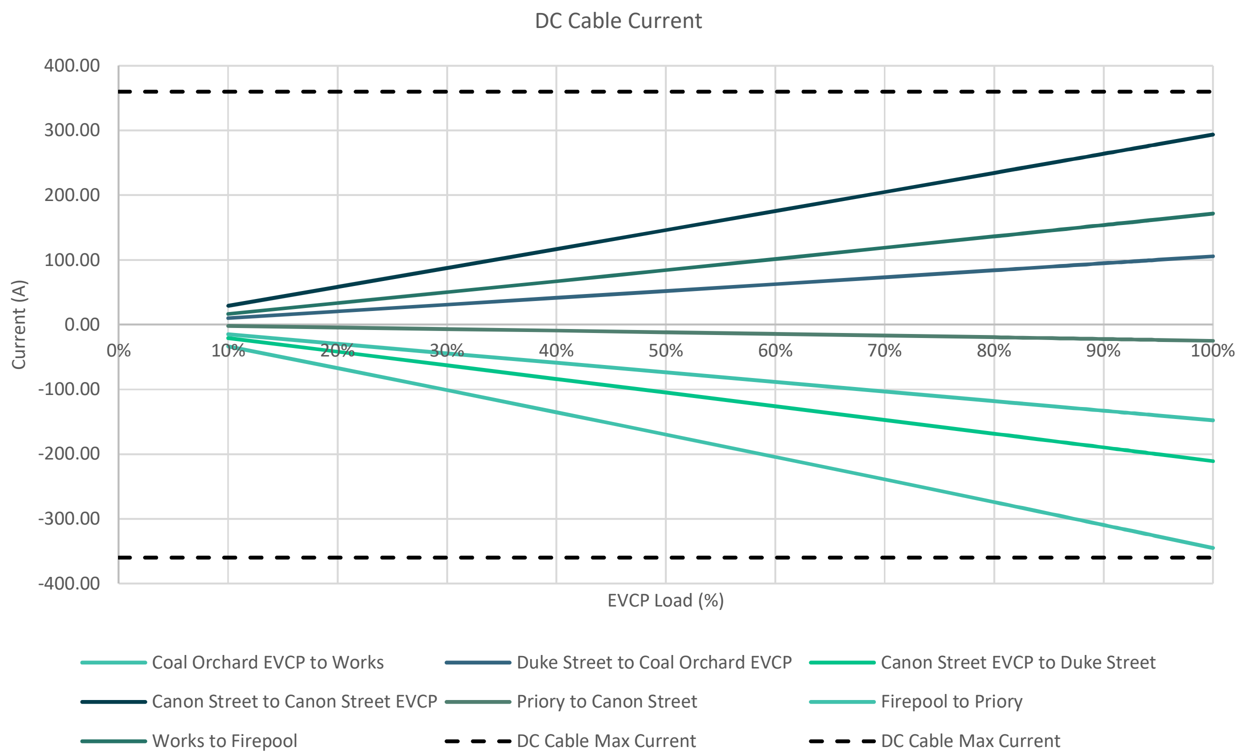


Figure 13: Current flow in the DC cable network

Our analysis also demonstrated that under cable or GTI outage conditions there would be situations where the load flow exceeded the summer continuous rating of the LVDC cables. From this analysis it also became apparent that if the supervisory controller were instructed into certain GTI sharing ratios, then the high flows on the Firepool to Priory and Duke Street to Canon street cables would be exacerbated. Prior to the request to halt, this limitation was to be investigated further using AC substation loading measurements to determine likely sharing ratios between substations to inform the prevalence of this risk.

To mitigate cable loading issues, the DC Share project team intended to review the cyclic ratings of the cables once evidence regarding daily load profiles had been gathered during the trial period.

AC Substation performance
Studies were undertaken to review how the LVDC equalisation network affected the AC substations which they connected to. Initially these studies were undertaken using Maximum demand indicators prior to installation of the LVAC Gridkey load monitors.

The voltage regulation and thermal loading of the transformers were checked. Because of this exercise, a recommendation was made that the DC Supervisory system should prohibit export from the DC system to an AC substation when that AC substation is lightly loaded.

3.8. Protection System Intent

A protection philosophy for the LVDC equalisation network was developed to ensure that the LVDC could meet the needs of the electricity safety quality and continuity regulations as well as provide a useful service to customers.

To ensure that the LVDC equalisation network could be applied in a public space, a set of seventeen requirements were established. These requirements defined the minimum acceptable performance criteria for sensitivity and speed, coverage, discrimination, and planned depletion. It was then the task of the design team to show that the available systems could be set to meet these requirements.

These requirements were to be delivered using a main protection system, a backup protection system, and EVCP protection, as described in the next three sections.

3.8.1. LVDC network analysis

To be verify that all protection systems were sensitive enough, protection calculations were undertaken to inform how much fault current would flow through a GTI for an array of different fault locations and fault types on the LVDC equalisation network. To be able to make these calculations, the DC Share team needed to model the contribution of the AC system to the DC System.

GTI contribution to LVDC faults

The AC to DC conversions in the GTI utilises a full bridge configuration with reverse voltage diodes. Because of the presence of these reverse voltage diodes the GTI will still contribute current to a fault on the DC network even if it is not commutating. A GTI will only not contribute to a DC fault is if it is disconnected from the AC network, e.g. if the MCCB is open.

LVDC Fault level calculation

Fault calculations were completed using the Piecewise Linear Electrical Circuit Simulation (PLECS) package. Simulations were completed for both Pole-to-Pole and Pole-to-Neutral conditions. This data was then used to determine whether protection settings were sensitive enough to detect LVDC faults. This type of power electronic modelling is not typically undertaken by UK DNOs and a capability to manage LVDC fault levels would need to be cultivated to enable scaling of the LVDC equalisation proposition.

System intact fault levels

The System Intact Maximum Fault level is encountered for a Pole-to-Pole fault at the output terminals of GTI1, with maximum AC system fault infeed (200MVA). The results of this study are shown below:

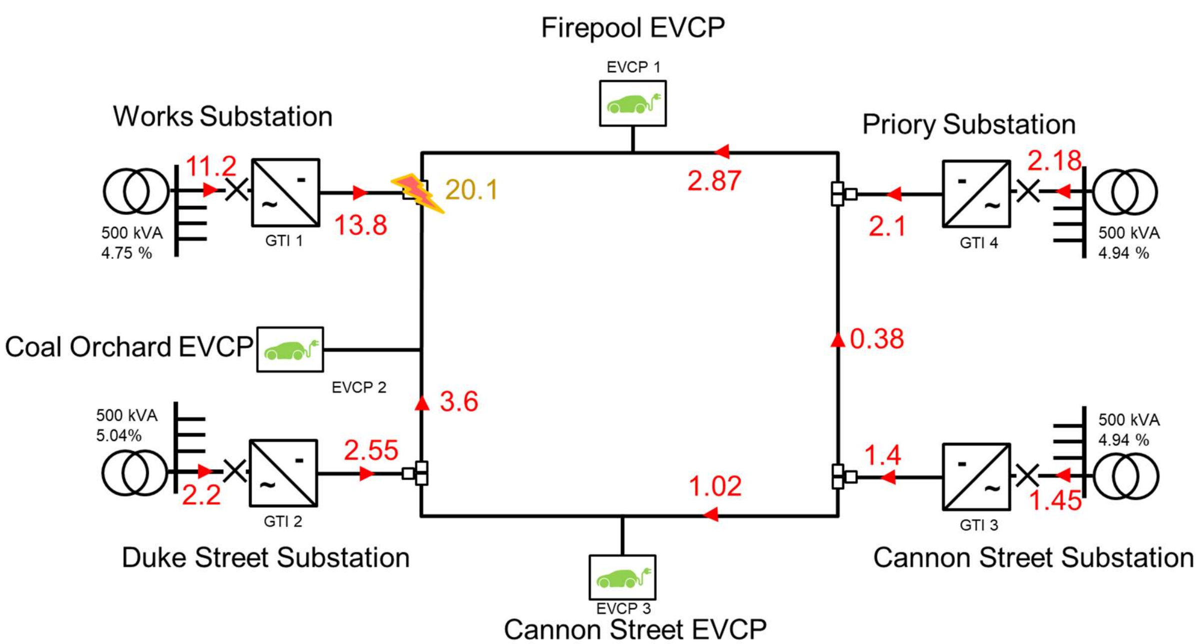


Figure 15. System intact maximum Fault Level Summary in kA

The System Intact Minimum Fault level is encountered for a Pole-to-Neutral fault at the halfway point between Works and Priory Substations, (420m cable distance from each) with the Minimum AC system fault infeed (50MVA).

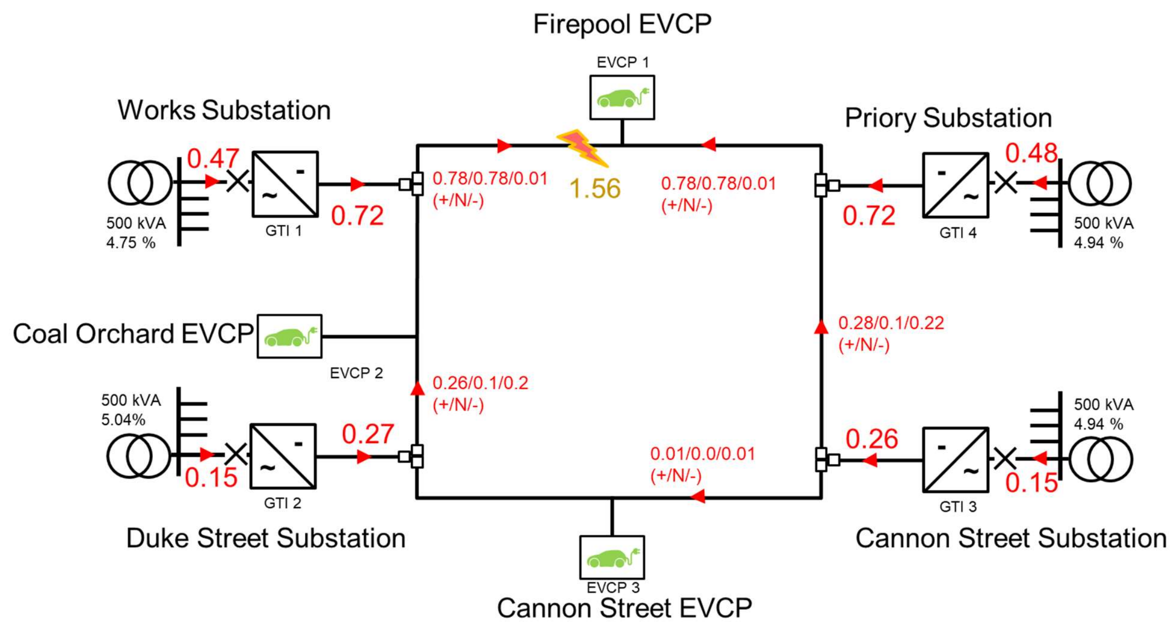


Figure 16. System intact minimum Fault Level Summary in kA

We also conducted studies to determine what condition would present the minimum fault level of the LVDC equalisation network. We determined that the N-1 Minimum Fault level is encountered for a Pole-to-Neutral fault at the Firepool EVCP with the Minimum AC system fault infeed (50MVA) as shown in Figure 17. It is notable that this running arrangement would only be achievable if one of the GTI Isolators at Priory was left open.

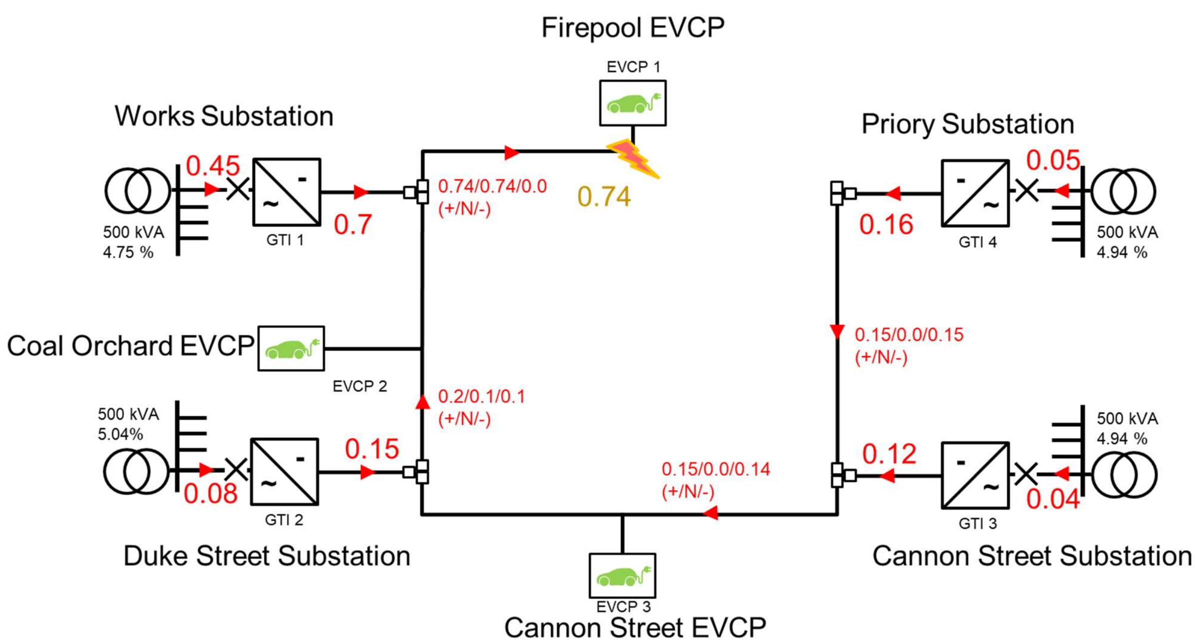


Figure 17. N-1 Scenario minimum Fault Level Summary in A

Maximum Loading
As part of the analysis for the protection philosophy, analysis of the maximum system loading was undertaken. The current flows for the maximum loading condition are summarised in Figure 18.

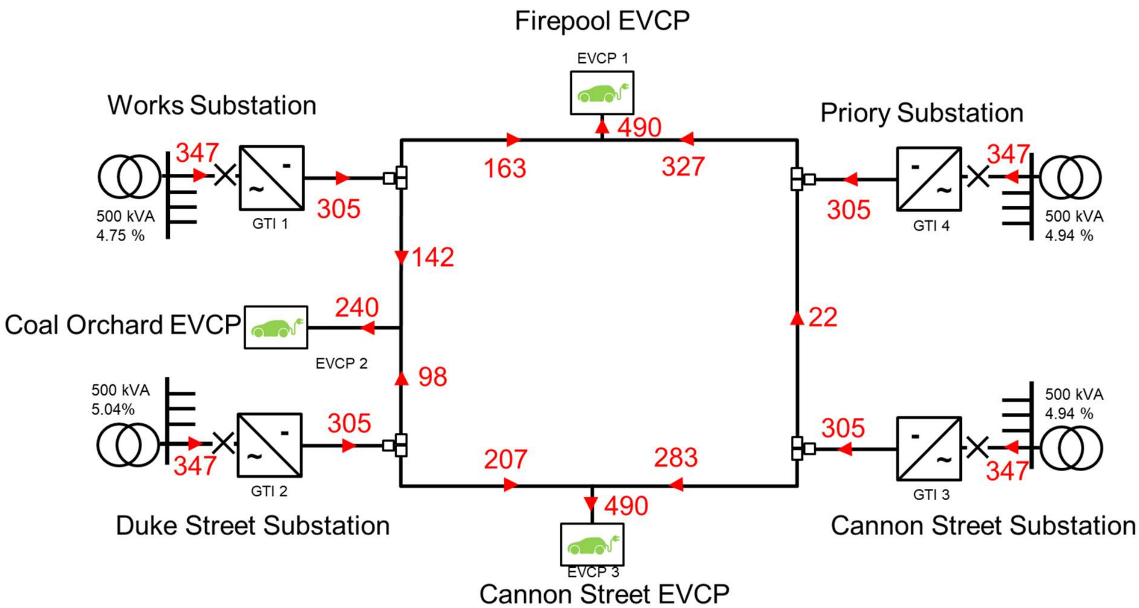


Figure 18. Maximum loading (Intact System) in A

3.8.2. LVDC Equalisation network main protection

The DC Share project was developing a novel main protection that could be used to protect the entire LVDC equalisation network. This main protection was first of type anywhere.

The overall key line diagram for the entire equalisation network is shown in Figure 19 and shows that a main protection interface is located at each GTI. This interface could send and receive tripping commands to and from any of the other GTI in-feeds.

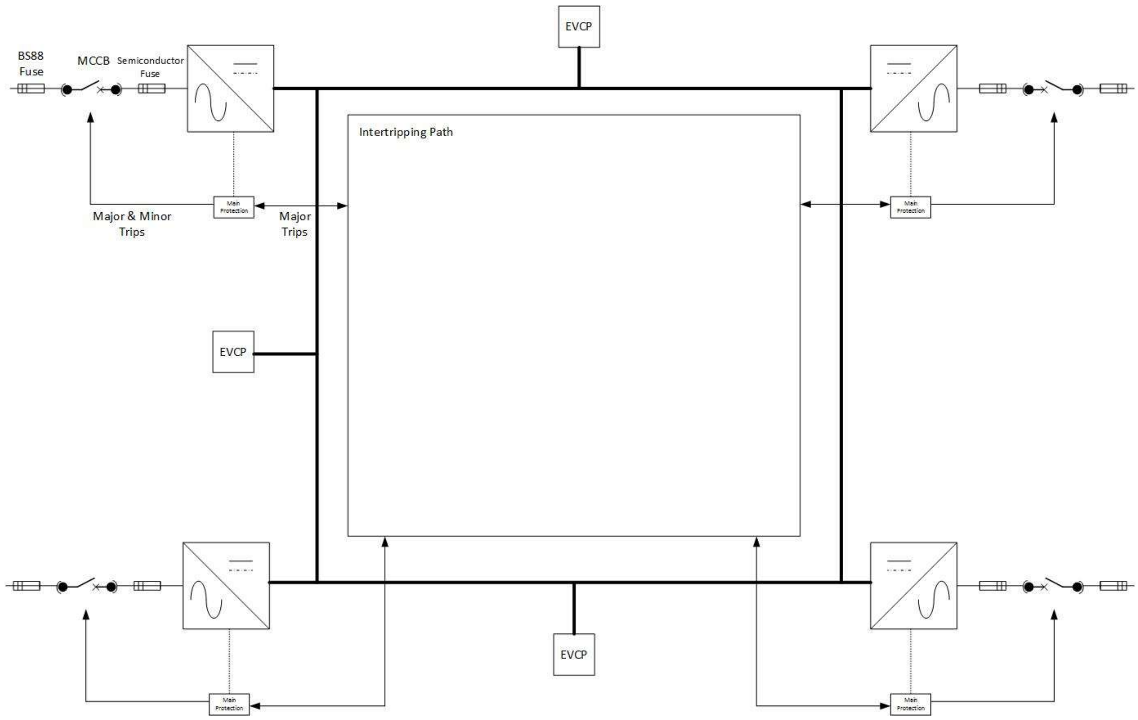


Figure 19: Key line diagram of the overall DC Share System

To determine if a fault condition was present, Voltage and Current was measured and reviewed at each GTI (in several locations as per Figure 19) Operation of the main protection results in either:

1. Minor trip: MCCB tripping and lockout of the affected GTI
2. Major trip: MCCB tripping and lockout of all four GTIs

Initiation of remote tripping was to be undertaken by the detecting GTI initiating a Generic Object Oriented Substation Event (GOOSE) message via the IEC61850 communications protocol. This was to which will be transmitted to all other connected GTI via the Fibre Optic ring. The total overall fault clearance time for this system was expected to be 58 ms.

The DC Share project team recommended the Key settings and operating times as detailed in Table 5:

Table 5. Main Protection key settings

Function	Setting	Response action
AC Functions		
Overvoltage (AC)[2]	Long: 256V, 1s Short: 276V, 10mS	Minor Minor
Undervoltage (AC)	Long: 205V, 10s Short: 184V, 500mS Immediate: 160V, 20mS	Minor Minor Minor
Overcurrent (AC)	Long: 400A, 10mS Short: 450A, 5mS	Minor Minor
DC functions		
Overvoltage (DC)	880V, 10mS	Major
Overvoltage (DC- Half Link)	475V, 10mS	Major
Undervoltage (DC)	680V, 10mS	Major
Undervoltage (DC- Half Link)	175V, 10mS	Major
Overcurrent (DC)	Long: 345A, 10mS Short: 390A, 5mS	Major Major
Overcurrent (DC -Half Link)	200A, 10mS	Major
Current Unbalance	The policy was still under development at the time of halt.	Major

We reviewed the settings proposed in Table 5 against the minimum system intact fault levels illustrated in Figure 16. We concluded that at under system intact conditions it was likely that the main protection would exceed the half link overcurrent threshold at all four ends, but pole to pole faults would only be detected at two out of four ends. For this reason the ability to cascade the tripping instruction around the ring via the optical fibre ring became essential to achieve acceptable clearance time.

Under system N-1 minimum fault level conditions (outage of the Works to Firepool circuit), we determined that only one GTI location would experience main protection operation. Meaning that we were dependant on this site to cascade the tripping instruction to all other ends.

As a result of this exercise we concluded that the main protection was sensitive enough, but acceptable clearance times from all four ends of the equalisation network was dependant on acceptable performance of the protection signalling channel carried on the fibre optic ring.

We also reviewed the scope to increase the sensitivity of the solution with regard to network expansion. As shown in Figure 18, the maximum GTI loading was expected to be 347 Amps, we would still need to respect this if we added a 5th GTI to the network. Good protection setting practice would normally leave a 10% margin between protection settings and the maximum demand to avoid mal-operation. For this reason, it was observed that the overcurrent settings could only have their sensitivity increased by a further 2-5% before encroaching on the load setting margin. This implies that the size of the LVDC equalisation network is reaching the maximum limit that can be supported by this protection philosophy (i.e. the limit being based on a 2 to 5% extension to the existing baseline of 1195M of cable).

[2] AC measurements are taken from each of the 3 phases

3.8.3. LVDC network backup protection.

To provide system protection should communications fail or main protection fail, an additional three-stage protection scheme is implemented within each GTI, as described below. These protections are on the AC side of the convertor as listed beneath.

1. BS 88 J-type fuse located at the substation LVAC board providing back up to the above protections, and also protection of the AC connection between the LV board and the connection to the GTI. Operation of this fuse requires manual intervention to restore supply to the GTI.

Table 6. BS 88 J-Type fuse details

Fuse	Value
Type	BS88 J-Type
Rating	400A

2. AC MCCB (ABB Type T5, Rating 400A) using an electronic protection module (Type PR222DS/P) unit located within the GTI. Operation of this device requires manual intervention to restore supply to the GTI. The DC Share project team recommended that the MCCB's be set according to the settings recorded in Table 7:

Table 7: Recommended settings for MCCB

Curve	Setting	Value
L	A	384
	T(s)	3
S	A	480
	T(s)	0.1
I	A	600
	T(s)	0.025
G	A	Disabled
	T(s)	Disabled

3. An AC semiconductor fuse located within the GTI. Operation of this fuse requires manual intervention to restore supply to the GTI.

Table 8. Semi-Conductor Fuse details

Fuse	Value
Type	PSCaR
Rating	350A

Note that the AC semiconductor fuse is rated at 350A, which is close to the full load rating of the GTI (250kW at 415V = 347A). Although the fuse should not operate at 347A, it is possible that the fuse will degrade over time if the GTI is run at full load for long periods and may eventually fail.

Back-up Protection grading

Discrimination between the above time graded protections was designed to provide operation of the MCCB for GTI or DC cable fault current for fault currents below 3.5 kA. For fault currents above 3.5 kA, the AC semiconductor fuse could operate first as the MCCB requires time to mechanically operate and extinguish the fault current, exceeding the time for the fuse to extinguish the fault. It should be observed that the MCCB protection curve is already set to the minimum threshold to avoid tripping of rated GTI load current. This means that the sensitivity of the back-up protection cannot be increased to cater for any reduction in fault level or planned extensions of the LVDC equalisation network.

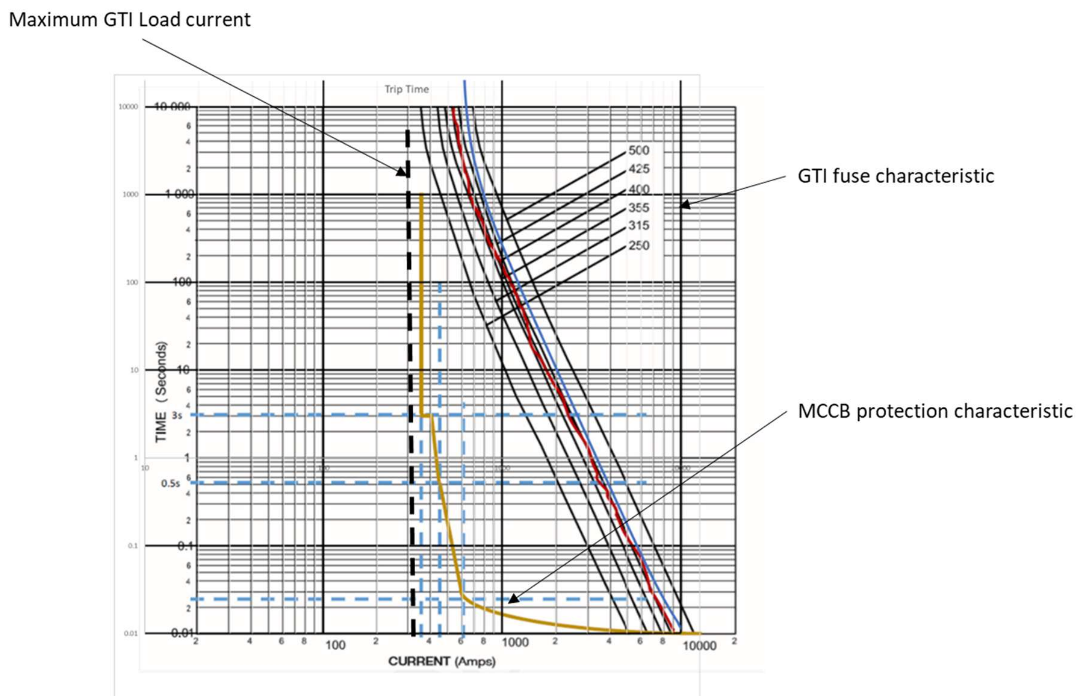


Figure 21: GTI Protection Coordination.

It was identified that under minimum system intact fault levels for a pole to neutral fault, the backup protection would not adequately clear the minimum intact fault level condition (summarised in Figure 16). In this case, adequate fault clearance was dependant on the main protection recognising the condition.

The GTIs have a common Protection Earth and Neutral Wire (PE/N) wire, provided as a bolted connection. The PE/N wire is split within the cabinet to Neutral and protection earth with current ground fault detection. Ground fault detection is provided by current detection in the PE wire and if a threshold is exceeded for a given time period tripping is initiated via the MCCB.

Table 9. Ground Fault monitoring details

Ground Fault monitoring	Value
Type	Bespoke system
Rating/Settings	50A, 1mS
Total Trip time	
Fault Detection	1mS
Local Trip Relay	5mS
MCCB opening time	25mS
Total	31mS

3.8.4. EVCP protection

The EVCPs are equipped with the Protection devices as follows.

Each stage of the convertor will have fast acting protection functions implemented locally on its control card. Operation of these Main protections will cause a Major Lockout, Power flow in the EVCP is stopped (via the opening of a contactor) and the charger is locked out.

The network protections are summarised below:

Table 10. EVCP Main Protection settings

Function	Setting
Input overvoltage	870V, 100mS
Input undervoltage	690V, 100mS
Input overcurrent	200A, 100mS

Note that the EVCP overcurrent protection has a 100mS delay time, meaning that the GTI main protection will operate faster for faults that are detected by both systems. This is a key point for the overall customer proposition for LVDC equalisation network, one single EVCP fault will collapse the entire equalisation network until the faulty EVCP can be disconnected and the equalisation network manually restored. At the time of project halting a mitigation for this was being considered by the project team.

The following Back up protections are installed in the EVCPs:

1. The input +/-400Vdc supply is isolated upon entry to the EVCP and protected by internal DC fuses.

Table 11. DC Fuse details

Fuse	Value
Type	PSR030UL0250Z PSR070UL0250Z
Rating	250A

2. The DC (and AC) supplies are protected from over voltage by self-protecting voltages suppressors.

Table 12. Voltage suppression device details

Voltage suppressor	Value
Type (DC)	T2PV2/40/1000
Type (AC)	ST2301PG

To ensure charging of the vehicle is conducted safely, the charger output to the vehicle has a ground fault monitor card. The charger will check the integrity of its ground fault detection circuit before turning on and should any failure be detected the charger will be prevented from operation. Upon detection of any ground fault between the output circuit and enclosure of the charger and/or between the charging circuit and the vehicle chassis, the charger shall stop charging and not be allowed to restart charging until the ground fault has been cleared.

Table 13. Ground Fault monitoring details

Ground Fault monitoring	Value
Type	Bespoke system
Rating/Settings	50A, 1mS

3.8.5. Protection system operational recommendations

The protection setting recommendations recorded in 4.8.3 have a limit to which faults they can reliably be expected to detect. For this reason, a set of operational rules were to be recommended that recognised the limitations of the protection system. These operational rules would have been as follows:

1. The LVDC equalisation network will have acceptable levels of protection sensitivity under the following conditions

- System intact, i.e. all GTIs and DC Cable Legs in service with main and back up protection in service.
- Outage of one entire cable branch spanning GTI isolator to GTI isolator incorporating any branched EVCP with main and back up protection in service.

2. To avoid uncleared faults, the LVDC equalisation network must not be operated unless both back up and main protection systems are in operation. In the event of a main protection failure or total failure of communications to or from any one location the entire LVDC equalisation network should be de-energised.
3. To avoid uncleared faults, the LVDC equalisation network must never be ran with an open point at one of the GTI stations or EVCP stations.

This exercise did show that with the geographic footprint of the DC Share project (i.e. 4 GTIs with 1195 m of cable), guaranteeing adequate back up protection sensitivity became problematic. This fact is an indicator that expansion of the LVDC equalisation network to accept a longer cable or additional GTIs would exacerbate this problem and would likely prohibit expansion of the system on the grounds of acceptable protection performance.

Customers and operators should also understood that a fault casing protection operation on one from the 15 EVCPs would result in unavailability of the entire LVDC equalisation network until the faulty EVCP had been identified and disconnected and the LVDC equalisation network restarted. At the time of project halting potential mitigations were being reviewed by the project team.

3.9. Earthing Philosophy

As part of the design development of the LVDC Equalisation network, an earthing and bonding philosophy was under development. Figure 22 gives a summarised view of the overall intent.

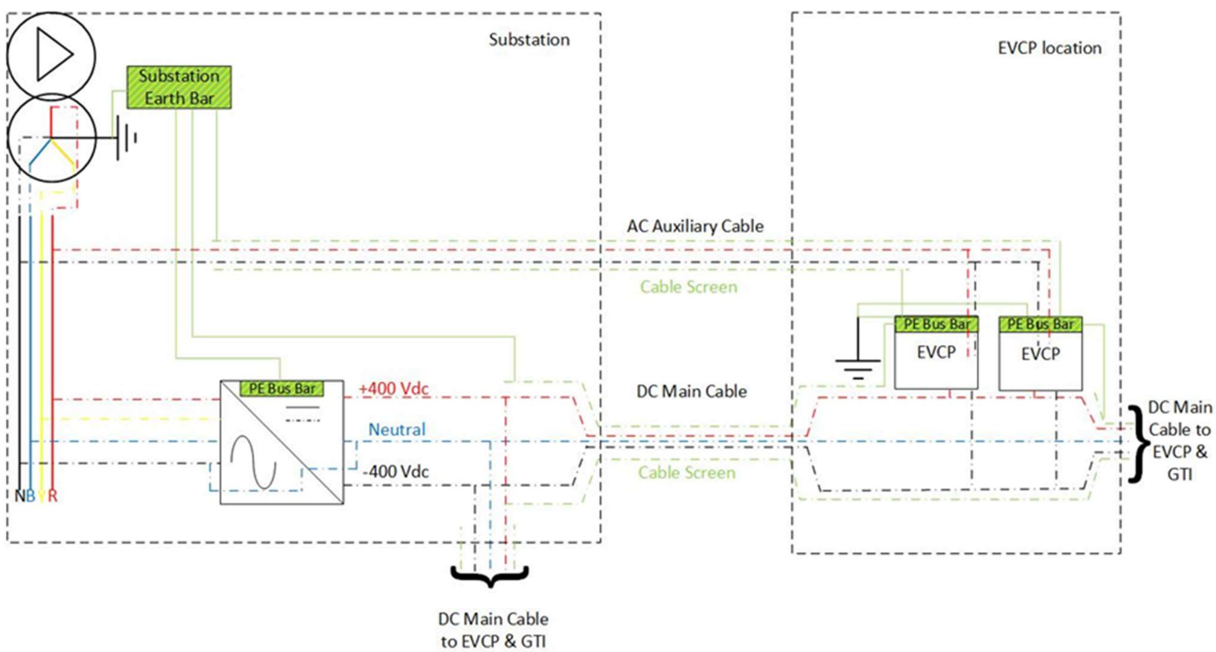


Figure 22: DC Share Earthing and Bonding

The DC system was proposed to share the same earth electrode as that of the AC substation, with additional earths at each EVCP. The entire system would have been bonded together via the cable screens. Each EVCP would have depended on auxiliary supplies from adjacent substations and the design assumption that EVCP auxiliary supplies would only be derived from LVAC substations that already hosted a connection to the LVDC network.

At the time of requesting the project halt, the project needed to resolve the final step and touch voltage performance and compliance with EN 50162 relating to Stray DC currents. We also recognised that a further policy decision would have need to have been made as to whether it would have been acceptable to supply the auxiliary supplies for the EVCPs from substations that were not directly connected to the LVDC equalisation network. To do so would made it possible for potential to be transferred to from the LVDC equalisation network to other substations not involved in the LVDC equalisation network.

3.10. Grid Tied Inverters

The DC Share project team developed a specification for the procurement of the Grid Tied Inverters that would be used to transform three phase AC supply into the DC Supply for the LVDC equalisation network. The overall parameters of the GTI are summarised in Table 14. Full details of the GTIs can be found in the system specification, but a summary of the GTI workstream is contained within this section.

Table 14: Main parameters of the GTI.

Parameter	Value
AC connection voltage	400V +10%, -6%
AC connection frequency	49.5Hz – 50.5Hz
AC connection power factor	0.9 to +0.9, nominal operation at unity power factor
AC connection number of phases	3
AC connection neutral connection	Solidly earthed
Continuous rating	1.8kV rms for 1 minute
Dielectric voltage withstands	20 kHZ
Nominal DC output voltage	Maximum 7.5 kW (3%)
Switching frequency	-20 to 40 ˚C
Heat output	Target of 56dB
Ambient temperature operating conditions	-20 to +40 ˚C
Maximum noise level	56 dB
IP rating	41
Dimensions	2004mm x 1450mm x 690 mm
Weight	~1300 kG

The GTIs could operate in three modes, which are all instructed by the DC Supervisory controller.

1. **DC Link Voltage control mode**

   This mode is only used during DC ring start up. It functions to enable the DC assets to be pre-charged and then closes the MCCB on the AC side of the GTI. Once the MCCB is closed, this function enables the MOSFETS on board the GTI to start commutating to ramp the DC bus voltage up to 800V.

2. **Droop control mode**

   In droop control mode the active power reference is calculated by the local droop controller based on the DC link voltage measurement. The droop control characteristic can be optimised using measurements from the other GTIs, or by the supervisory controller. In droop control mode the overloaded transformer can be supported by flattening the droop characteristic and by steepening the droop characteristics on the transformers designated to take the load. The responsibility for assigning these droop slope characteristics instructions comes from the supervisory controller to each GTI.

3. **Constant power mode**

In constant power mode the GTI active power reference is provided by the supervisory controller rather than calculated by the droop controller. The number of GTIs in constant power mode would be limited to maintain stability of the DC network, hence remaining the GTIs will stay in droop control mode.

In addition to these three power control modes, the GTIs were specified to deliver three additional control modes:

- Phase balance improvement
- Harmonic improvement
- Reactive power flow

The overall GTI is a modular design comprising of two physical enclosures:

- 3-phase grid-tied inverter (GTI) enclosure
- Neutral leg converter enclosure. This enclosure is required to deliver the Phase balance improvement use case.

The inverter is formed from three identical inverter leg modules. The inverter leg modules incorporate the following parts:

- Heatsink and mounting frame
- Over temperature thermal protection sensor
- SiC MOSFET power devices (two in parallel)
- DC link capacitors
- Gate drive card
- DC link discharge resistor
- DC Isolator chamber (externally mounted)

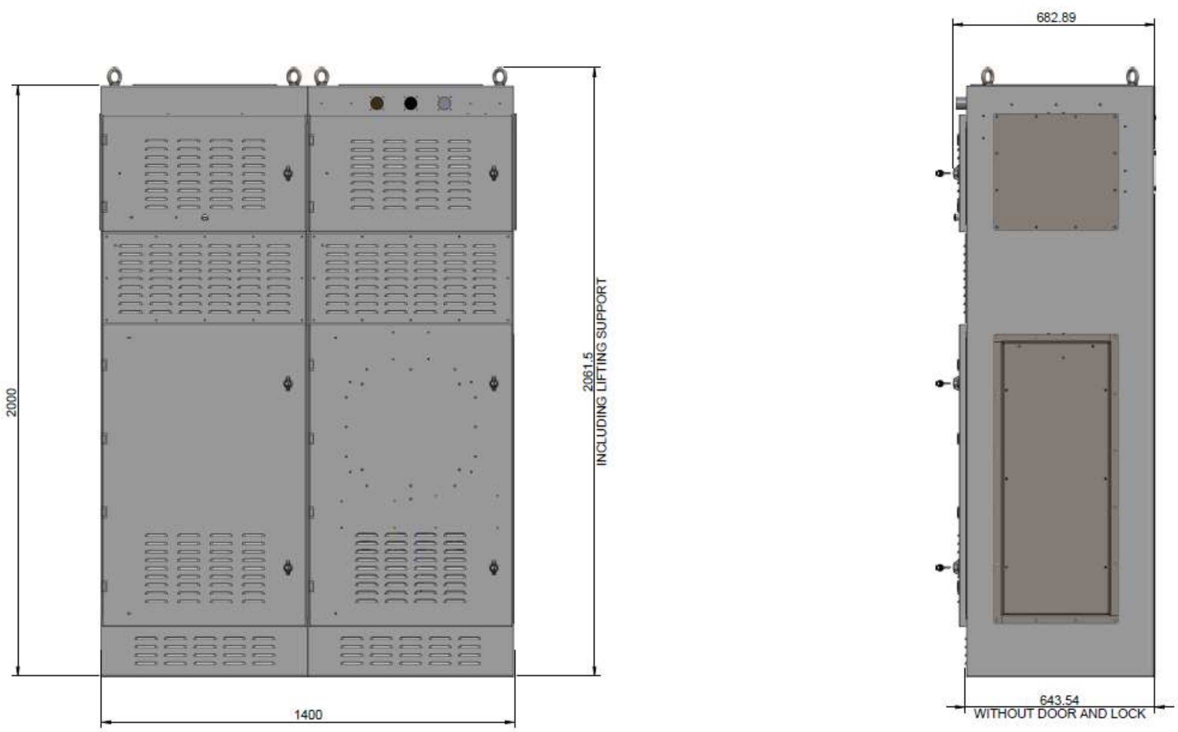


Figure 23: Inverter Enclosure (Left) Neutral Bridge Enclosure (Right) internal view

Figure 25. Photo of GTI in construction in the TPS works

It should be noted from Figure 23 and Figure 24 that the neutral bridge cabinet was an additional compartment that was needed to provide the phase balancing functionality. Investigations confirmed that in the future smaller GTIs could be delivered if some of the non-core features including phase balancing were not specified. Section 5 discusses whether this opportunity would have been enough to improve the commercial viability of LVDC equalisation networks.

Prior to the instruction to halt, the DC Share project had progressed to the point of manufacturer testing of a prototype GTI but acceptance testing had not yet taken place.

3.11. AC Substation design

We conducted design studies to investigate whether the GTI could be installed within a standard WPD GRP substation enclosure. Ensuring that GTIs could fit within a GRP substation would support the aim of being able to scale the proposition because of the proportion of our substations that are based on a GRP package template.

We made several key conclusions from this design study. Firstly, we concluded that the cable entry to and from the GTI must be bottom entry rather than top entry. This was for reasons of cable bending radius and the amount of headroom that was available in the GRP. We also observed that GRP structures are not designed to accept cable trays in the roof of the substation, due to the requirement for the roof to lift in the event of an internal explosion.

We also decided that to be able to access all existing and new equipment, a new GRP design would have to be sourced that enabled access on the side and front of the structure. Because of the space constraints within the plots of land that the trial substations were located in, these GRPs would need bi-fold doors instead of our standard swing doors.

This design would have also been dependant on having a sufficiently large plot of land surrounding the GRP to enable the LVAC cable to leave the fuse pillar and GRP, curve around the GRP and then re-enter the GRP and GTI without encroaching on the smallest allowable cable bending radius.

We also reviewed the application of GTIs within GRP substations. Learning from ENWL's Celsius project indicated that ambient temperatures within GRP buildings can reach high temperatures in the summer. In particular, it was observed that 27% of GRP substations would experience an ambient temperature greater than 40 degrees and 1.8% of GRP substations would experience ambient temperatures greater than 50 degrees.

These ambient temperatures were reached without the extra heat output associated with the GTI and the increased transformer loading. For this reason, we adopted the position that forced cooling systems would be required in DC substations located with GRP fabric to keep the GTIs within rated temperature. This would add to the costs of construction.

To deliver the trial, we also reviewed designs for the three other substations. Two of which would have been a bespoke design for installation within a brick substation and the final site would have required a dedicated GRP for the GTI to be installed next to an external unit substation. We observed that the two bespoke designs would always be required should we wish to roll out LVDC equalisation networks, whereas the GRP approach would enable a standardised approach to be pursued.

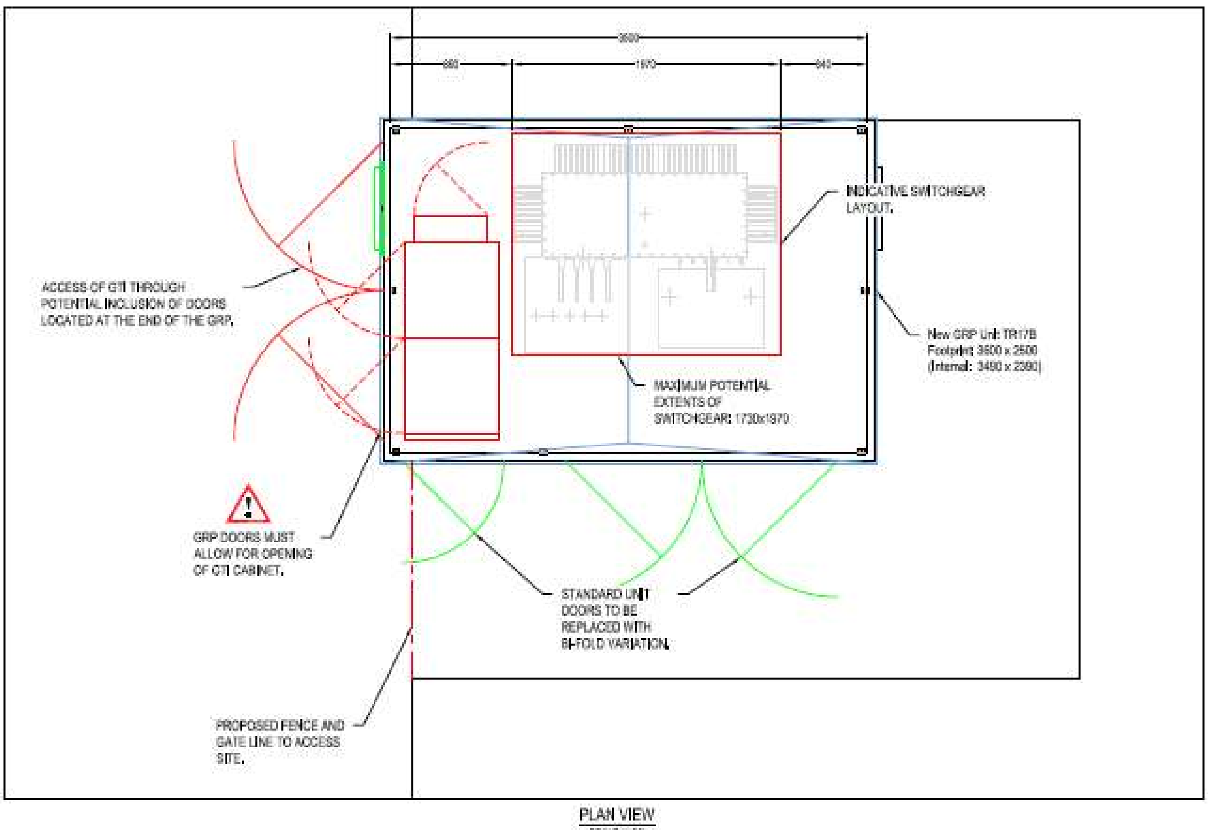


Figure 26: GTI installation in a GRP substation.

3.12. Electric Vehicle Charge Points

The DC Share project team developed a specification for DC connected EV charging points. An overview of the key ratings are summarised in Table 15.

The specification for the DC Connected EVCP contained requirements for:

- Functional requirements
- Mechanical design
- Electrical Protection

- Physical Components
- Commercial systems
- Communications and HMI

This document also contained electrical and thermal analysis to verify the basis of design.

Table 15: Main parameters of the ECVP

Parameter	Value
DC connection voltage	400 V +10%, -6%
AC connection voltage (Auxiliaries)	230 V
Continuous rating	100 kW (although a proportion were to run at 50 kW)
Dielectric voltage withstands	1.8 kV rms
Nominal DC output voltage	200-500V
Switching frequency	>20kHZ
Ambient temperature operating conditions	-20 to 40 degrees
Maximum noise level	56 dB(A) at 5 m
Dimensions (mm)	1800H x 800W x 600D

Figure 27: EVCP in construction in the TPS works

The EVCP design was progressed to the points of prototypes being available in the TPS factory. We one design change was identified that required relating to the presence of the 230V AC socket within the EVCP. The original intention was that a 230V AV socket should be available within each EVCP for testing. The original metering philosophy for the LVDC equalisation network was that there would be metering on the AC terminals of the GTIs, this meant that the 230V AC auxiliary supplies to each EVCP would require individual metering arrangements. The options that we reviewed were either to install one electricity meter per EVCP or to remove the 230V AC socket to enable an unmetered supply to be arranged for the EVCPs. At the time of halting the project, the design intent was to remove the 230V AC socket and use an unmetered supply contract for each EVCP.

3.13. Supervisory Controller

To co-ordinate the overall LVDC equalisation network operation and EVCP demand network a supervisory controller was required.

3.13.1. Supervisory Controller specification and procurement

To be able to procure deliver of the DC Share supervisory controller, a system specification was developed. This specification described the following project requirements:

1. Scope and location overview
2. Project timeline
3. General requirements, standards and service conditions
4. Reliability, availability and performance
5. System architecture
6. Control system hardware
7. Control system software
8. Telecommunications system
9. Cyber security
10. Factory acceptance testing
11. Shipment
12. Warranties and defects
13. Spares
14. Training
15. Documentation

3.13.2. Interfaces and hosting

The supervisory control system was to be located in a secure computer cabinet within Taunton primary substation (Adjacent to the proposed Works GTI substation). The DC Supervisory controller was dependant on the following interfaces to be able to work:

Table 16: Summary of GTI interfaces

Interface system	Description	Data exchanged	Medium
AC Substations, electrical Measurements	Lucy Gridkey LVAC monitors were to be deployed in the interface AC substations. These LVAC monitors were to measure loading on the local transformers. This data would be made available to the DC Share Supervisory Controller	Transformer loading	Direct Ethernet WAN
GTIs	The Supervisory system sends control instructions to each GTI to achieve the overall system goals	Acquisition of status flags Acquisition of measured data Issue of control modes to individual GTIs Issue of set point values to individual GTIs	Direct Ethernet WAN
EVCPs	When there is insufficient capacity on the LVDC	Acquisition of status flags	Direct Ethernet WAN

	equalisation network, the supervisory system curtails power consumed by the EVCPs	Acquisition of measured data Issue of curtailment instructions	
Local human Machine interface	Local computer to enable on-site control and management		
Remote human machine interface	Remote interface to enable review of alarms and control settings	All alarm points All analogue and indication points Access to all control points	The initial recommendation was remote dial in via a VPN

The initial project intention for the remote human machine interface was that this could be a simple remote dial in over a VPN with automated emails or text messages being sent on an alarm condition. As the design phase revealed the operational complexity of operating an LVDC equalisation network, the DC Share project team began to adopt the position that certain alarms and indications needed to be relayed directly to WPD's control room, especially any indications that main protection had failed in service.

3.13.3. Overall functionality

To be able to deliver the required functionality for the LVDC equalisation network, the specification for the supervisory controller set out 28 use-cases that the controller needed to implement, as summarised in Table 16. For each use case the specification provided a description and process flow for how the use case would work.

Table 16: Summary of Controller use cases

Title	Description	Goal
S1: Manual start-up of the DC Share network through the DC Share Visualisation and Control	Describes the actions of the user to start the DC Share network using the Supervisory Controller HMI from the supervisory visualisation and control interface	Sequential starting of the DC Share network equipment
S2: Manual adjustment of the DC Share network thought the DC Share Visualisation and Control	Enables a user to view a visualisation page and options page that allows settings in the control algorithm / GTI set-points to be changed	Manual adjustment of DC Share network parameters
S3: Shutdown of the DC Share network through the DC Share Visualisation and Control	Describes the actions of the user to disconnect the DC Share network using the HMI from the supervisory visualisation and control interface.	Disable the EVCPs and place the GTIs in Off mode to disable the DC Share network.
S4: Reporting of the measurement data to the DC Share Visualisation and Control	Describes the measurement data transfer from the devices on the DC share network to the DC share supervisory controller.	Accurate data transfer between measurement points and the Supervisory controller
S5: User access to the measurement data from the DC Share Visualisation and Control	Details how a user would access and download measurement information collected by the Supervisory Controller	Access to the DC Share network Data Historian
N1: Pre charge the DC cable in normal operation	First step in the re-energisation sequence following disconnection of the DC Share network	DC cable network charged to 550V, with no EVCP load
N2: Energising the DC Voltage to 800V after pre-charge	Second step in the re-energisation sequence following disconnection of the DC Share network	DC Cable charged to 800V and control mode changed to Droop Control

N3: Enabling a GTI when the DC cable is at +-400 Vdc in normal operating conditions	GTI enters Standby Active Mode, AC MCCB is closed, and the GTI synchronises to the AC network.	GTIs running on no load
N4: GTI enters standby due to no EV charging or power transfer through the DC network in normal operating conditions	GTIs enter Standby Mode due to no load on the DC Share network	Reduction of GTI losses
N5: Discharge the DC cable in normal operation	Sequence to shut down the DC Share Network under no load conditions	DC cable discharged and GTIs disconnected from the AC network
N6: Interface for charging EV with communications	Management of Charging Events on DC Share EVCPs	EV charging is managed
N7: Calculating if limits are exceeded	Use of measured data to calculate power flows on the DC Share equipment	Accurate determination of power flows
N8: Responding to limits at the AC substation or DC network	Reduction in EVCP load or change of GTI loading in response to power flow limits	Equipment loading is kept within safe operating limits
N9: Algorithm for reducing EVCP demand	Reduction in EVCP demand through instruction from the supervisory controller in response to equipment loading calculation	Reduced DC Share network demand
N10: Increasing the maximum charging demand at an EVCP	Reinstatement of maximum charging rate available following a demand reduction event	Increased DC Share network demand
N11: Disabling the EVCP	An EVCP is removed from operation	Termination of charging event at an EVCP, and disablement
N12: EV charging load shared equally among GTIs	All connected GTIs are instructed to transfer power to the DC network to the same level	GTIs sharing EVCP demand equally
N13: EV charging shared depending on AC substation utilisation	The substations with the lowest utilisation are used to supply a greater share of the EVCP demand. The substation with the highest utilisation will be used to supply the least EVCP demand.	GTIs sharing EVCP demand in accordance with the conventional loading at each substation.
N14: Equalising the AC substation loads through the DC network	The load from the EVCP and the load at the AC substations is equalised through the DC network such that every transformer in the network is operating at the same utilisation	Uniform substation utilisation
N15: Minimising DC cable and GTI losses for EVCP load	The GTI droop setting or PQ set-points are altered to share power of the EVCP load to minimise the DC cable and GTI losses	Optimal network condition to minimise losses
N16: Calculating optimal number of GTIs required on the DC network	Sequence for progressive energisation of GTIs to keep the number connected to a minimum	Minimisation of the number of connected GTIs
N17: Phase balancing at an AC substation	GTIs change the power exported or imported on each of the phases to remove any power imbalance at the substation	Equal phase loading
F1: Pre charge the DC cable with a DC fault	Pre-charge of the DC cable with a faulted section of cable isolated via the DC Isolators	DC Cable pre-charged with faulted leg isolated

F2: DC cable fault	Detection of a DC cable fault and communication to GTIs to shut down.	Rapid detection and isolation of DC cable faults.
F3: Identifying the faulted section of DC cable	An engineer uses DC cable fault finding equipment to identify the faulted section of DC cable	Identification of faulted DC Cable section
F4: GTI fault	Detection of GTI fault, shutdown of all GTIs, disconnection from the AC network of the faulted GTI via its MCCB and lockout to prevent re-energisation	GTI fault detected and isolated
F5: EVCP fault	For a fault an EVCP, the EVCP should detect it has an internal fault and disconnect. An alarm should be sent to the Supervisory Controller to allow the alarm to be saved in the event historian.	EVCP fault detected and isolated

The process flow for each use case was described using an intention description and also a logical flow diagram, as shown in Figure 28 and Figure 29.

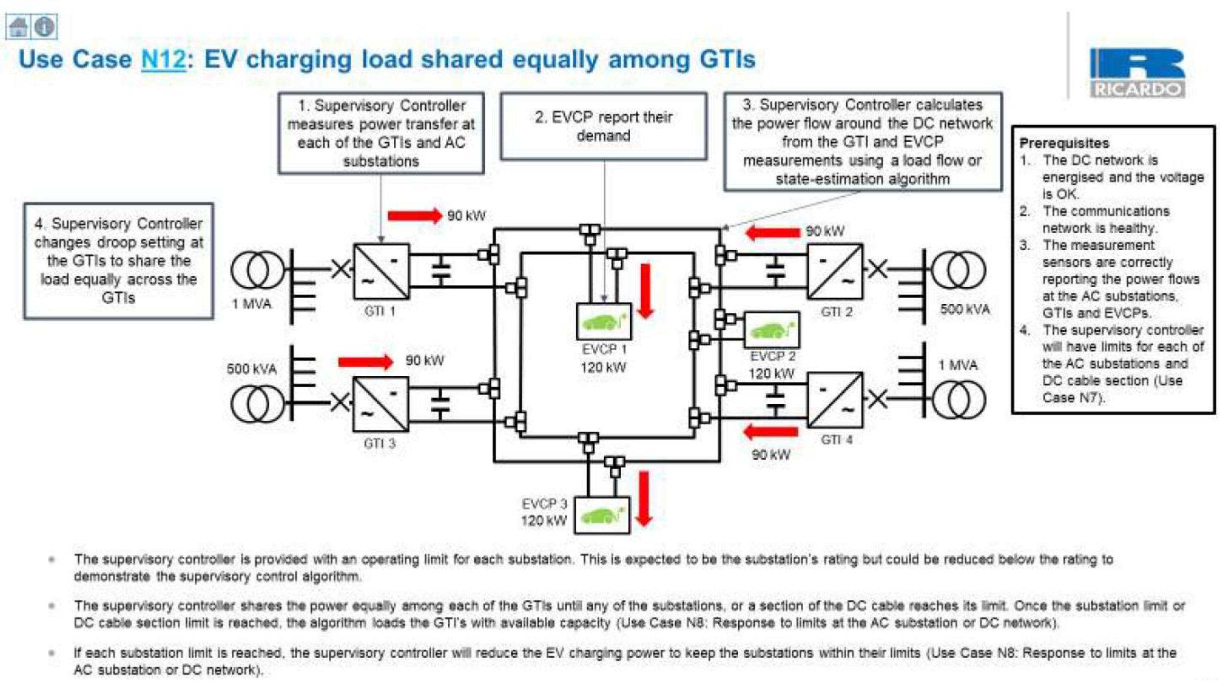


Figure 28: Example use case description (for Use case N12)

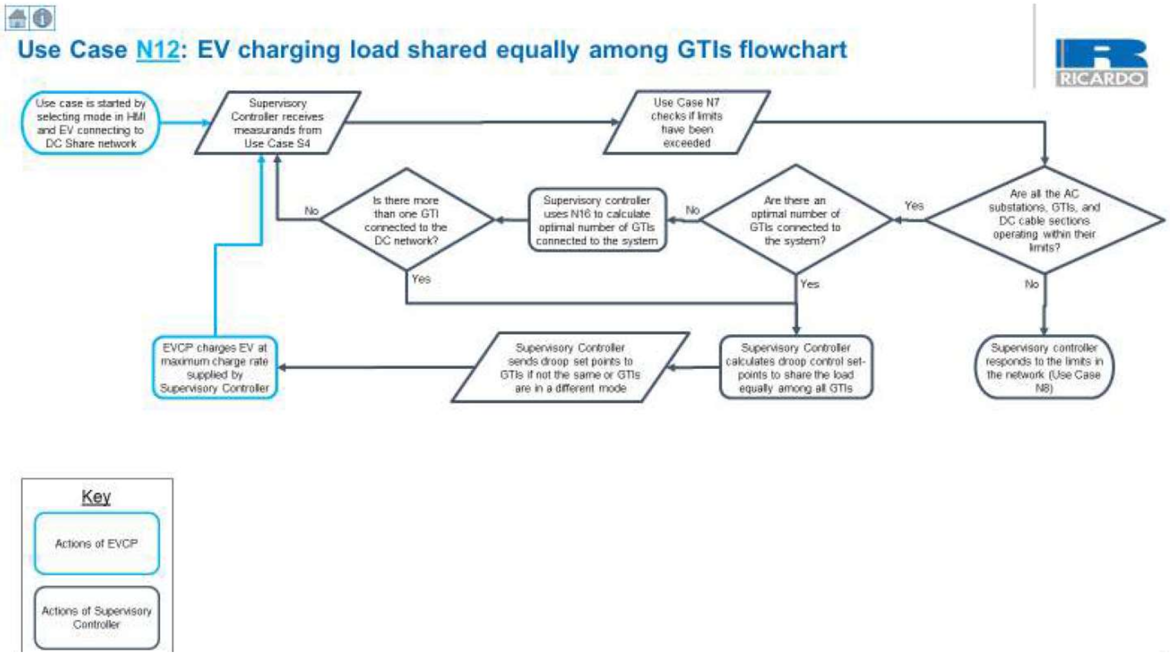


Figure 29: Example logical flow diagram (for Use case N12)

To enable the supervisory controller to co-ordinate use of each of the use cases a compatibility matrix was developed to instruct the controller as to which use cases needed to work simultaneously. This matrix is shown in Figure 30.

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Transforming the electricity network

Use Case Matrix

Use Case	Name	Prerequisite	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19
		Priority																			
			Pre-charge the DC cable in normal operation	Energising the DC Voltage to 800 Vdc after pre-charge	Enabling a GTI when the DC cable is at +-400 Vdc in normal operating conditions	GTI enters standby due to no EV charging or power transfer through the DC network in normal operating conditions	Discharge the DC cable in normal operation	Interface for charging EV with communications	Calculating if limits are exceeded	Responding to limits at the AC substation or DC network	Algorithm for reducing EVCP demand	Increasing the maximum charging demand at an EVCP	Disabling the EVCP	EV charging load shared equally among GTIs	EV charging shared depending on AC substation utilisation	Equalising the AC substation loads through the DC network	Minimising DC cable and GTI losses for EVCP load	Calculating optimal number of GTIs required on the DC network	Phase balancing at an AC substation	Power factor control at an AC substation (reactive power)	Voltage support at the AC substation
N1	Pre-charge the DC cable in normal operation																				
N2	Energising the DC Voltage to 800 Vdc after pre-charge	N1																			
N3	Enabling a GTI when the DC cable is at +-400 Vdc in normal operati	N2												N3	N3	N3	N3	N3	N3	N3	N3
N4	GTI enters standby due to no EV charging or power transfer through the DC network in normal operatin						s			N8				N4	N4	N4	N4	N4	N4	N4	N4
N5	Discharge the DC cable in normal operation	N11											N11								
N6	Interface for charging EV with communications									N8	N9	N10	N11								
N7	Calculating if limits are exceeded																				
N8	Responding to limits at the AC substation or DC network	N7				N8		N8			N8	N8	N11	N8	N8	N8	N8	N8	N8	N8	N8
N9	Algorithm for reducing EVCP demand	N6, N8						N9		N8		N9	N11								
N10	Increasing the maximum charging demand at an EVCP	N6						N10		N8	N9		N11								
N11	Disabling the EVCP						N11	N11		N11	N11	N11									
N12	EV charging load shared equally among GTIs				N3	N4				N8								N16	N12	N12	N19
N13	EV charging shared depending on AC substation utilisation				N3	N4				N8								N16	N13	N13	N19
N14	Equalising the AC substation loads through the DC network				N3	N4				N8								N16	N14	N14	N19
N15	Minimising DC cable and GTI losses for EVCP load				N3	N4				N8								N16	N15	N15	N19
N16	Calculating optimal number of GTIs required on the DC network				N3	N4				N8				N16	N16	N16	N16		N17	N18	N19
N17	Phase balancing at an AC substation				N3	N4				N8				N12	N13	N14	N15	N17		N17	N19
N18	Power factor control at an AC substation (reactive power)				N3	N4				N8				N12	N13	N14	N15	N18	N17		N19
N19	Voltage support at the AC substation				N3	N4				N8				N19	N19	N19	N19	N19	N19	N19	

Key

(grey)	No parallel operation / user selects
(green)	Use cases can operation in parallel no conflict
Nxx	Potential use case conflict, use case in box takes priority

Figure 30: Supervisory controller use case compatibility matrix

3.13.4. Supervisory Controller development

During the design stage of the project, we conducted works to deliver the Supervisory Controller. The first activity on this work stream was to develop a functional specification describing what the Supervisory controller should do to enable a competitive tender for selection of the system provider. This tender took place across Q4 2020. As a result of this tendering process, Lucy Electric UK were selected as the control system supplier in Q1 2021.

Prior to further development work, Lucy Electric issued a detailed functional design specification document in Q2 2021. This document confirmed key details and design intentions, including system architecture as summarised in Figure 31, communications architecture as summarised in Figure 32. This document also set out the design and performance expectations for the following headings:

1. System Architecture
2. Communication Architecture
3. Hardware and Software Specifications
4. Gemini SCADA system specification
5. Signal list
6. Quality
7. Cyber Security
8. FAT testing
9. SAT testing
10. Warranty

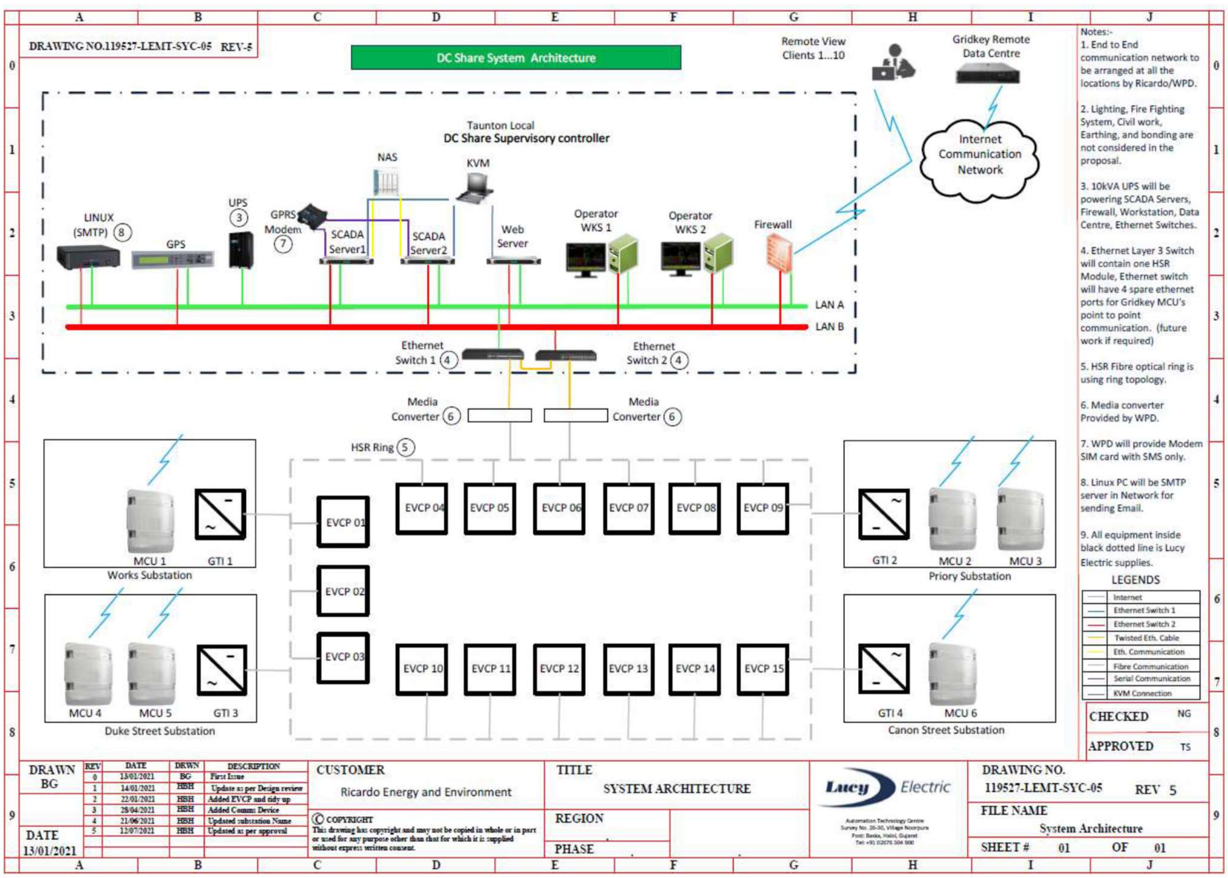

Figure 31. Supervisory Controller system Architecture

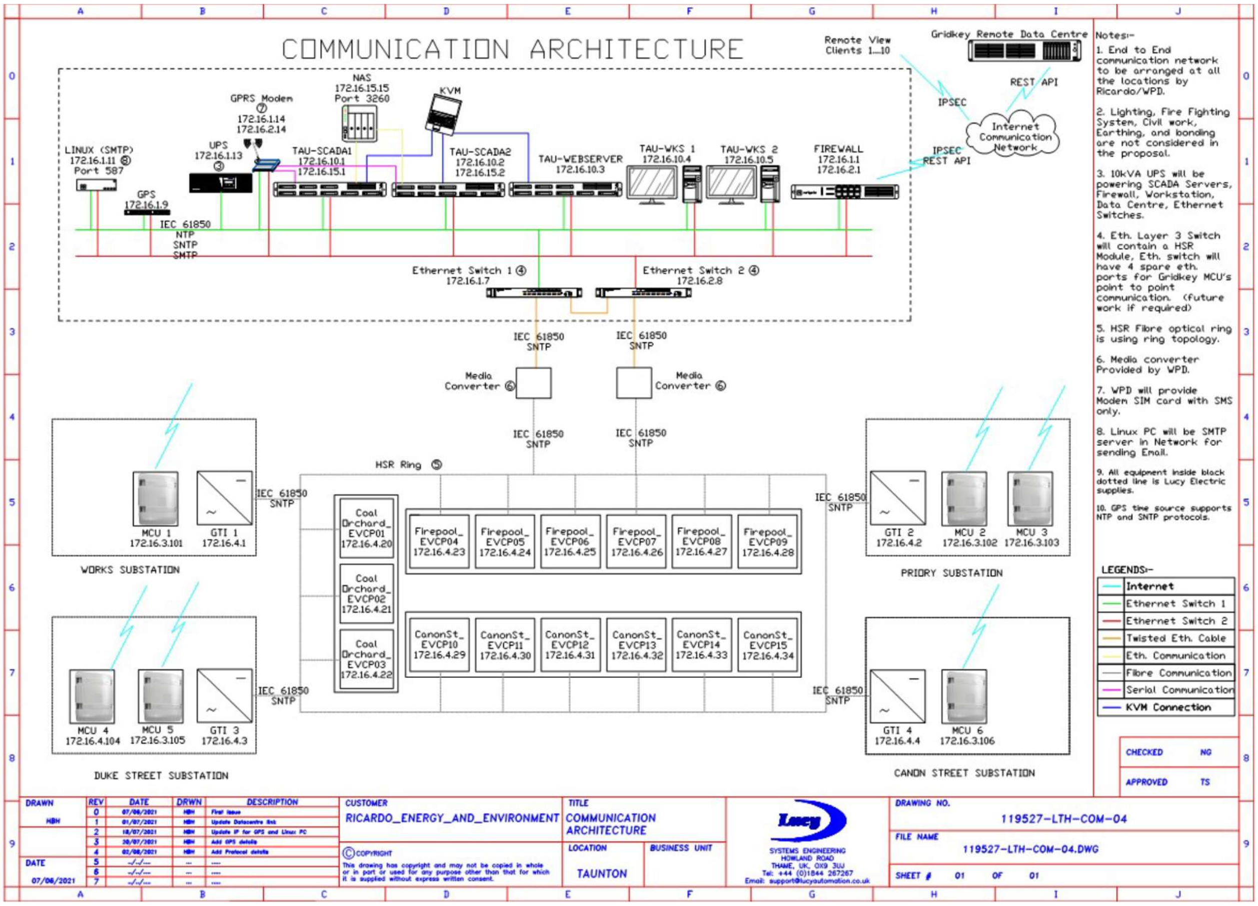

Figure 32. Supervisory Controller Communications system Architecture

Development also began on developing the control screens that would be used as a human machine interface. These screens were numerous and one of which is illustrated in Figure 33.

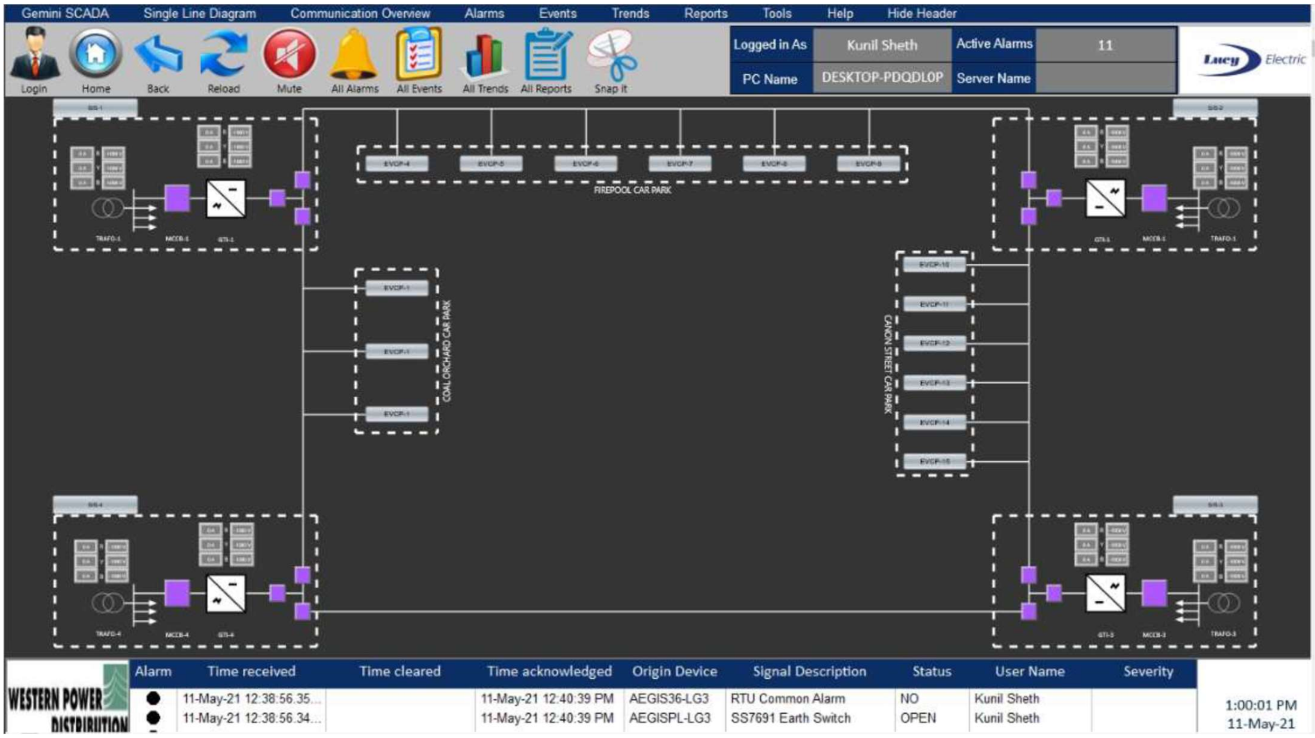

Figure 33. Network Overview Control scheme (Typical)

3.14. Metering

Part of the concept behind LVDC equalisation networks was that in addition to equalisation of AC substations, customers would be able to connect to the DC cables. At the FSP stage, it was recognised that the UK industry had no capability for metering of DC supplies to customers, hence the project intention was to place settlement meters on the AC side of the GTIs and explore the application of DC meters on each of the EV chargers.

Pursuant to this intention, we specified that each EVCP should be able to comply with the following requirements:

- Be able to measure up to 600 Amps of current
- Be able to withstand up to 1000V DC
- Be able to communicate with the charge controller

3.15. Curtailment estimation

3.15.1. Underlying Customer demographic

To understand the reliability of the capacity mechanisim and how the demographic of customers influence the we reviewed the amount of capacity that would be released and how reliably this could be predicted and repeated across the network.

The results of this analysis in were influenced by the demographic of substations around Taunton town centre. Table 17 provides an overview of the customer makeup at these substations. These figures help explain the drivers of the the observed load cycles. It is notable the majority of customers connected were domestic and this is reflected in and the four daily load profiles for the DC Share substations. From the daily load cycles it can be seen that the Priory and Canon Street substations have a strong domestic load cycle pattern, whereas Works and Canon St and St

Augustine's are of a much more commercial pattern, but constituting a much lower contribution to the overall load in the area.

We believe that review of the demographic of our ground-mounted substations would indicated that the majority were skewed towards the domestic demographic. Some data sets indicate that may be applicable to 50% or less of WPD's substation demographic, with the remainder being purely domestic. Analysis in the next section discussed the effect of load profiles of increasing similarity.

Table 17. Summary of customer demographic across DC Share substations

	Domestic customers	Non-domestic customer[3]	Maximum demand metered customers[4]
Works	103	59	0
St Augustine's	50	9	2
Canon Street	31	12	3
Priory	267	17	0
Total	**451**	**97**	**5**

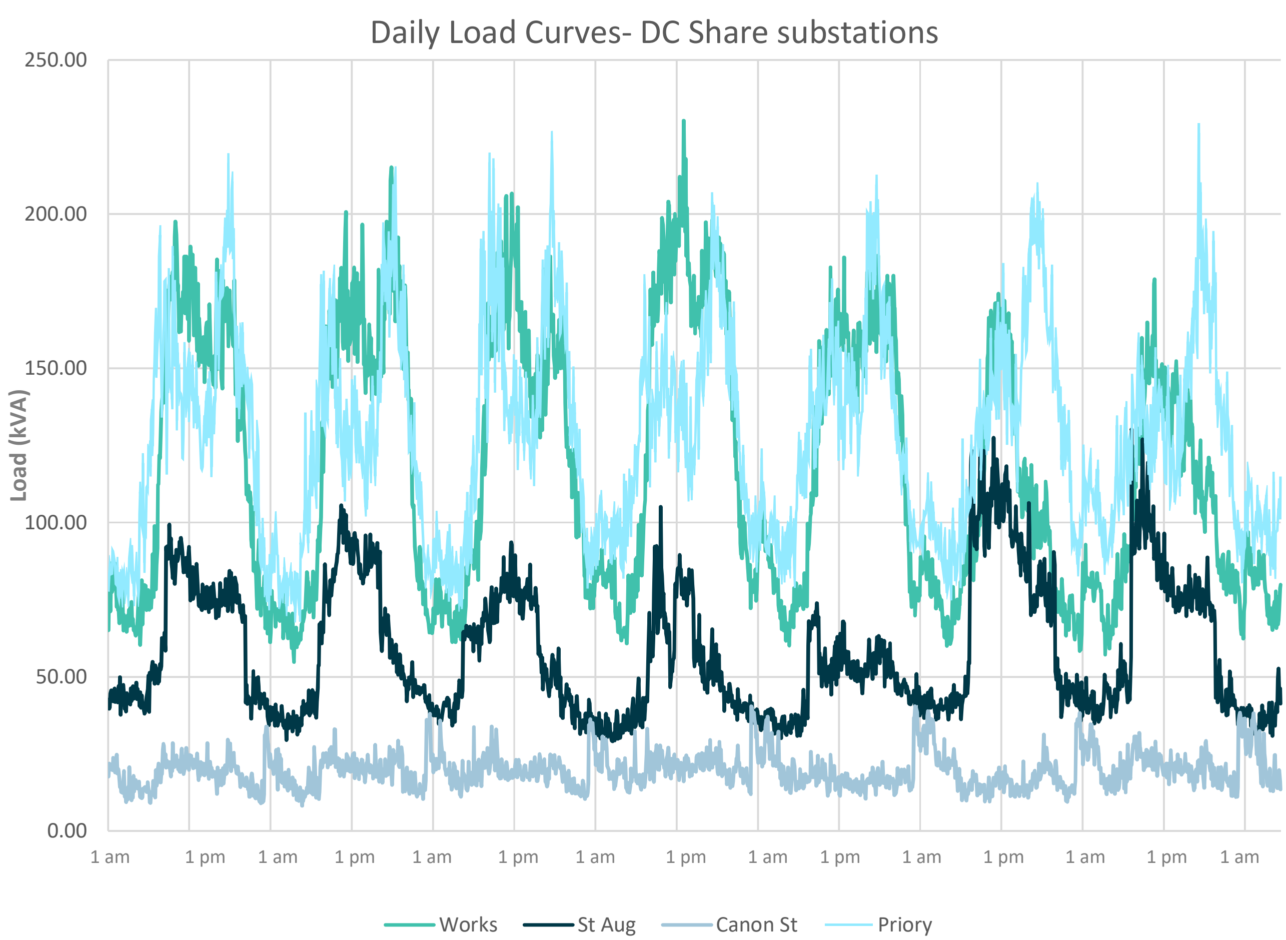

Figure 34: Comparison of daily load cycles in the DC Share network

[3] e.g. small offices, small shops community halls etc
[4] Customers with a maximum demand greater than 45 kVA

Because not all substations will have LVAC monitors in the future, we conducted an exercise to assess whether estimation of substation demand profiles from MPAN data and standard settlement profiles was an effective means to screen for which substations. Because settlement profiles do not typically discuss diversity patterns, we concluded that using MPAN data as an initial feasibility screen for prospective LVDC infeed substations was unlikely to be reliable. This was because this methodology would only reveal the substations that had spare headroom rather than the combination of substations that have complementary diversity patterns. The implication of this is that the only reliable methodology for deciding which combinations of substations is to install LVAC monitors and conduct a monitoring campaign before deciding which substations were good candidates for participation,

3.15.2. Curtailment estimate

The FSP recorded an assumption that the expected uplift per DC Share installation would be 1,110 kVA. To understand how effective four ended LVDC equalisation network would be in sharing untapped capacity an exercise was undertaken to simulate the capacity that would be released.

We did this by using the actual daily load profiles that we measured at each of the DC Share substations, but scaled up to simulate that each of the four substations were already at nameplate capacity (otherwise the existing headroom would be confused with capacity released through sharing). In addition, the capacity that was made available was limited to the capacity of the GTIs that would undertake the AC to DC transformation. The results from this analysis are shown in the probability distribution depicted in Figure 35

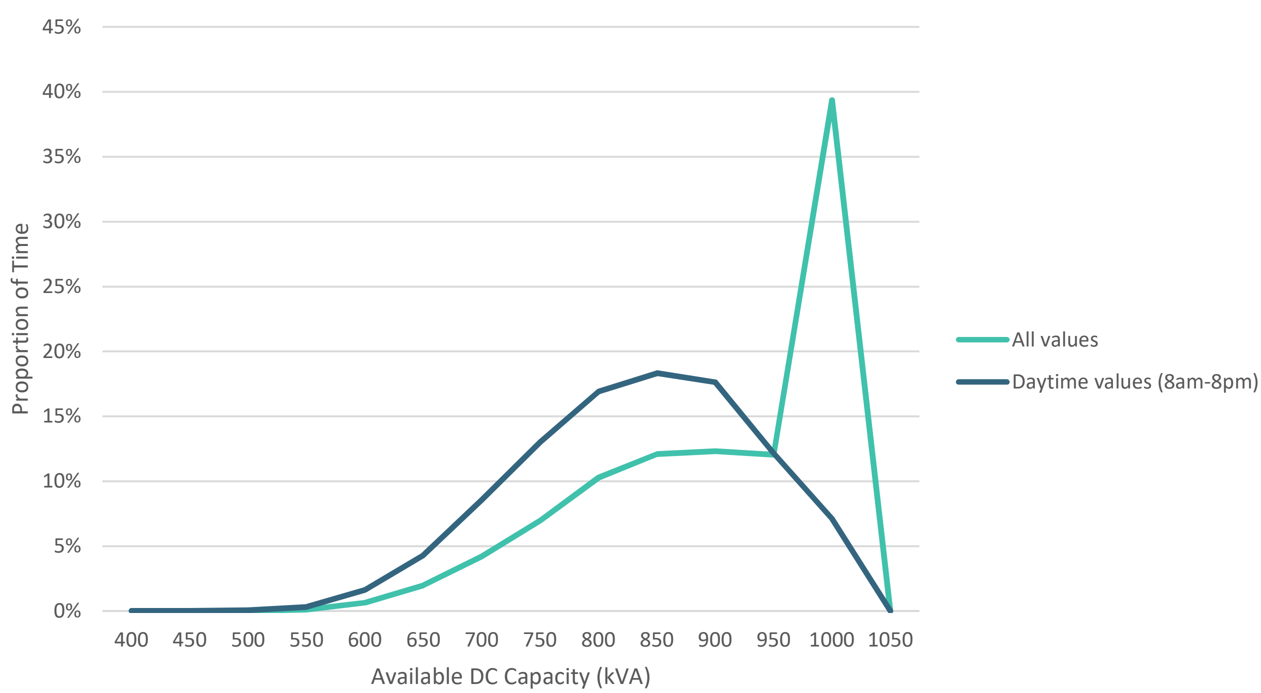

Figure 35: Histogram of endurance of available capacity to LVDC customers

During the daytime (8AM until 8PM), the available capacity would be beneath 814 kVA for 50% of time, beneath 739 kVA for 25% of time and beneath 676 kVA for 10% of the time despite the fact there was an installed capacity of 1000 kVA. The amount of capacity that was available in other LVDC equalisation networks would be dependent on the specific customer demographic.

3.15.3. Different equalisation network configurations and effect of demographic

A further analysis was undertaken to understand how the probability distribution for available capacity would change if the LVDC equalisation network was based on a smaller template (i.e. two infeed's rather than four). This analysis considered the effect of creating the equalisation network based on the two most diverse substation load profiles and the two least diverse substation load profiles and also compared these results against the capacity created in a four infeed equalisation network. These results are summarised in Table 18.

This shows that in general, the larger the LVDC equalisation network, the more enduring the capacity will be over time. This also shows that selecting similar substations does not have much effect on the larger percentile markers, but the least diverse LVDC equalisation networks will experience more extreme curtailment for shorter periods of time.

Table 18: Comparison of capacity available histogram under different configurations

Percentile point	Capacity of a 4 infeed equalisation network. (8am-8pm) (% of installed GTI capacity)	Capacity of a 2 infeed equalisation network using the least diverse substations. (8am-8pm) (% of installed GTI capacity)	Capacity of a 2 infeed equalisation network using the most diverse substation (8am-8pm) (% of installed GTI capacity)
90th percentile	93%	89%	90%
75th percentile	88%	82%	85%
50th percentile	81%	73%	77%
25th percentile	74%	64%	71%
10th percentile	67%	55%	65%

This analysis shows that there is likely to be an effect within the application of LVDC equalisation network which means that customers connected to bigger equalisation networks will have better access to the capacity before curtailment.

This analysis also shows that the capacity that may be available in an equalisation network is not always predictable and will be influenced by the existing customer demographics within each substation. Customers connected to a diverse set of substations, would be benefit from between 5-10% more capacity availability than in situations where substations where existing customers were similar. It should also be understood that as there was load growth within the properties of existing customers, this available capacity would reduce, resulting in greater levels of curtailment for the now incumbent DC customers.

This learning highlights a particular challenge with offering customers capacity on the basis of DC Share. This challenge LVDC equalisation networks work by rationing out the remaining capacity rather than boosting capacity in an area. This means that customers dependant on an equalisation network would need to be confident in the amount of curtailment to verify their business case for development. The host DNO would not be able to help them verify this unless there had been a long term monitoring campaign prior to construction. Because LV substations typically do not have monitoring, these would have to be fitted ahead of need.

Reviewing this difficulty in light of the recent decision to socialise all demand led reinforcement and limit curtailment, it becomes apparent that the DNO would need to be able to predict and eventually remove the need to curtail. This would require reinforcement of the LVDC equalisation network, but as shown previous sections, existing substations have limited space for addition of additional plant and the protection philosophy has limited scope for increased cable distance.

4. Updated Business Case and lessons learnt for the Method

Prior to committing to project construction, we reviewed the DC Share business case against the initial aims. This business case was updated to recognise the learning gathered during the design stage. To do this, we compared the cost and timescales for conventional BAU connections against the method case.

4.1. Lessons learnt that impact upon the business case.

In this section, we highlight the key learning that justified an update of the structure, or assumptions within the base case.

4.1.1. Updated view of base case

Since 2019, the volume of connections for clusters of rapid chargers have grown from few instances, to become regular part of the connections sector. This has allowed us to update the business as usual costs beyond the FSP assumption.

We observe that it is common for new connections to rapid charging clusters to be delivered by an Independent connections provider. We also observe that there is a preference to have a HV point of connection, with the EV clusters fed from a dedicated HV/LV substation located on land provided by the EV cluster developer adjacent to the chargers. We believe that this is partly due to ease of construction, but mostly because this form of scheme design has grown to be the least cost connection for the customers' needs in comparison to an LV point of connection. We believe that connection projects of this nature can be delivered within 3 to 9 months from offer.

4.1.2. Learning regarding the method case

Since embarking on the design of the DC Share project, we have learnt more about the cost base requirements to establish a DC equalisation network, including:

1. In 60% of instances, the LV point of connection will require remodelling, at a cost of between £6k and £25k not including the cost of any cooling or land purchases that would be required.
2. It would be prudent to allow for a proportion of the cable route to be installed in the public carriageway.
3. To have an equivalent resilience of supply to a BAU connection, the infeed's into the equalisation network need additional redundancy).

4.1.3. Learning regarding alternative innovations

Since the commencement of the DC Share project, two NIC projects fully delivered their output. These two projects were WPD's OpenLV project and ENWL's Celsius project. Both of these projects investigated the use of site-specific thermal ratings on HV/LV transformers. Both of these projects demonstrated that this technique could release significant additional capacity in HV to LV transformers. As an example, the Celsius project indicated that in a population of transformers:

- 40% of the HV/LV transformers could carry greater than 130% of nominal rating
- 38% of HV/LV transformers sites could have a rating enhancement of between 110% and 120% of nominal rating. The OpenLV project projected similar learning.

This learning is significant for two reasons. Firstly, it indicates an alternative path to avoid reinforcement of the HV/LV transformers (which was one of the value streams that DC Share intended to respond to). Secondly, to deliver site specific ratings, exactly the same kind of LV monitors would be required to be fitted to the substations, that would be required to device it sites were able to participate in a DC equalisation network.

To deliver the capability, the host DNO would be required to install a monitoring device in the substation with a suitable thermal ratings app loaded within it. These devices are laptop computer size and can be retrofitted into existing substations. Experience shows that WPD can install these in ground-mounted substations with few exceptions. We have already committed to install significant numbers of these monitors into our substations across RIIO ED2.

The lack of engineering complexity to deliver this capacity uplift should be contrasted against the learning in described in other sections to deliver LVDC equalisation networks.

This exercise presented learning that there are different approaches to release HV/LV transformer capacity to customers.

It should also be understood from 4.15 that before an LVDC equalisation network could be constructed, a monitoring campaign would have to be undertaken using the same technology that could deliver site-specific thermal ratings. This means that HV/LV transformer capacity uplift could be delivered without having to commit to the engineering tasks described in 3.1and 3.3. This approach could also be delivered without the complexity of combining different load profiles described in 3.4.Figure 3

The cost of procuring the infrastructure required for this approach to increasing HV/LV capacity would be less than £5k per installation and would provide additional benefits in addition to the capacity uplift.

We believe that this is relevant learning to the DC Share project as it shows how significant capacity uplift on HV/LV transformers can be released, without having to resort the expense of creating an LVDC equalisation network or installing GTI's in substations. This technology can also be easily installed into existing HV/LV substations because of their small size. This observation illustrates the importance of ensuring that LVDC equalisation networks is contrasted against the results from other NIC projects that have recently published their final learning.

4.2. Updated business case

In this section we compare the updated cost of business as usual costs versus the method costs.

4.2.1. Business as usual connections.

To reflect the learning stated in 5.1.1, we updated the base case cost assumptions as per Table 19.

Table 19: updated cost assumptions for the business as usual case

Cost heading	Low cost range	High cost range
New HV/LV substation (500-1000 kVA of capacity)	£40,500	£50,000[5]
HV cable and route (per metre)	£95	£152[6]
Assumed HV connection distance to POC (per HV/LV substation)	33 Metres	200 Metres
Cost per connection	£43,635	£80,400
Cost per 1000 kVA of load (Three connections)	£130,905	£241,200

To deliver 1000 kVA of capacity across three connection sites, we believe that the total cost of the connection assets would be in the range of £130k to £241k.

[5] We acknowledge that WPD's connections and charging methodology publishes a maximum cost of £105k to establish a connection including a new HV/LV substation. We have not used this cost base as we wished to separate out the pure substation cost for this analysis

[6] This is reflective of 100% of the cable route being installed in Class 2 public carriageway, which is an unrealistic, but pessimistic assumption. This assumption is also more onerous than LVDC cable which only assumed 33% of the cable route would be in the carriageway

4.2.2. Method Case connection assumptions

In the FSP, it was assumed that the method case for a DC equalisation network would be £664k to feed 2150 kVA of rapid charging demand. This would comprise of the following infrastructure:

- Five Grid Tied Inverters to convert AC to DC
- Connections into five existing HV/LV substations
- 1000 metres of DC Cable

Since embarking on the design of the DC Share project, we have learnt more about the cost base requirements to establish a DC equalisation network, including:

- In 60% of instances, the LV point of connection will require remodelling, at a cost of between £6k and £25k.
- It would be prudent to allow for a proportion of the cable route to be installed in the public carriageway. Our work on the DC Share cable routes indicated that 33% carriageway installation would be required.
- To have an equivalent resilience of supply to a BAU connection, the infeed's into the mesh need additional redundancy (as per 4.7).
- There is not yet a clear indication of what the mature cost for a GTI would be.

Table 20: Updated assumptions and structure for the method case

Cost Headings	Low range costs	High range costs
DC Cable and route (per metre)	£77	£122[7]
Cost per GTI	£40k[8]	£59k
Cost of Substation remodelling (expected in 60% of cases)	£6k	£25k
Cable route distance (per infeed)	280 Metres	400 Metres
Cost of DC Supervisory system	Ignored to assess best case competitiveness of LVDC equalisation networks	
Proportion of substations with sufficient land to host a GTI.	We demonstrated in 4.2 that 68% of substations had insufficient space or land issues to be able to host a GTI. This factor has been ignored to assess the best case competitiveness of LVDC equalisation networks, but it is a significant barrier to roll out.	
Total cost (4 GTI network)	£260k	£491k
Total cost (5 GTI network)	£325k	£614k

A 1000 kVA four-ended LVDC equalisation network could be constructed at a cost between £260k and £491k, but customers would have to agree to have their capacity curtailed and accept a lower level of network security than BAU connections[9] . This also assumes that adequate protection coverage can be engineered, but as discussed in 4.8, there is concern that this may not always be achievable at large geographic footprints.

To deliver 1000 kVA of installed capacity on an equivalent level of service to the BAU base case, we believe that five DC installations would be required. This is due to the project learnings regarding resilience of supply) and capacity creation. The cost of delivering the capacity on this basis would be in the region of £325k to £614k.

[7] This is reflective of installation of 33% of the cable route in Class 2 public carriageway. The per-unit cost difference between installation in the footpaths and carriageway is 194%. This value of £122 per metre could easily increase in congested urban environments if more carriageway installation is required.

[8] Engagement with the supply chain indicates that at a substantial market scale for GTIs then the price could reduce, but there is not a committed position from the supply chain as to what the price could be. We have used a mid-range value of £40k to represent some, but not total, economy of scale.

[9] A four GTI LVDC equalisation network feeding 1000 kVA would completely collapse after the loss of a GTI. A five GTI LVDC equalisation network feeding 1000 kVA would withstand the loss of one GTI. BAU connections would limit the load at single point loss to the amount of EVCP per transformer.

4.2.3. Comparison of BAU to Method case.

Comparison of the base case against the method case costs demonstrates the following outcomes, as summarised in Table 21. This comparison leads to the conclusion that LVDC equalisation networks do not support faster, cheaper or more reliable capacity for customers.

Table 21: Comparison of base case against updated method case costs

Case	Low range cost base	High range cost base+	Connection time
Base Case (HV points of connection)	£129k	£241k	3-9 months
Method Case (LVDC equalisation networks)			
- With curtailment risk and reduced security of supply	£260k	£491k	> 12 months
- With equivalent capacity-firmness and security of supply equivalent to the base case	£325k	£614k	> 12 months

We acknowledge in that in 4.10 that we discussed whether removing the neutral link cabinet would have reduced the cost of the equalisation network to become break even with the base case. We do not think this would have resolved the fundamental problem of LVDC equalisation networks being more expensive than BAU. This is because the incremental cabling cost to establish the interconnecting DC cable is more expensive than the value of the GTIs. Because the cost of the LVDC equalisation network is dominated by the cable cost, it means that even if economies are made in the GTI supply, BAU solutions will remain cheaper to do the reduced exposure to long LVDC cable routes.

5. The outcomes of the Project

The work conducted in section 4 and the updated business case in 5 enabled us to review whether LVDC equalisation networks were likely to be applied on the network.

We reviewed the prospect of LVDC equalisation networks against the following use cases

5.1. Key outcomes and observations

Because of the work completed in section 4, we were able to distil our learning about LVDC equalisation networks into the following insights about their application.

5.1.1. Enablers prior to the decision to build an equalisation network

As shown in 4.15, the amount of capacity that is available in an LVDC equalisation network is dependent on the demographic of the customers, but also that it is essential to know the detail of the daily load cycles before understanding how much capacity is available across a selection of substations.

As also shown in 4.15, we showed that use of a simple model use typical MPAN settlement profiles is an unreliable method to estimate the capacity available in for an Equalisation network as it tends to underestimate the capacity available for sharing.

This means that to be able to deliver LVDC equalisation networks at scale, there would be a dependency to have measured the daily load profiles of candidate substations before deciding which substations shall for the equalisation network. Because estimation of load profiles based on settlement profiles is unreliable, it means that LVAC modelling needs to have been in place at candidate substations for a suitable period of time to fingerprint the capacity available for sharing.

This in effect means that an enabler for LVDC equalisation networks is to have LVAC substation monitoring in place to be able to decide whether an LVDC equalisation network would make sense. WPD's position on LVAC monitoring is that we believe it adds value at sites that are at high risk of having their ratings exceeded, but installing monitoring at sites that are likely to remain underutilised is a poor use of customer money.

In addition to the need for visibility of LVAC load profiles, we believe that DNO's would need to work with suppliers to establish a new capability to be able to model load flows and fault levels within potential LVDC equalisation networks.

5.1.2. The need for the right substation fabric, in the right location with the right type of capacity

The work done to date demonstrates that delivery of an LVDC equalisation network requires several conflicting factors to be resolved.

- The LVDC equalisation network needs to be proximate to where developers would like to construct EVCPs. Outside of trials, this is not something we would typically expect the DNO to have direction influence over.
- In section 4.6 we demonstrated the practical problems of installing the DC cable route across a town centre. In particular, it was observed that substations that look promising from a fabric perspective, may have a challenging cable route
- In section 4.8 we demonstrated that the protection philosophy will place a limit on the total amount of cable that can be allowed in an LVDC equalisation network. This is in tension with the cable route logistics needing to circumvent engineering obstacles by going around them.
- In section 4.2 we demonstrated that less than one in in two substations will be able to host the infrastructure required to convert AC to DC electricity. This will mean that the LVDC equalisation network will need a bigger footprint to connect the substations that can host GTIs. This is in tension with the protection philosophy need to restrict maximum circuit length to be able to link up with substations that have sufficient space or assets.

- In Section 4.15, we demonstrate that not all substations will have the right load profile for equalisation. This will be tension with the protection philosophy's need to limit cable route length.

We believe that these tensions make the prospect of LVDC equalisation networks unsuited to mass application.

5.1.3. Efficient network development

The minimum commitment that can be made towards an LVDC equalisation network would be installation of two GTIs at two substations, one supervisory controller and the DC cabling, in addition to any EVCP. This would be required, even if there is only one overloaded substation or EVCP site requiring connection.

We also believe that the maximum footprint allowable footprint of a LVDC equalisation network would be in the region of a maximum cable route of 1227 metres, after which a new and separate LVDC equalisation network would need to be established to avoid insufficient protection coverage.

These limitations do not leave much flexibility for development of the equalisation network in between the two extremes.

As also shown, LVDC equalisation networks will require EVCP customers to accept a certain level of curtailment. Any load growth or new connections on the AC side of the infeeding substations will increase the amount of curtailment experienced by EVCP over time. In the event that the curtailment experienced becomes untenable, the only strategy that the DNO will have will be to either reinforce the existing HV/LV transformers or alternatively establish new HV/LV transformer substations to relieve the existing substations.

As shown in 5.2, the BAU solutions which establish new HV/LV transformers in first place are cheaper upfront. As a result, we consider that selecting an LVDC equalisation network as the first step in the network development path leads to the greatest potential investment regret, rather than the minimising the investment regret.

5.1.4. Customer proposition

We have shown that use of LV equalisation networks and DC connected EVCP does no not necessarily provide an equivalent level of service to BAU connections. In particular:

1. LVDC equalisation networks are likely to provide a slower connection than comparable BAU connections with a greater delivery risk.
2. LVDC equalisation networks are likely to provide a more expensive overall connection scheme than an equivalent BAU connection.
3. LVDC equalisation networks will not have the same level of redundancy as a BAU connection with equivalent capacity
4. LVDC equalisation will require the capability to curtail customers.

It should be remembered the DC Share project was commissioned prior to the output of the Significant Code Review (SCR) regarding system access and charging. This means that the customer barriers that DC Share sought to respond to have moved significantly. Firstly, in the FSP it was assumed that EV charge point developers would have to fund any reinforcement but as a result of the SCR, all reinforcement costs for EV demand will be socialised. This means that the upfront cost of reinforcement expected by EVCP developers will be approximate to the connection assets. The FSP also assumed that it would be acceptable for the DNO to curtail customers if they didn't wish to fund reinforcement. As a result of the SCR, DNO's will now be required to set a limit to the amount of curtailment a customer will experience. Both of these changes substantially alter the aims of the original DC Share FSP. This is because reinforcement cost socialisation mean that traditional reinforcement approaches are no longer the barrier to decarbonisation that they were.

The requirement for DNO's to limit the curtailment experience would make the use of LVDC equalisation networks problematic because there would need to be a development strategy to reduce curtailment. As shown section 4.8, the protection system will limit expansion of the equalisation network meaning it is unlikely additional DC cable route and GTI's can be added. Therefore, the only strategy the DNO would have to reduce curtailment would be to create new

HV/LV AC substations and construct new AC cable routes to transfer the incumbent AC load across to these new substations

6. Performance compared to the original Project aims, objectives and SDRC/Project Deliverables

This section provides a comparison of the work that we completed against the demonstrations and deliverables that were stated in the FSP. Because the DC Share project was halted before the end of the project, we clarify which topics were completed and those which were scheduled to take place after the request to halt.

6.1. Project Demonstrations

In the FSP, a commitment was made to deliver certain demonstrations. In sections 7.1.1 to 7.1.4 we review the intention against the outcome.

6.1.1. Control System

Demonstration 1
A new control system will be required to manage the DC Share system, incorporating communication between the vehicles, the chargers and the substation converters. The system will autonomously assess the charging load, where to draw this demand from, and the level of equalisation possible. Management of the charging load and its impact on users will be investigated during the trial, to gain insights as to the optimum ratio of charging and converter capacity that should be installed to provide optimal system utilisation against capital expenditure

As shown in 4.13, we progressed design and development of the DC Share supervisory control system in a manner pursuant to these aims up until the point when we requested that the project be halted. This item was not complete prior to the request to halt.

6.1.2. Equalisation network

Demonstration 1
DC Share will expand the equalisation concept into an equalisation network, balancing a wider area and offering broader benefits. DC Share will demonstrate this at LV, where the effects of aggregation are low (i.e. the number of connected customers is relatively small, and load generally reflects a distinct domestic or commercial/industrial profile) and the potential benefits are pronounced.

As shown across section 4, we progressed design and development of the overall equalisation network in a manner pursuant to these aims up until the point when we requested that the project be halted. The request to halt occurred prior to commencement of construction of the equalisations network.

6.1.3. AC to DC converters

Demonstration 3
The AC-to-DC converters to be deployed in the trial will be an evolution of the “Soft Open Point (SOP)” technology developed by Turbo Power Systems Ltd in previous innovation projects. The new units will be smaller and will connect the DC bus to a cable circuit. The smaller unit means that siting devices within substations will be possible in more locations, which will reduce the visual and audible impact.

As discussed in section 4.10 we did conduct design and development of GTIs to an advanced stage and a prototype unit was under construction prior to the halt request.

These units were substantially smaller than the units that had been developed for some, but non-comparable, applications in previous application projects. These units were similar in size to the LV Soft Open point that was previously developed in UKPN's active response project. We also demonstrated that if there was a future requirement to site these devices in distribution substations, then functionality such as the neutral bridge enclosure would have to be sacrificed in order to be able to better fit the GTI into substations. Sacrificing this compartment would only remove the capability to phase balance and would not remove the ability to equalise between substations.

6.1.4. DC Chargers

Demonstration 4
As existing commercially available EV rapid chargers are all AC network fed, new EV chargers that are fed from the DC network will be developed.

As shown in 4.12 , we progressed design and development of the DC EVCP's in a manner pursuant to these aims up until the point when we requested that the project be halted.

6.2. Deliverables

Table 22 compares the deliverables that were stated within the FSP against their status.

Table 22: Status of deliverables as stated in the FSP

Reference	Project Deliverable	Status
1	Site Selection Complete. Evidenced by a report detailing: • Process used to select the site including equalisation benefits estimations, planning considerations, charger usage estimations • Evidence of support from relevant Stakeholders • Final trial site decision • Next steps action plan	Delivered
2	Final System Design Report. Evidenced by a Report detailing: • Full description and specification of the trial installation • Final system design and product specification, • System Functional Definition Document, • Detailed status of developments of hardware and software	Delivered
3	Factory Acceptance Evidenced by a report detailing: • Description of the testing, installation and commissioning processes, • Equipment acceptance and compliance certification, • Detailed plan for onsite installation, • Analysis of the results and improvements for future iterations.	The DC Share project was halted prior to completion of this deliverable, but some of these items were already in progress.
4	Installation Completion as evidenced by Installations completed and presented for inspection: • Equalisation at substations, • DC ring cabling, • DC charge points, • Other system components such as switching, metering, control, and Comms system.	The DC Share project was halted prior to this deliverable

Reference	Project Deliverable	Status
5	Trial Interim Report detailing: • Lessons learned during installation and initial testing, • Details of activities and success in engaging with potential users, • Customer survey interim results, • Details of events and conferences.	The DC Share project was halted prior to this deliverable
6	Trial Results Report and EV Charging Customer Experience Report detailing: • Analysis of the data obtained from the trial installation, • Its effectiveness to deliver rapid charging and network equalisation benefits, • Public presentation of the results from customer engagement to determine positive and negative elements of the trial installation (e.g. location and logistical factors, prioritisation logic/curtailment of charging	The DC Share project was halted prior to this deliverable
7	Close Down Report. Final Conclusions and BaU recommendation	As per this document

7. Required modifications to the planned approach during the course of the Project

Although the project remained with the FSP and governance parameters up until the point of requesting a halt, the following changes were made to our original intentions.

7.1. Request for project halt

The most significance change to our planned methodology is the fact that we asked the project to be halted before trial commencement.

In accordance with our project management governance, we review the expected benefits of our projects in light of the ongoing and incoming learning about the benefit creation and potential to scale. Towards the end of the DC Share design phase, we reviewed what we had learnt regarding the application of LVDC equalisation networks, including:

- Updates on the cost base that should be expected when constructing the LVDC equalisation network
- Insight into the “firmness” of the capacity that would be offered from LVDC equalisation networks to EVCP customers
- Understanding gained through the detailed design of the proposed trial installation
- Protection system limitations
- Whether there were any specific operational benefits to EVCP customers from adopting a DC point of connection.

As a result of this, we refreshed the cost benefit comparison of BAU connections and connections using LVDC equalisation networks (as shown in section 5). We consider that this updated cost benefit demonstrates that LVDC equalisation networks do not create a positive benefit for customers and that other strategies better promote the interests of our customers.

7.2. COVID and project time lines

The 2020 COVID outbreak impacted early in the project. This outbreak had two clear impacts on the project. Firstly, we experienced delays to direct deliverables whilst contingency ways of working were implemented. One example of this was the fact that this disruption caused a delay to the final system design report of three months.

During the COVID lockdown period, we also experienced the lead time for factory acceptance extend by 9 months. As discussed in the June 2020 progress report, this was attributed to disruption in global supply chains.

Our response to the COVID outbreak was to ensure that all project partners had an effective pandemic policy and contingency arrangements in place and to ask suppliers to review lead times from suppliers.

8. Project finances and variances

The project direction for the DC Share project recognised that the project budget was £5,287k and the NIC offered £4,715k of funding.

At the time of requesting the halt in Autumn 2021, the project finances stood as per Table 23. In accordance with NIC governance, the project was instructed to hold still from during the period between the request for project halt to the issue of closedown decision.

Table 23: Project finances as per October 2021

Budget Category 1	Original cost Allocation[10] £	Total spend	Remaining Budget (£)	Remaining Budget (%)
Labour	£490,950	£178,455	£312,495	63.7%
Equipment	£1,189,060	£593,615	£595,445	50.1%
Contractors	£2,352,110	£1,511,885	£840,225	35.7%
IT	£420,160		£420,160	100.0%
IPR Costs	£0		-	-
Travel and Expenses	£104,690		£104,690	100.0%
Payments to users	£0		-	-
Contingency	£509,960		£509,960	100.0%
Decommissioning			-	-
Other	£220,380		£220,380	100.0%
Total	£5,287,310	£2,283,956	£3,003,354	56.8%

In accordance with the project termination process within NIC governance we submitted our net closedown funding request to Ofgem. This submission contained the costs that were contractually due for works underway or sums that were contractually due to bring the agreements to an early halt. As per Ofgem's closedown decision of 13th of May 2022, an additional £222,870 was granted to enable winding up of the project and £2.48M of funding is to be returned to customers.

[10] As per Project Direction

9. Lessons learnt for future innovation Projects

This section records key lessons for delivery of future projects.

9.1. Network concept development

This project demonstrated the value of ensuring that there is a clear grasp, prior major manufacture or design commitment, of the overall network concept and who the system is expected to help customers. This concept needs to include the following:

- The required customer experience, including business case, connection experience, ongoing capacity availability and service levels.
- Expected loading on assets and the operational events which mark the limiting conditions
- The protection philosophy confirming whether acceptable levels of protection sensitivity and clearance speed will be delivered and under which conditions the system reaches performance limits.
- The expected device performance and the boundaries which mark the limiting conditions
- The means to ensure that acceptable performance of the earthing system will be delivered
- The means with which a safe system of work can be embedded into the system operations.
- The likely constraints to be expected at the installation sites.

To some extent, this learning has already been adopted into the future Strategic Innovation Fund (SIF) structure and the DC Share project would have benefitted from this structure. For example, the discovery phase could have reviewed approaches to supplying EVCP and the viability of LVDC equalisation networks against alternative technology. The alpha phase could then have been used to develop and verify the network concept for LVDC equalisation networks then progressing through the beta and trial phases, had the concept still appeared viable.

When developing new concepts for LV networks, innovators must consider the diversity across substations that will be experienced. For this reason, network concepts should be stress tested to understand in how many instances they are expected to be viable instead of depending on a small number of case studies.

9.2. Reducing construction delivery risk

The DC Share project infrastructure was to be located in the middle of a town centre. Construction project in urban environments do often come with delivery constraints that a network operator has little influence over (limitations on road opening periods or temporary one way systems etc). These delivery constraints increase the cost and timescale of delivering the trial. When planning future innovation projects consideration should be given as to whether there are cheaper methods or locations to gather the same learning.

9.3. Adoption of trial assets into daily operations

The project intention was for the LVDC equalisation network and LVCP to be adopted into daily network and car charging operations. Had the network performance or the EVCP performance began to deliver unacceptable performance beyond the warranty period, there was a strong likelihood of stranded assets.

In the future we recommend that any application for SIF funding where new assets are to be trialled should contain an indicative business plan and risk management plan for the assets for ongoing operations after the trial. These documents should demonstrate how the post-trial operations of the new infrastructure are expected to technically and commercially protect customers. In the event that there is too much uncertainty as to whether post-trial operations would be successful, then the trial methodology should be reviewed to minimise any regret if the trial demonstrates a non-viable proposition.

10. Planned Implementation

We have provided a reasoned argument that we believe LVDC equalisation networks are highly unlikely to be used as a strategy for making capacity available to customers. We have demonstrated that this position is due to the following facts.

1. The cost of the GTI and incremental cabling costs for an equalisation network cannot be reduced beneath the cost of the BAU cost and the speed.
2. The introduction of the recent changes to the access process for distribution network capacity means that DNOs would want to be able to ensure that they can meet customer curtailment expectations. Whereas we have shown that LVDC equalisation networks have limited scope for expansion meaning that curtailment mitigation strategies can be harder than the base case method.
3. We have shown that BAU connections are likely to be delivered at a much faster speed than equalisation networks with greater scope for appointment of independent connections providers to construct the connection assets.
4. We have shown that DC metering is a pre-requisite to being able to roll-out LVDC equalisation networks.

For all of these reasons we believe that the LVDC equalisation method set out by the DC share is unlikely to deliver satisfactory outcomes for customers at scale. For this reason replication of this method is not recommended.

We observe that Scottish Power are exploring the application of radial LVDC networks as part of their LV engine project. Whilst the DC Share project has not developed any opinions on the commercial viability of radial DC networks, some of the work undertaken in section 4 could support roll out of LVDC radial networks.

11. Project replication and key learning documents

We have reached a position where we do not expect to apply LVDC equalisation networks upon our electricity distribution network. Section 5 provides our expected view of business as usual LVDC equalisation network unit costs against alternative costs. A list of the documentation which describes the components and knowledge developed are summarised in Table 25, all of which are available to other network licensees on request (please see section 12 for how to apply for this information).

Table 25: List of components and knowledge for replication

TOPIC AREA	DOCUMENT OWNER	DOCUMENTATION
LVDC equalisation network modelling system	Project Partners.	
DC Share Model outputs and network intent	Project Partners	DC Share Network Design Intent DRAFT V1
		DC Network Calculations v2-3.xlsm
		DC Share DC Load Flow Results UC12.xlsx
DC Share Protection system intent (including fault level analysis, settings and functional design)	Project Partners	DC Share –Protection Review ISSUE 2.0.docx
Earthing philosophy and functional design	Project Partners	DC Share – Earthing Document Issue V1.docx
System integration approach	Project Partners	DC Share – System Integration Draft V0.1
GTI Design and functional specification	Turbo Power Systems	DC Share Grid Tied Inverter Specification System Specification – Revision 6. 05/05/21
Standard AC Substation Design	Project Partners	
EVCP Design and Functional Specification	Turbo Power Systems	EV Charger System Specification DC Share REV 5 WIP
Supervisory Controller design and functional specification	Project partners and LEUK	DC Share Supervisory Controller Specification Volume #2 Final v1
		119527-LEMT-FDS-01 - 11-08-2021
Cable System Specification	Project Partners	DC Share Cable Specification Draft V1.0.

12. Learning Dissemination

Further details on this project can be made available from the following points of contact:

Innovation Team

Western Power Distribution,

Pegasus Business Park,

Herald Way,

Castle Donington,

Derbyshire

DE74 2TU

Email: wpdinnovation@westernpower.co.uk

A list of the documentation, which describes the components and knowledge developed, is summarised in Table 25. Any of this information can be obtained by making a request to us at this address and we will then arrange for the relevant IP owner to present this information to the network licensee.

13. Data access details

Key progress reports are available on the WPD innovation website and the documentation described in section 11 are available on request using the contact details in section 12.

14. Material Change information

The DC Share project has only submitted one material change, which relates to the early halt of the project.

In accordance with WPD project governance, we reviewed the likely project benefits throughout the project. In autumn 2021, we reached the point where we believed that the concept of LVDC equalisation networks were unlikely to be deployed on public electricity networks due as they appeared unlikely to be able to deliver the expected benefits. In accordance with NIC governance, we submitted a halt request to Ofgem explaining our position and reasons supporting this position. Upon requesting a project halt, all project activity was frozen until Ofgem issued an instruction to halt, at which point activity to wind up the project was commenced.

15. Contact Details

Further details on this project can be made available from the following points of contact:

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Glossary

Abbreviation	Term
AC	Alternating Current
DC	Direct Current
DNO	Distribution Network Operator
ENWL	Electricity North West
EVCP	Electric Vehicle Charger Point
GOOSE	Generic Object Oriented Substation Event
GRP	Glass Reinforced Plastic
GTI	Grid Tied Inverter
HSR	Hide Speed Ring
IGBT/MOSFET	Insulated Gate Bipolar Transistor/Metal Oxide Field Effect Transistor
kW	Kilowatt
LVDC	Low Voltage Direct Current
MCCB	Miniature Circuit breaker
MDI	Maximum Demand Indicator
MVA	Mega volt-ampere
NIC	Networks Innovation Competition.
NJUG	National Joint Utilities Group
SAMC	Scheduled Ancient Monument Consent
SCR	Significant Code Review
TPS	Turbo Power Systems
WAN	Wide Area Network
WPD	Western Power Distribution

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