LV ENGINE

Technical Recommendations for LVDC Schemes

About Report

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Contents

Abbreviations

B2B	Back to Back
BESS	Battery Energy Storage System
CB	Circuit Breaker
CPO	Charge Point Operator
DC	Direct Current
DEM	DC Energy Meter
DNO	Distribution Network Operator
HPC	High Power Charging System
IEC	International Electrotechnical Commission
LED	Light-Emitting Diode
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
MCB	Miniature Circuit Breaker
MCCB	Moulded Case Circuit Breaker
PCC	Point of Common Coupling
PE	Protective Earth
PV	Photovoltaic
OLTC	On Load Tap Changer
RCD	Residual Current Devices
RTU	Remote Terminal Unit
SSCB	Solid State Circuit Breaker
ST	Smart Transformer

Executive Summary

This LVDC Technical Recommendations document presents possible LVDC network configurations for the most appropriate, early-stage LVDC distribution applications. The network topology, voltage, earthing, protection solutions and integration options are considered, to assist the design specifications of a Smart Transformer (ST) and to support the project trial-site selection process. This is the Task 3 deliverable from the University of Strathclyde, which is one of three key deliverables in the LV Engine Work Package 1 (the others being D1.1 trial site selection document, and D1.2 technical specifications of the Smart Transformer document).

The trials and system recommendations in this report are structured with a view towards creating a viable public LVDC distribution system. This requires the establishment of standard LVDC voltages, power quality requirements, earthing and protection standards. By determining these design parameters, future LVDC customers can ensure their applications conform to these requirements. Based on this approach, the public LVDC distribution system efficiency is considered a design priority and therefore the voltage selection and wiring configuration (3-wire, +/-700V_{dc}) is recommended to minimise distribution losses and maximise power transfer capability while operating within the IEC limits for LVDC systems [1]. However, as part of the ST design process it is necessary to evaluate the anticipated ST cost for both a bi-polar and uni-polar LVDC output, at varying voltage levels, against the distribution efficiency of each option before a final conclusion can be determined. Furthermore, the integration of both AC and DC distribution through the same power electronic device (Scheme-5) requires complex converter control, which may be simplified if uni-polar DC distribution is adopted.

An incremental approach to LVDC trial applications is suggested that begins with a low power LED street lighting application with additional, higher power loads added to the system once ST performance and protection solutions have been validated. Both old and new cable options are considered for the trials with an evaluation of the power transfer capabilities of 3-core and 4-core distribution cables. Although it appears feasible to utilise existing LVAC cables for LVDC distribution, it is recommended that new cable is laid for the trial applications, and if desired, this may be accomplished in a manner that enables interoperability between LVDC and LVAC distribution to allow the network to revert back to LVAC should any challenges arise during or after the LVDC trials.

Protection and earthing recommendations are offered for both Scheme-4 (dedicated LVDC output from ST) and Scheme-5 (combined LVDC and LVAC output from ST). It is necessary to provide a TN-S earthing arrangement for the LVDC system to minimise the risk of corrosion, but on the LVAC side standard TN-C-S earthing can be implemented. The protection strategy for these schemes is dictated by the low fault current provision from the ST. Therefore mechanical DC breakers with Definite Time Over-current relay characteristics can be used to protect outgoing LVDC feeders or alternatively electronically controlled mechanical or solid-state circuit breakers (SSCB) may be utilised with specialised protection algorithms.

Further recommendations are offered with respect to DC load control through the use of a voltage droop band on the public LVDC supply. This may assist in controlling flexible (or active) loads to either balance power output on the AC or DC side of the ST and/or to improve system efficiency by optimising loading on the ST at its maximum efficiency point.

1 Project Overview

LV Engine aims to add flexibility and release additional network capacity within LV networks by informing the design and selection of a cost effective intelligent secondary transformer solution. This enhances the adaptability of LV networks to enable the future uptake of low carbon technologies. The primary objective for LV Engine is to design and trial the first UK Smart Transformer (ST) for deployment within secondary substations (11kV/0.4kV) and produce smart tools for the efficient reinforcement of future LV networks. STs will be trialled within five different schemes and their performance will be technically and financially compared with conventional reinforcement and transformers fitted with on-load tap changers (OLTC).

In response to the increased adoption of native DC electrical loads such as electric vehicle (EV) chargers, LED street lighting, data centres and office spaces that contain IT equipment, two out of the five considered schemes incorporate an LVDC supply from the ST. This project therefore has the opportunity to trial not only a novel ST but also to make direct performance comparisons between LVAC and LVDC distribution, and to establish LVDC network design principles.

This LVDC Technical Recommendations document is the Task 3 deliverable from the University of Strathclyde, which is one of three key deliverables in LV Engine Work Package 1: D1.1 trial site selection document, D1.2 technical specifications of the Smart Transformer document, and D1.3 technical specification of the LV Engine schemes document.

This document presents possible LVDC network configurations for the most appropriate, early-stage LVDC distribution applications. The network topology, voltage, earthing, protection solutions and integration options are considered to assist the design specifications of the ST and to support the trial-site selection process.

1.1 Overview of LVDC Schemes

At the time of writing this report, the specific ST power electronic topology is still under consideration and it is likely the ST design process will follow an iterative approach as each of the project variables become better defined. This report assists the ST design process by defining the most appropriate LVDC trial network topologies and the subsequent electrical power output, control and protection options for the ST. The LVDC recommendations discussed in this report refer to Scheme-4 and Scheme-5 as outlined in the LV Engine project documentation [2].

1.1.1 Scheme 4 – DC Output Only

As depicted in Fig-1, this scheme aims to demonstrate the DC supply capability of the ST. The aim is to provide a DC supply for solely DC customers. This scheme will demonstrate the basic requirements for design, installation and operation of an LVDC network using an ST. Incremental steps may be taken to increase the complexity of the DC network by adding more DC loads at different voltage levels e.g. the supply of an EV charger at 400-950V_{dc} and the supply of a street lighting network at 200-400V_{dc}.

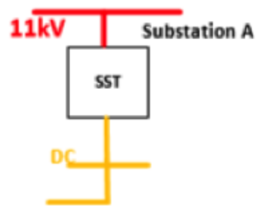


Fig-1: Scheme-4

1.1.2 Scheme 5 – Combined AC & DC Output

As depicted in Fig-2, this scheme aims to demonstrate the hybrid AC/DC functionality of the ST by supplying DC customers along with AC customers. This scheme will demonstrate the optimal design, installation and operation of a hybrid LVDC/AC network. The same LVDC distribution configurations from Scheme 4 may also be applied in this Scheme, but further consideration of earthing arrangements and galvanic isolation will be required. Also, additional ST control will be required to manage the combined AC and DC power demand to avoid surpassing the ST power capacity.

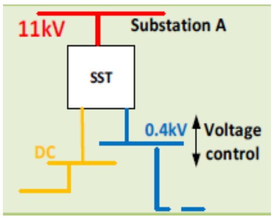


Fig-2: Scheme-5

1.2 LVDC Customers

Over the past decade, LV direct current (LVDC) distribution networks have received increased attention for the provision of unique and flexible infrastructure for enhancing LV networks controllability and increasing LV cables power capacity [3], [4]. LVDC systems are becoming increasingly feasible due to increased experience and cost reduction curves of power electronics (continuous 5% cost reduction in the last two decades [5]) and development of new DC protection solutions [6].

In this trial project it is recommended that the LVDC network is limited to low-risk applications where an interruption in power supply would not have serious consequences. It is also suggested that the LVDC network trial is structured progressively, starting with low power, single load type applications then moving to more complex networks with two or more types of DC loads at varying voltage levels.

With these factors in mind, the LVDC deployment strategy may take the approach outlined in Fig-3 with the following four trials:

1. **LED Street Lighting (single run or lighting control box):** The lowest power LVDC trial could be the supply of a single radial feeder of streetlights at a power capacity of between 1-5kW. This trial would test the DC/DC drivers for each lighting module and the main DC/DC buck converter with isolation transformer that would convert from the DNO DC supply voltage to the applicable street-lighting voltage. Once successfully tested, the street-lighting trial could be expanded to include an entire lighting-control box, which may control multiple radial street-lighting feeders traditionally totalling up to 60kW [7]. If these lighting columns were to convert to LED, the demand at this lighting control box would be 50-80% lower (i.e. 12kW-30kW) [8].

2. **High and Low Power EV Charging:** Concurrently, or subsequently after the street-lighting trial, a LVDC supply could be offered to a high power (100-350kW) EV charger or alternatively, a series of smaller (10-50kW) chargers. If this trial is integrated into Scheme-5, then it is likely to require additional charging control to minimise interference with the AC demand.

3. **Segregated Street Lighting & EV Charging:** This trial introduces two DC customers to the public LVDC supply from the ST. The EV customer and the street-lighting customer are likely to each have their own DC/DC converter with a galvanic isolation transformer. This is important to convert the voltage to the specific application at a safe level and eliminate any possible common mode noises between AC and DC systems, especially for Scheme-5.

4. **Integrated Street Lighting & EV Charging:** This trial is arguably the most complex to implement but could offer significant benefits to local authorities that require on-street charging solutions. Although integrated EV charging and street-lighting exist for AC applications [9], the use of DC is still at the early trial stages with some testing taking place in the Netherlands [10]. Two proposals are offered for this trial: a fixed solution that uses a charge controller at each lighting column to control the EV charging and a switched solution that uses a centralised DC/DC converter to control the EV charging by routing power to each EV and lighting column battery pack according to a network Energy Management System (EMS). The integration of lighting column batteries may also have the potential to offer additional resiliency benefits as requested in a recent Innovate UK competition for UK Power Networks (UKPN) [11].

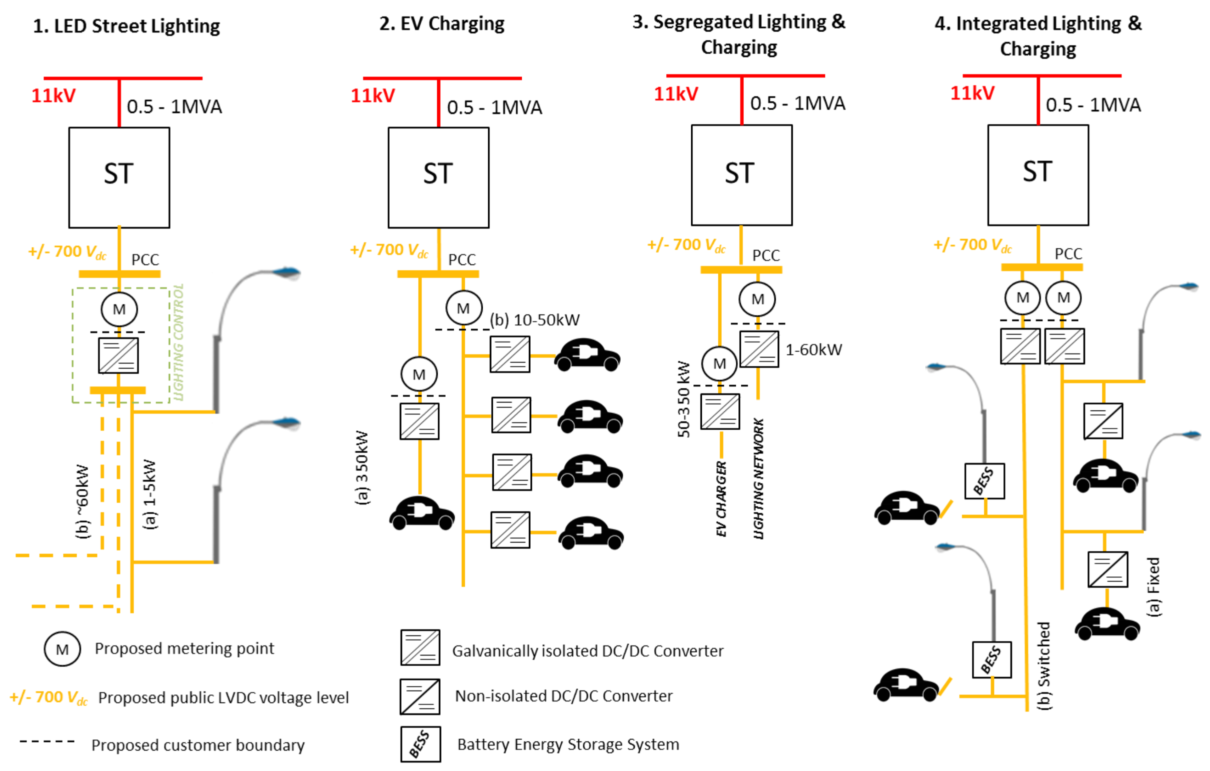


Fig- 3: LVDC network trial options with indicative voltage level and possible LVDC customers.

LVDC trials 1-3 are all feasible with existing 'off-the-shelf' products, however further consideration is required to define the DNO supply voltage and protection solutions that meet UK regulatory requirements. Trial 4 will require additional custom engineering and control solutions to ensure seamless integration of both lighting and charging options. Finally, it is necessary to define the boundary between the DNO's LVDC network and the customer's.

1.3 Customer Boundary

It is proposed that this should occur at the customer's converter, which has a three-fold purpose: to regulate the voltage level to suit the application, to manage the power flow and to implement the most appropriate galvanic isolation and earthing configuration. However, discussions remain as to whether this converter should be the responsibility of the customer or the DNO – in the case of high power charging (HPC) systems, it is likely that the converter will be part of the charger and owned by the charge point operator (CPO). However, for public street lighting networks, will local authorities be willing to own and operate their power converters? This raises the secondary question as to where the metering should be applied. If the converter is owned by the DNO, metering should be on the customer's side of the converter. This decision is likely to depend on the DNO's appetite to own many, small-scale power electronic DC/DC converters where the potential exists to provide some operational services to the public network (e.g. local voltage control and fault locations/interruption) and the need/desire for LVDC customers to access/control their own DC/DC converter. Based on these considerations it is recommended that the boundary be located on the DNO's input side of the customer's DC/DC converter and therefore metering will take place at this point.

1.4 DC Energy Metering

DC energy metering (DEM) is still not widely available for DC customers. There are currently no standards available for (DEM). However, there are already some proprietary products which are not standardised but they have been used for specific applications such as solar PV systems, industrial DC control systems and data centres. In DC circuits, the measurement of DC currents and voltages is normally based on 'Hall Effect' current and voltage transducers. Three existing examples of DC power metering which are based on Hall Effect technologies are discussed as follows.

- Direct Current BV DC Current router [10] is equipped with a kWh meter and widely used in the LVDC trials in the Netherlands such as DC-powered street lighting, DC greenhouses, and the ABN-Bank DC building.
- ACCUENERGY (AcuDC 240 Series) DC power and energy meter which is ISO9001 certified and used for different applications such as data centres, wind power generation, DC excitation systems, and EV charging monitoring. Further technical information on this meter is presented in Table 1.
- Eaton DC Energy Meter (DEM) measures the current and voltage of DC powered equipment, and samples the supply voltages and currents at regular intervals, and along with the sampling period will compute the accumulated energy consumption as an Energy Meter reading .[12]

Table 1: Technical parameters of the AcuDC 240 Series DC power and energy meter [13].

Parameters	Ranges	Resolution	Accuracy
Voltage	0-1.2kV	0.001V	0.2%
Rated current	0-±50kA	0.001A	0.2%
Power	0-±60MW	0.001kW	0.5%
Energy	0-9999.99MWh	0.01kWh	0.5%

All three meters are fitted with other advanced controls and communications to provide different control and monitoring features. For example, optional Modbus RTU communications and SCADA controls for energy management systems are embedded in each meter box.

2 Voltage Selection Considerations

The specific voltage selection for each of the LVDC trials can be defined by examining prior international trials and considering the operational characteristics of each LVDC application. The specific application voltage levels will arguably be defined and controlled by the customer, as this will vary depending on the application. However, the DNO LVDC supply voltage can be standardised and should be close to the IEC limit for LVDC distribution (1500V_{dc}) to minimise distribution losses and maximise power transfer capabilities. Prior projects in the Netherlands have suggested a distribution voltage of +/- 700V_{dc}, with a +/-60V_{dc} droop control band [10]. For active LVDC networks, the ST should be able to provide a nominal voltage with droop, and only controllable loads such as EV chargers and controllable street lighting can be connected. If the customers are considered as constant power loads, then the ST supply does not require droop control.

Since the LV Engine Scheme-4 and Scheme-5 customers will be mainly EV charging points and smart street lighting, the ST should provide nominal voltage (e.g. 700V_{dc} or ±700V_{dc}) with a droop band of ±50V_{dc} to allow customers with active control applications and to operate within the required IEC voltage limits. However, the final voltage and distribution configuration will be dependent upon a design optimisation process with the following constraints: ST capital cost and complexity, distribution system efficiency and customer power quality requirements.

The following voltage discussion provides a justification for this proposed voltage selection and is segregated according to wiring configuration, protection and safety requirements.

2.1 Bi-polar (3-wire) vs. Uni-polar (2-wire) systems

LVDC power can be distributed using either uni-polar or bi-polar topologies. According to assessments conducted in [14], bi-polar distribution offers the highest power transfer capabilities and should be considered for a DNO's public distribution system if supplying loads with high power density is required. Furthermore, bi-polar systems can offer greater redundancy as a short circuit on one pole will not affect customers connected to the remaining pole. However, specific LVDC customer applications may elect to use a uni-polar system for lower power applications and to minimise converter interface and cable costs.

It is important to note, that the design of the ST will be more complex if it is to provide bi-polar DC output compared to uni-polar output. In bi-polar systems, the ST may require two DC-DC converters in addition to well-designed controllers to control the DC mid-point voltage and balance the positive and negative pole voltages. The costs of the ST design with bi-polar outputs and the losses in power electronics switches need to be assessed against the need for longer distribution distance, power transfer capability and system losses; a power transfer comparison of three different distribution systems is offered in Fig-4.

With respect to the DNO cable configuration, [14] highlights that 4-core cables offer the highest power delivery option under DC distribution compared to 3-phase LVAC distribution in either a conventional 4-core or 3-core cable. This is due to the fact that existing LVAC cables are generally rated at a voltage level of $600V_{rms}$ (phase-ground) and $1000V_{rms}$ (phase-phase). Therefore, in a 4-core bi-polar DC distribution conversion, the maximum voltage that can be accommodated per core is +/-707V_{dc}, which represents the peak phase-phase voltage (1414V) and it also remains less than the peak phase-ground voltage (849V). Conveniently, this bi-polar voltage range also corresponds with new LVDC installations in the Netherlands that recommend a distribution voltage of +\-700V_{dc} with a +/-60V_{dc} droop control. This voltage level may be appropriate for existing UK LVAC cables, however, in certain operational states the voltage may rise to +/-760V_{dc}, which would not only exceed the core-to-core voltage insulation limits on existing LVAC cables but also the $1500V_{dc}$ IEC low voltage limit, but this is likely to be short in duration or may be avoided entirely if voltage droop control is not required. Alternatively, in new LVDC distribution systems, the cables may be specified with sufficient insulation capacity and cores to support the intended application.

In general, [14] concludes that existing LVAC cables are heterogeneous in nature, are of different ages and have multiple branches of varying sizes. Therefore converting existing public (DNO owned) LVAC cables to LVDC has a number of practical challenges to overcome and may only be appropriate where the cable integrity is well understood and the cable is of a uniform size throughout the proposed DC network. It is most likely that LVDC distribution will occur on new cable installations to deliver DC power to dedicated DC customers. In this scenario, as shown in Fig-5, a 4-core bi-polar distribution system minimises material costs and maximises power transfer capabilities. However, in this case the mid-point return path would require the use of the earthing sheath around the cable, and it is unknown how this will affect the long-term integrity of the cable, especially under unbalanced loading conditions. Considering this unknown, the safer initial configuration is a 3-core bi-polar cable that can utilise a dedicated core for the mid-point return; although, the power transfer capacity of the cable is not optimised. In the 4-core scenario, two of the cores may operate under bi-polar distribution and the remaining two used for earthing and/or mid-point return but this could be considered an inefficient use of conducting material.

For customer side applications such as street lighting, the power load and cable system is relatively homogenous and therefore the prospect of converting existing underground lighting cables to LVDC may be easier to accomplish. In general, the wiring configuration, voltage and protection system on the customer's side of the LVDC network is likely to vary according to operational requirements.

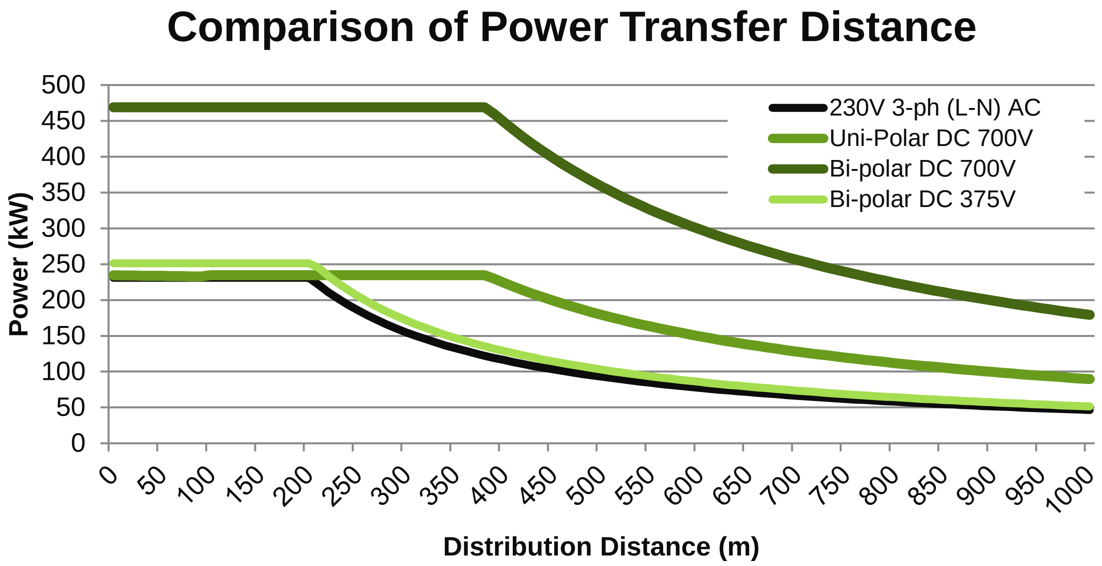


Fig- 4: Power transfer capability of different distribution systems, while adhering to a 6% voltage drop on a 3-core, Aluminium XLPE 185mm^2 cable.

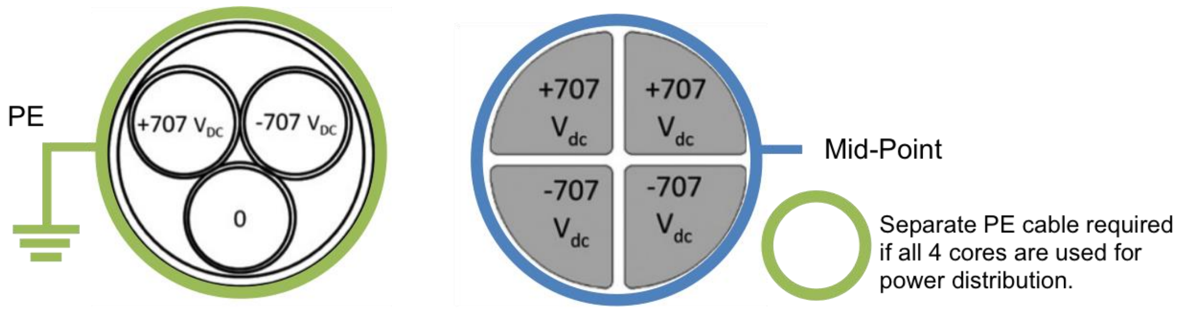
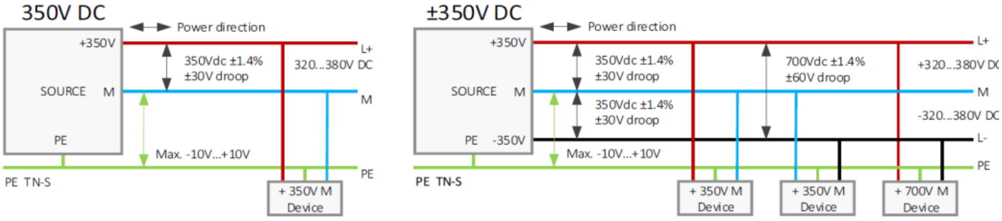


Fig- 5: Conversion of LVAC cables to LVDC – 3-core and 4-core bi-polar options, adapted from [14].

2.2 Customer's Operating Voltages <+/-380Vdc

The next two sections highlight discussion points for consideration with respect to potential LVDC customers that may connect to the public DNO LVDC supply and the possible voltage levels and wiring configurations that may be required to support their operations. The sections have been defined by applications that require a voltage level of less than +/-380V_{dc} and more than +/-380V_{dc}. This voltage level indicates a separation between the protection solutions that are required to safely operate the network and the requirement for galvanic isolation. Furthermore, prior testing of DC voltages on AC appliances concluded that, depending on the appliance, existing 230V_{ac} electrical products can accommodate between 100-370V_{dc} input voltage with minimal modifications as the peak AC voltage level is 326V (e.g. $326V_{dc}=\sqrt{2} \times 230V_{ac}$), [15]. Therefore there is potential to operate existing AC based LED street lighting modules with LVDC, however they will still have an electrolytic capacitor which new installations may be able to avoid – it is believed that some LED lighting modules which do not contain the AC/DC rectifier may experience a longer operational lifespan due to the absence of an electrolytic capacitor.

With respect to converting existing street lighting networks to DC, it is important to consider that the UK has already embarked on significant lighting upgrades and therefore the replacement of existing AC connected LED lighting modules will not be required for at least 15+ years. It may therefore be important to consider a DC distribution voltage level that is compatible with existing LED modules and street lighting cables to ensure future LVDC adoption for business as usual (BAU). For the conversion of existing street-lighting networks, it is likely that this will be in the range of 200-350V_{dc}. Fig-6 highlights a 350V_{dc} uni-polar and bi-polar LVDC distribution system implemented in the Netherlands, in both cases a TN-S protective earthing solution is utilised. The control of the lighting network (such as dimming) can be performed through voltage droop control by varying the main voltage by +/-30V_{dc}.



(a) (b

Fig- 6: (a) Unipolar (2-wire) 350Vdc system and (b) Bipolar (3-wire system) ±350Vdc system [10].

For the implementation of new LVDC street lighting networks, the cable configuration and voltage selection are less restricted. The most inexpensive solution is a uni-polar network, however, it may prove difficult to accommodate both LED lighting and EV charging on a uni-polar network as LED lighting will require an input voltage of 230-326V_{dc} and EV charging requires 380-500V_{dc}. Therefore, the integration of both lighting and EV charging will likely require a bi-polar network at a voltage level that does not exceed 500V_{dc} from pole to pole, as existing Mode-4 chargers (up to 60kW) generally operate up to 500V_{dc}, which is the limit that most EV batteries can currently accommodate.

The voltage selection for either a low-power EV charging network or an integrated EV charging and street lighting application will be regulated by IEC 61851 and IEC 62196 which limits Mode-4 DC charging to 380-500V_{dc} and specifies the communication as well as plug requirements for conductive charging systems. This voltage level is suitable for most DC charging compatible vehicles currently on the market and for low power charging applications (10-50kW) it is unnecessary to design for a voltage much higher than this. Higher voltages, for HPC systems, will be recommended in a forth-coming amendment to IEC 61851.

2.3 Customer's Operating Voltages >+/-380Vdc

This voltage classification requires faster operating protection solutions and is likely to incorporate both the DNO public distribution system operating voltage (proposed at +/-700V_{dc}) and it also represents the voltage range for high power EV chargers (in the region of +/-475V_{dc}). Although tram traction systems have historically used uni-polar 750V_{dc} systems, it may prove beneficial to utilise a bi-polar wiring configuration to maximise power transfer and minimise losses for a public LVDC distribution system but this depends on the additional converter cost and complexity for the ST. Furthermore, from initial discussions with HPC infrastructure manufacturers, some utilise a bi-polar distribution system, however, input voltages to their DC/DC chargers vary between manufacturers. It is therefore recommended that technical specifications are collected from the likes of Tritium, Enercon, ABB and Siemens to identify similarities in DC configurations, voltage levels, allowable voltage variations and power control capabilities.

To meet the safety requirements within these higher voltage ranges (i.e. >+/-380V_{dc}), galvanic isolation between the public LVDC network and the end users becomes essential. Most of the existing LVDC trials have been designed as an IT earthed system when the DC voltage is >380V_{dc}, and isolation transformers are used to break the earthing loop between main LVDC feeders and the customer's side. The decoupling between LVDC and the end users will also allow for the mitigation of noise migration between the loads and the MV AC grid. However, in the Netherlands, an IT system is not desirable, and instead a TN-S system with double insulation is used as this corresponds to their existing AC earthing regulations and it is believed that this will avoid confusion if both AC and DC systems adopt the same earthing configuration.

For an LVDC trial application in this voltage range it will be necessary to identify an HPC EV charging manufacturer that can accept a 700V_{dc} input voltage from the DNO and to thoroughly understand the acceptable voltage variations as well as their ability to accommodate voltage droop control. This will help to inform the LVDC power quality standards that a public DNO should meet. Alternatively, for Scheme-4 the ST could be optimized based on capital cost, efficiency and voltage level compatibility with emerging HPC EV charging systems.

For LVAC distribution systems, statutory voltage limits are set between +10% and -6% but for LVDC voltage deviation, there is no standard available for public LVDC networks. However, the IEC 60092: Electrical Installations in Ships - Part 101 has defined that the steady-state DC voltage deviation limits should be no more than ±10% [16] and for traction systems, that use thyristor based rectifiers, this can be up to +20%/-33% voltage variations under normal operations [17]. Therefore, the final power quality specifications are likely to be influenced by the specific customer requirements.

2.4 LVDC Network Control Options

Frequency droop control is an established load sharing principle between generators on an AC electrical system with minimal communication between generating units. The same droop control principles have been applied to DC electrical systems based on voltage set-points. This voltage droop control approach for LVDC networks enables optimal operation of the flexible loads according to a variety of system constraints.

The implementation of voltage droop control on the public LVDC network may assist the DNO in managing constraints on the ST or wider distribution system by indicating to connected LVDC customers that curtailment of demand is required [18]. Voltage droop control can be achieved without the use of an additional communication system on the LVDC network, which may enhance the resiliency of the system. It is important to note that the ST could operate with one droop curve, which the customer’s DC/DC converters respond to, but on the customer network side another droop curve may be implemented to control customer loads based on the power requirements set by the ST or according to the customer’s independent energy management system.

In Dutch and Finnish LVDC trials, voltage droop control was adopted for both building level LVDC applications and public DNO distribution systems. The DC operating systems designed by Direct Current BV in the Netherlands utilise a +/- 8.6% voltage droop but their networks are independent of the DNO and the sources/loads operate on the same energy management system, therefore customers wishing to connect to a public LVDC supply will have to ensure their converters comply with the network droop control specifications.

Alternative communication options can be employed to control loads connected to the public LVDC network but they arguably add additional points of failure to the system. For Scheme-5, it is worth discussing the additional costs and any interference on the AC output of the ST that the incorporation of DC side voltage droop control would cause, and the level of variation that can be accommodated on the DC link voltage.

2.5 System Energy Efficiency Considerations

A 2014 report by Imperial College outlines the primary causes of electrical distribution system losses for various distribution regions in the UK [19]. It is clear that a number of factors affect electrical losses and it is not just the efficiency of the electrical components and cables but also the electrical power factors and phase-imbalance contribute to system in-efficiencies. With respect to evaluating the efficiency of LVDC it is important to take a holistic approach that not only considers the efficiency of power converters but also the power quality improvements that can be recognised.

An integral part of the LVDC trials should be to quantify the real energy losses from the 11kV side of the ST to the appliance level on the LVDC network. This should then be considered against the equivalent, existing AC grid connection options and the additional power quality improvements that can be recognised by implementing a centralised ST.

The LVDC network can be designed to minimise voltage drops (<1.4% in LVDC trials in the Netherlands [10]) and the resulting energy losses. In addition, it may prove feasible to consider an Energy Management approach for certain LVDC customers (e.g. flexible EV chargers) to ensure the loading on the ST is maintained at its optimal operating efficiency.

2.6 Section Summary

The available voltage parameters are presented in Table-2, where the ST DC output parameters are recommendations from LVDC trials in the Netherlands and the customer application parameters are a mixture of values from LVDC trials, EV charging standards and AC wiring regulations. The primary unknowns associated with the public LVDC voltage selection, wiring configuration and power quality requirements can be summarised as follows:

- Can high power EV charging manufacturers accept an input voltage of $700V_{dc}$ with a voltage droop band? What variation of input voltage can they tolerate and are there any other power quality requirements that must be specified?

- The implementation of LVDC street lighting will require cooperation with a Local Authority and a technology supplier such as Direct Current BV, Eaton, Bosch, Philips, ABB, to procure the necessary DC/DC LED drivers. Further information on existing street-lighting electrical design would be useful to fully assess the viability of utilising existing in-ground cables.

- Integrated DC charging and Lighting will require additional design considerations and testing, which includes the identification of appropriate lighting networks and their wiring configurations. It may prove easier to implement this scenario on a new lighting network, however, the future benefit is the conversion of existing street lighting cables to increase power capacity for additional EV charging.

Table 2: LVDC Recommended Voltage Parameters

Network Section	Input Voltage	Output Voltage	Droop Band	Voltage Unbalance	Voltage Drop
ST DC Output	MV AC	2-wire: $700V_{dc}$ 3-wire: $+/-700V_{dc}$	+/-7.1%	2.85%	1.4%
Street-lighting ***Trial (a)***	2-wire: $700V_{dc}$ 3-wire: $+/-700V_{dc}$	2-wire: $230\text{-}380V_{dc}$	8.6% at $350V_{dc}$	2.85%	1.4-3% (AC standard)
EV Charging ***Trial (b)***	2-wire: $700V_{dc}$ 3-wire: $+/-700V_{dc}$	Depends on EV charger type	TBD	TBD	1-2%
Segregated EV & Lighting ***Trial (c)***	2-wire: $700V_{dc}$ 3-wire: $+/-700V_{dc}$	As in (a) and (b)	As in (a) and (b)	As in (a) and (b)	As in (a) and (b)
Integrated EV & Lighting ***Trial (d)***	2-wire: $700V_{dc}$ 3-wire: $+/-700V_{dc}$	3-wire: $\sim+/-250V_{dc}$	TBD	TBD	1.4%-3%

3 Cable Considerations

The focus of this section is to discuss the main cable specifications for both future, standard public LVDC distribution systems and the use of transferable AC/DC cable requirements that may mitigate some of the risk associated with these LVDC trials. The European standard that harmonises LV cable specifications is CENELEC HD603 [20]. Currently, there are no commercially available LVDC cables on the market. However, Nexans are working with other companies active in the LVDC distribution area to develop bespoke cables that contain an auxiliary core for additional communication and protection requirements. These bespoke LVDC cables have yet to be trialed in a project and are likely to be proprietary to Nexans's customers.

Other DC applications such as DC data centres tend to use cable specification HO7RNF, which offers the required flexibility to enable electrical distribution within tight spaces. Nexans produce a cable product for this purpose known as Titanex, which is the only halogen free HO7RNF cable. Tram cabling adheres to the insulation standards in IEC 60502-1 [21] and utility scale solar PV cable installations are required to conform to IEC 62930:2017 which primarily outlines the insulation requirements and environmental testing for DC cables.

3.1 Old vs. New Cables

Although much of the benefit associated with the adoption of LVDC distribution is the concept of converting existing LVAC cables to facilitate higher power transfer and reduced losses, as discussed earlier, this may be challenging to implement in practice unless the integrity and sizing of the LVAC cable is well understood. With this in mind, it is recommend that, for the purpose of the LVDC trials, the public LVDC supply should utilise new cables that are selected for the voltage and expected power demand.

If sufficient information can be obtained about a specific street lighting network it may prove feasible to convert an existing AC street lighting cable to LVDC as part of the trial. Perhaps it would be prudent to select a lighting network that is due for an upgrade or replacement soon, as any cable deterioration associated with the use of LVDC will have minimal consequences.

The long-term impact of operating LVAC cables with LVDC distribution is still unknown, further accelerated lifetime testing in the laboratory and in-field trials are required to capture the impact of LVDC on cables. In theory, the constant polarity of a bi-polar system will place a constant force on the insulation between cores, in addition any charged impurities in the insulation will have a constant one-directional force on the impurity which may over time pass through the insulation causing it to fail. It would also be useful to consider the level of imbalance that can be accommodated on a cable earthing sheath that may be acting as the mid-point of a bi-polar system.

3.2 Cable Cores

The specific number of cable cores will depend on whether the LVDC system is uni or bi-polar and the need for a robust protective earth core. As mentioned earlier, the use of existing 4-core LVAC cables offers the highest power transfer capabilities under LVDC distribution, however, for the implementation of a new LVDC network cable, the cable requirements should be specified to minimise cost and voltage drop while allowing sufficient power transfer capabilities. For the public LVDC distribution system associated with this project's trials, it is recommended that at least a 3-core cable be utilised to allow for a bi-polar distribution at +/-700V_{dc} and the third core as the mid-point return.

3.3 Cable Interoperability

For the purpose of these LVDC trials it may be useful to design the cable and protection solutions so that they are interoperable between LVDC and LVAC. If, for some reason, the LVDC trial is not suitable for long-term operation, this ensures that the fixed infrastructure can still be utilised under traditional AC distribution. This requires further consideration between conductor colours and markings. Table 7E of IET's 17th Wiring Edition Standards specifies the colours and markings for DC cables used for data centres and solar PV systems in the UK. Fig-7 outlines the old and new AC cable core colourings with possible 4-core and 3-core DC options that adhere to the colour requirements set by the IET.

The closest match between cable core colours can be achieved with a 4-core configuration, which will possess one redundant core (or this could be made a PE core but it would be non-conformant, as a PE should be green rather than black), this is represented by the question mark. However, if the cable has a copper sheath it may prove possible to utilise this as both the mid-point return and earth, which would allow for maximum power transfer across all 4 cores but they also would not fully conform to the IET colour regulations for DC cables. A 3-core solution would need to use the black core of a normal 3-phase AC cable as the mid-point return which is non-conformant with the blue colouring recommended by the IET for the mid-point (M) of a bi-polar DC system. Therefore, a new 3-core DC cable should ideally have brown, grey and blue coloured cores, which would help to distinguish between 3-phase AC cables but it would also mean the cable would be non-conformant if converted back to LVAC use. A more appropriate/distinguishable DC cable colouring system is recommended in the national electrical code in the Netherlands. They promote cable core colours: white / blue / red, which are likely to be adopted by IEC working group TC20 in the next revision of IEC 60502-1 but according to technical committee members this release may be 1-2 years away.

From this project's perspective, it is recommended that LVAC cables are utilised based on SPEN's standard LVAC cable specifications and procurement guidance. During the LV Engine project, it may be useful to contact Nexans (and other cable manufacturers) periodically to receive an update on the development of DC specific cables and to determine whether there is an opportunity to trial and test these cables as part of the LV Engine project. In all cable scenarios, the connection voltage and polarity should be marked at any termination where access is available and for additional safety it is worth considering the use of cable-marking tape that states a LVDC cable is buried rather than a standard low voltage AC cable. Recommended signage is presented in Fig.8 according to experience in [22] and ISO 60417 labelling standards for direct current systems.

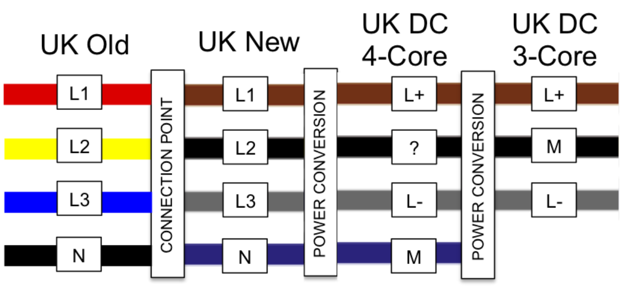
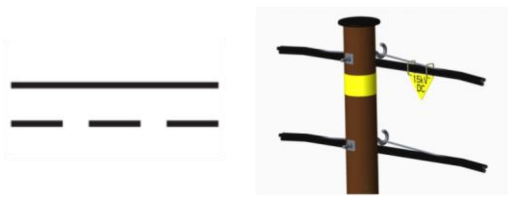


Fig- 7: Cable core colours using existing AC cables, according to IET Wiring Regulations [23].



Direct Current Symbol According to IEC 60417 — Graphical Symbols for Use on Equipment

LVDC Rules Project in Finland: displayed a DC label and voltage on overhead cables. A yellow line separated two cables, operating at different voltage levels.

Fig- 8: Direct Current symbol and cable labelling option.

4 Protection & Earthing Requirements

4.1 Overview of Protection Challenges

In the UK, most of the existing distribution networks are protected by simple overcurrent protection schemes, and LV outgoing feeders and end users are commonly protected by LV fuses. Such overcurrent devices are selected to detect the presence of fault conditions and initiate the required protection operation based on inverse time-current characteristics. Thus, the speed at which the protection will operate is directly dictated by the amount of the fault current that will flow through the protective device.

When the ST is deployed at an MV/LV substation, it will make fundamental changes in LV fault profiles on the associated LV distribution networks. STs with suitable controls and configuration can have the ability to limit the AC grid fault current contributions for the purpose of self-protection against downstream faults. STs are required to operate with reduced fault levels (e.g. 1.2-1.3 of the rated current). This might be enough to initiate the operation of overcurrent protection (MCCBs and fuses), but it does not guarantee the operation within the required speed. This is not just related to the equipment short circuit thermal ratings, but also to the duration and magnitude of the voltage sags on the network. Any reduction in the speed of protection will lead to more severe voltage sags. This can create power quality and stability issues for the ST and any other associated active loads connected to the LV network.

The deployment of the ST will also radically change the requirements of earthing arrangements in LV networks. For the LV Engine Scheme 4 & 5 where there is a LVDC supply, the earthing arrangement will be different. For the LVDC system, the following earthing requirements should be met:

- **Safety**

  TN-C-S system can be used only with certain voltage levels (<±380Vdc if DC-RCDs are used). For applications above this voltage threshold such as high power (e.g. 350kW) EV chargers will require floating IT systems. In the UK, IT systems are currently not permitted for public distribution networks. It is challenging to detect earth faults in IT systems and protect against double faults. TN might be used in LVDC with double insulation.

- **Corrosion**

  If the LVDC supply in Scheme 4 & 5 is configured as a TN, it is important to consider the impact of corrosion on any other metal surfaces connected to the same earth of the LVDC. This can be achieved by preventing DC current leakage through the protective earth conductor during normal operation, and ensuring the flow of the current occurs only under earth fault conditions.

- **Common-mode noise currents and parasitic capacitors impact**

  The LV Engine Scheme-5 will provide power to both LVAC and LVDC customers. A common protective earth path (PE) between the AC and DC supply could potentially lead to common-mode noise currents. A relatively high noise current magnitude may trip the nearby RCDs. High frequency noise currents might also cause power quality issues, if they are passed to the AC system through the PE conductor.

The MV-LV ST presents a single point of failure, and any undesirable disconnection of the ST may directly lead to penalty compensation to the customers who lose their supply due to remote system faults. Due to the lack of Grid Code requirements associated with this issue, ST fault ride-through requirements are necessary to enable the continuity of service and need to be defined.

4.2 Available Solutions

LVDC distribution networks with voltages >±380V and configured as IT systems can be protected against earth faults using an Isolation Monitoring Device (IMD). The IMD has already been used in the LVDC trials in Finland [24], and it mainly monitors the insulation between the DC poles and the earth. If the insulation resistance reaches <1MΩ, the main AC-DC converters will be disconnected from the AC grid side within 5 sec. This meets the Finnish standardisation requirements to minimise the risks of double faults occurring in accordance to [24] . The LVDC main feeders of the Finnish trials are protected against DC short-circuit overcurrent using mechanical DC-rated circuit breakers. The reason for relying on conventional inverse time-current overcurrent protection is because the AC-DC main converters are two-level voltage source converters, and such converters do not limit the fault current contributions on the DC side. Therefore, such overcurrent magnitude dependent protection will not be applicable to the LV Engine Scheme-4 and 5 due to the limitation on the overcurrent.

A smarter device with integrated protection and control functionalities to protect against reduced DC fault currents is used in the LVDC project trials in the Netherlands. The device called a “DC Current Router” is embedded with a solid-state circuit breaker (SSCB), which can detect and clear DC faults within 8µs. The router also contains an RCD that can be set for different ranges of residual operating currents 1-80mA with 0.1s operating time or 80-500mA with an operating time of <0.025sec (meeting the IEC 60479-2 requirements [25]). The device detects DC faults using di/dt magnitudes and not steady state fault current magnitudes. To date, this DC protective device has been used as a proprietary solution for low power loads (<16A), and not available for higher ratings (e.g. 100-400A) [10].

4.3 LVDC Earthing Arrangements

Based on the operational characteristics of the ST and expected DC loads, this section makes a recommendation for the most appropriate earthing configuration that is compliant with UK wiring regulations.

4.3.1 Earthing arrangements for Scheme-4

Depending on the design of the ST, the LVDC supply voltage for Scheme-4 could be provided as a 2-wire system (i.e. 700V_{dc} with droop band ±50V) or a 3-wire system (i.e. ±700V_{dc} with droop band ±50V) in addition to a separate earthing conductor connected to the system earthing point at the substation as

shown in

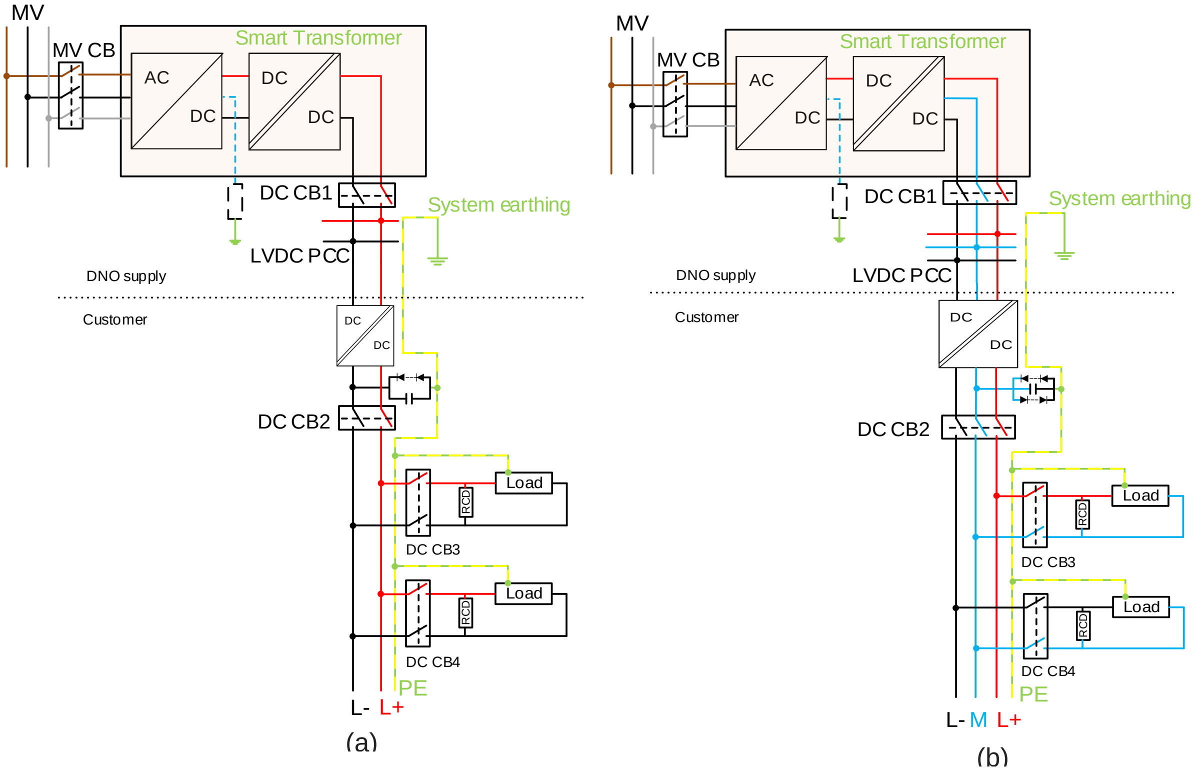


Fig- 9. The positive (L+) and negative (L-) poles from the ST terminals to the customer's boundaries (DC-DC converter) will not be earthed. This can be similar to the existing practice of 3-wire 11kV in MVAC distributions. Between the supply side ($700V_{dc}$) and the customer, and as explained previously in Fig- , a DC-DC converter with isolation transformer will be used to bring the voltage to a level within the safety margins as identified by the IEC 60479 which can be protected by 30mA residual current devices (RCD) against personnel indirect contact faults.

The earthing conductor can then be connected to the copper sheath of the cable connected to the output terminals of the customer's DC-DC converter. It is worth emphasising, that LVDC installation will work only as a TN-S to avoid the impact of corrosion.

In the 2-wire LVDC and as shown in

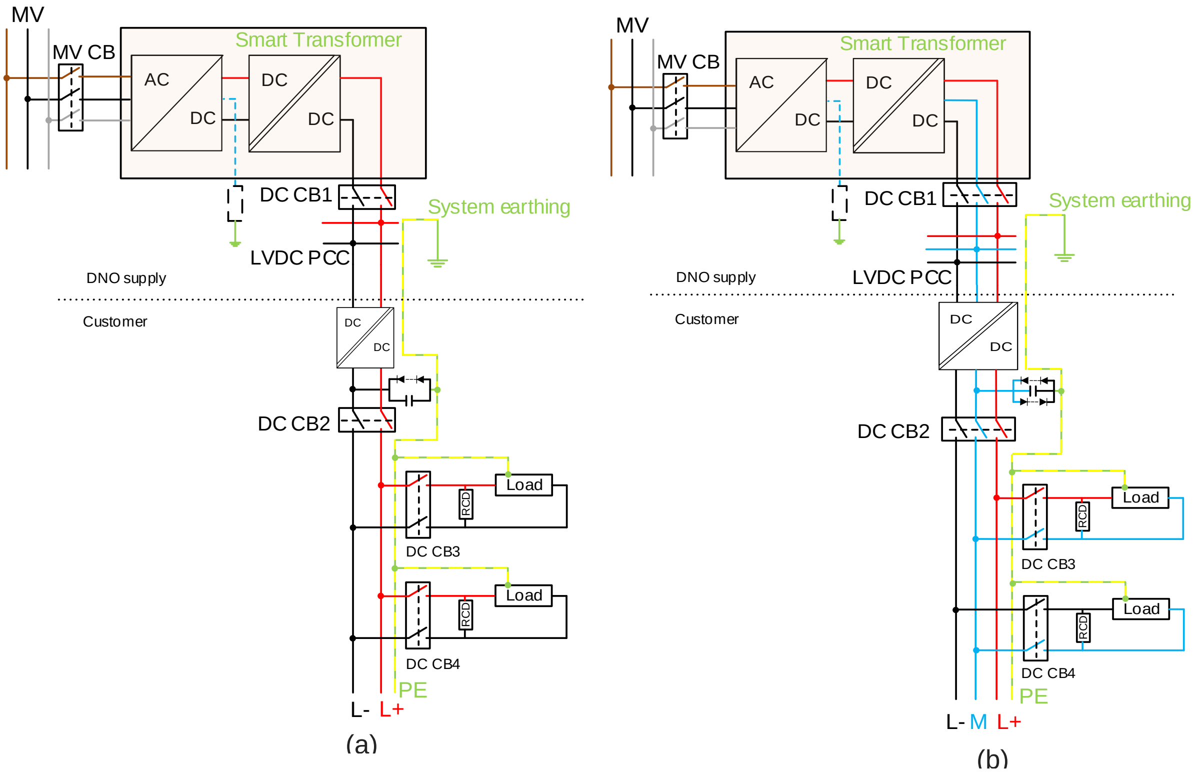


Fig- 9 (a), the TN-S configuration needs to be formed using diodes or diodes in parallel with a capacitor to connect the protective earthing (PE) conductor with the negative pole (L-) conductor. The cathode of the diode should be connected to L- and the anode should be connected to PE (a number of diodes in series can be used to withstand the fault current ratings). This will ensure no earthing current leakage during normal operation as the diode(s) will act as an open circuit, and provide earthing during a L+ to PE fault. Just a few mAs of earthing current leakages could lead to corrosion of the metal surfaces connected to the PE.

As for the 3-wire LVDC and as presented in

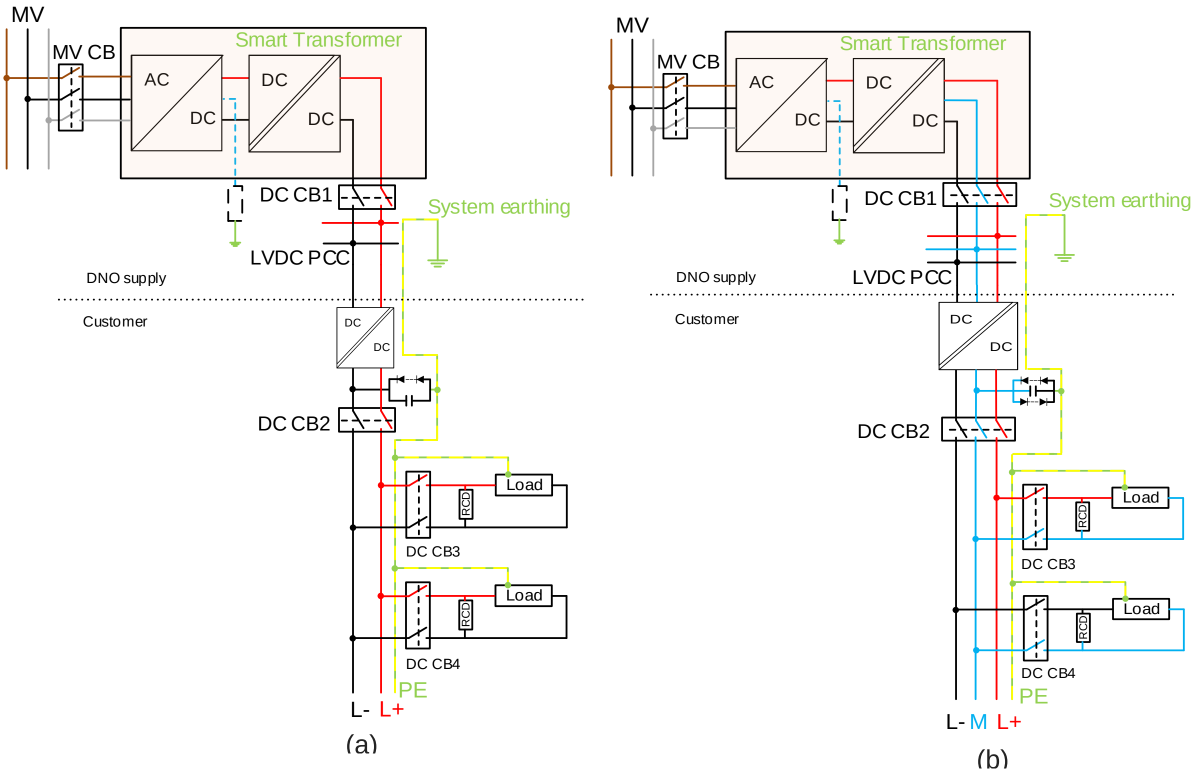


Fig- 9 (b), the TN-S is formed using anti parallel diodes connected in parallel with a capacitor to connect the protective earthing (PE) conductor with the mid-point (M) conductor. The anti-parallel diodes will ensure the provision of the required earth paths for L+ to PE and L- to PE faults.

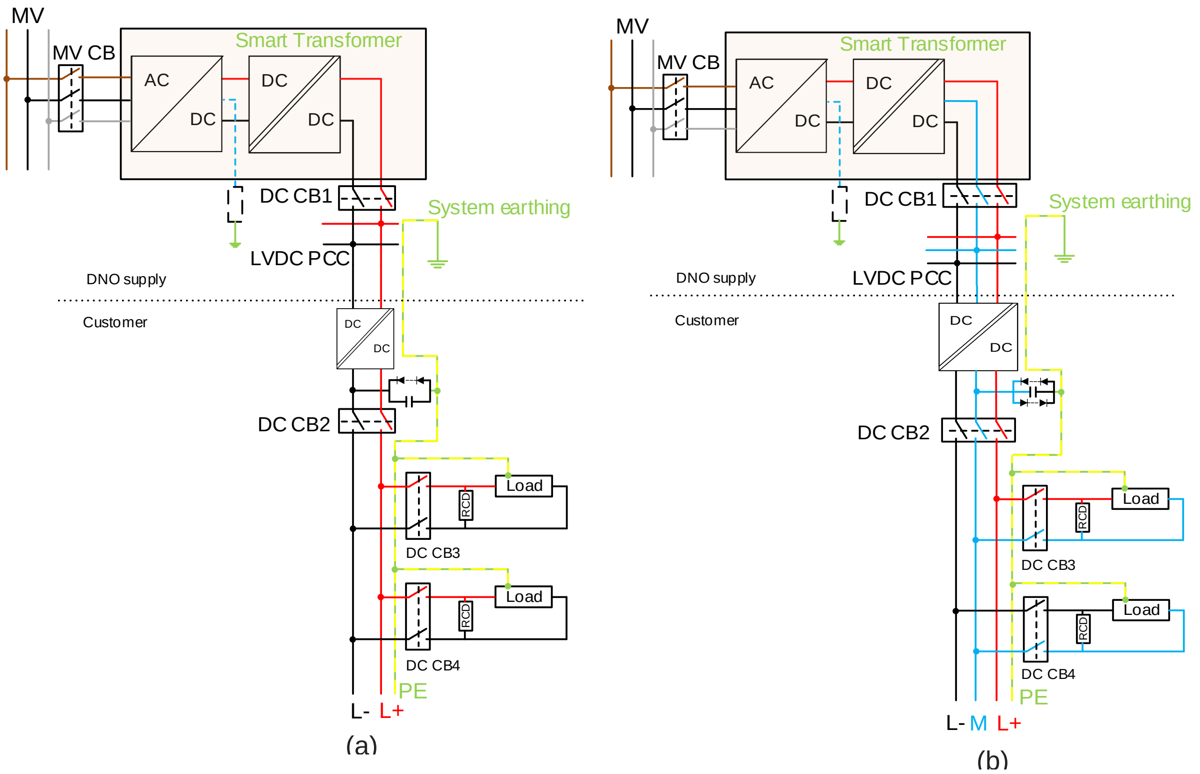


Fig- 9: Earthing arrangements for scheme-4: (a) uni-polar (2-wire) LVDC network and (b) bi-polar (3-wire) LVDC network

4.3.2 Earthing arrangements for Scheme-5

The earthing configuration of Scheme-5 where the ST provides both AC and DC outputs requires more careful condiseration. The same earthing system point could potentially be used and connected to the AC neutral (N) point to provide TN-C-S as shown in Fig- 10 and Fig- 11 for the LVAC network and connected to the LVDC customer side through diodes and a capacitor to provide a LVDC with TN-S configuration. On the LVDC side, it is very important to ensure good isolation between the PE and the L- (for 2-wire systems) and the PE and the M (for 3-wire system), and this is not just to avoid the impact of corrosion, but also to eliminate the impact of common-mode noise currents between AC and DC under normal operation. Also, it is very important for the DC-DC converter that interfaces the DNO to the customer includes galvanic isolation to ensure the LVDC network remains isolated from the LVAC network.

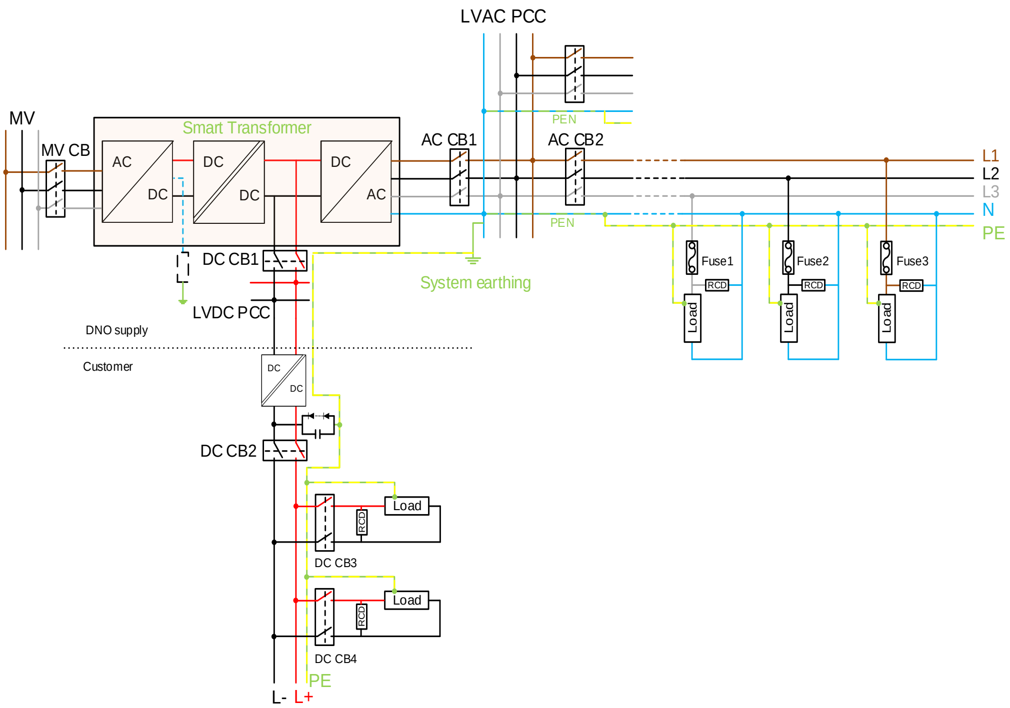


Fig- 10: Earthing arrangements for scheme-5 hybrid LVAC/LVDC with 2-wire LVDC configuration

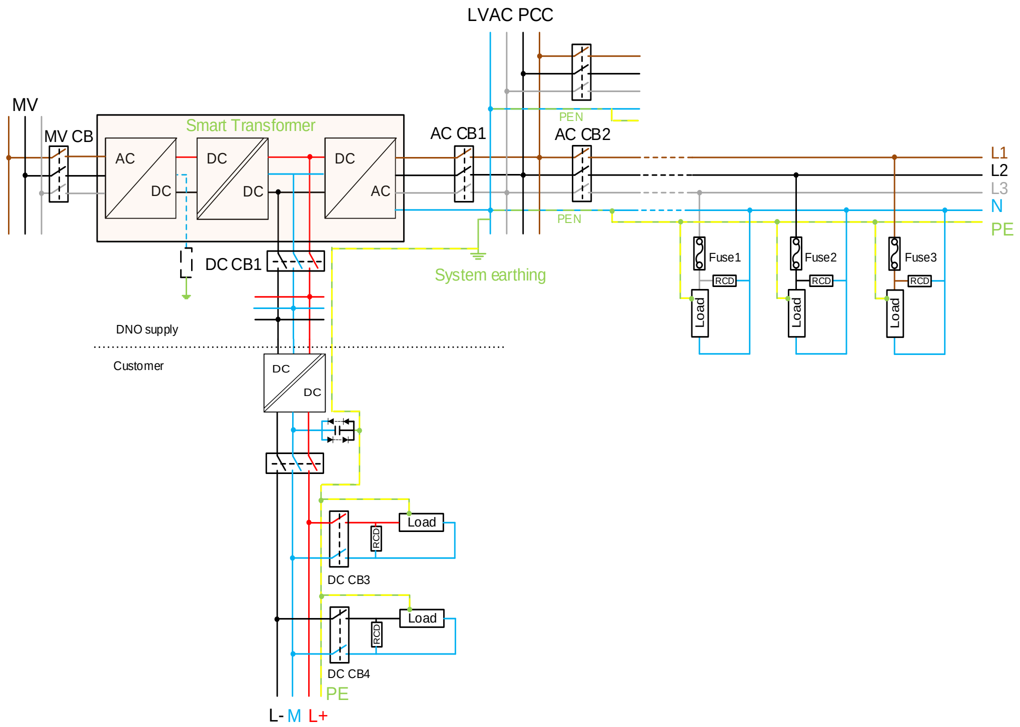


Fig- 11: Earthing arrangements for scheme-5 hybrid LVAC/LVDC with 3-wire LVDC configuration

4.4 Recommended Protection Strategy

In general, DC protection systems need to isolate DC faults far faster than conventional protection because of two reasons: One is the rating issue due to the limited short circuit handling capability of the ST power electronics, and the other is an operational issue due to the sensitivity of ST to DC link voltage collapse caused by faults with high risk of tripping the ST. Stressing the LVDC voltage link for a relatively long time will also have direct impact on the LVAC customers' voltage when Scheme-5 is considered. Addressing such problems will require DC protection operation within a few milliseconds. Consequently, using conventional LV breakers or fuse blowing schemes based on inverse time-overcurrent characteristics will not guarantee meeting such requirements. It is true that inverse time-overcurrent protection can be easily coordinated with overload protection and have relatively low pickup current to detect the fault quickly, but the time to completely clear the fault will be slow at reduced low fault currents.

This section recommends the following two options that are independent of the fault current magnitudes when the faults are detected, and can be used to protect Scheme-4 and 5 against external DC faults.

- For the purpose of simplicity and cost, LVDC mechanical breakers with Definite Time Overcurrent (DTO) relay characteristics can be used to protect the DC outgoing feeders and the load. A predetermined pick-up current setting value (shown as I_p in Fig-) can be set to detect the fault (e.g. 1.1-1.2pu depends on the ST fault contribution), and the desired tripping time (shown as t_t in Fig-12) can be set irrespective of the fault current magnitude. The DTO relay can also be easily coordinated with other DTO or instantaneous protection located on the load side. It is important to ensure the breaker does not trip on load starting currents. In some cases and since the DC loads can be capacitive in nature a high current might be drawn when such loads are connected. This can be addressed by setting the DTO pick-up current to be higher than the starting current but this option is not desirable, as the fault sensitivity of the breaker will be reduced. The other option is to set the breaker operation time (t_t) to be longer than the time of the transient starting currents (t_s), and DTO relay will reset when the starting currents fall below the relay pick-up current value. In general, DC transient starting current will last only for very few milliseconds (<5ms).

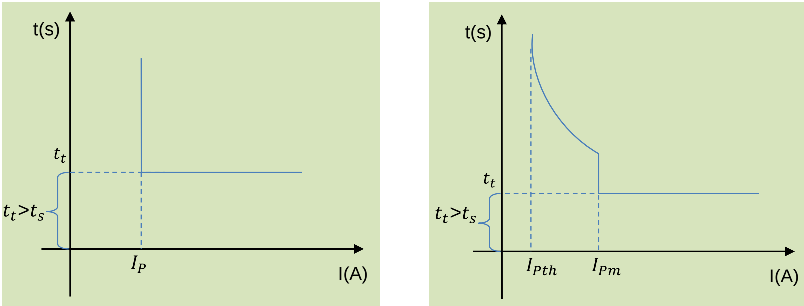


Fig- 12: Definite time overcurrent relay characteristics

Table 3: Examples of commercially available breakers

Network Manufacturer	Type/Name	Trip Type	Ratings	Applications
Eaton	DC and PVGuard MCCB	Thermal Magnetic	150A-3000A, 600-1000VDC	Earthed or unearthed systems for EV charging, BESS, UPS, industrial.
ABB	SACE Tmax	Thermal Magnetic	Up to 1200A and 1500V_{dc}	Solar PV
Schneider	PowerPact	Thermal Magnetic	30-1200A, up to 600V_{dc}	Battery, data centres, health care.
Siemens	VL600 VDC MCCB	Thermal Magnetic	50A – 1600A, up to 600V_{dc}	Solar PV

- The other option is the use of more advanced fault detection methods which can be implemented through mechanical breakers equipped with electronic trip units (measured parameters processed by a microprocessor), or used with solid state circuit breakers (SSCBs). Two examples of DC breakers with electronic trip units are listed in Table 4.

The SSCB devices are currently not standardised and implemented only at trial stages. As an example, a device with lower ratings called "DC Current Router" with 16A solid-state circuit breaker (SSCB) has been used in DC powered greenhouses and DC buildings in the Netherlands. Currently, a 100A DC current router is under development and will be ready at the end of 2018 [26]. The current router is embedded with an SSCB which can detect and clear

DC faults within 8µs. The router also contains an RCD which can be set for different range of residual operating currents 1-80mA with 0.1s operating time or 80-500mA with operating time <0.025sec (meeting the IEC 60479-2 requirements). The router is also fitted with advance measurements, kWh meter, and communication.

Table 4: Examples of commercially available electronic breakers

Network Manufacturer	Type/Name	Trip Type	Ratings	Applications
ABB	SACE EMax DC Circuit Breakers	Electronic trip unit	Up to 5000A and 1000V_{dc}	Solar PV, industrial, marine power systems.
Direct Current BV	N/A	SSCB	16A at 700V_{dc}	DC LED lighting systems in green houses
Schneider	Micrologic trip units	Incorporated with standard MCCB products	See Masterpact and Powerpact products	Several applications: For enhanced protection system control

5 Further Safety Considerations

In addition to the protection and earthing solutions outlined in the previous section, the following safety aspects should also be considered:

- Installation and servicing standard operating procedures (LVDC training for electricians)
- Capacitor discharging requirements prior to servicing
- Independent isolation of DC side and AC side
- Lightning / surge protection – especially for street lighting applications
- Fault location on DC side
- Balancing power demand between the AC network and DC network.

6 Site Selection Criteria

There will be much learning associated with these trials and therefore customer disruption is likely to be high. It would be prudent to select a trial location that will have minimal disruption to LVDC customers during the commissioning and testing phase. Ideally, the site should coincide (or pre-empt) with other infrastructure upgrade works such as laying of new lighting cables or the planned implementation of EV charging infrastructure. Consideration should also be given to the DC supply contract between the customer and SPEN during and after the LV-Engine trial. In the case of AC customers, it is possible to revert to existing AC infrastructure but for DC customers it may be necessary to provide a permanent DC supply during testing of the ST and beyond its operational lifetime. For LVDC trials, it seems logical to begin with the direct LVDC ST and gradually add more complex LVDC customers to the network using a progressive implementation approach. Once the control, protection and operation of the LVDC networks have been assessed, it will be easier to apply the lessons learned to a hybrid AC/DC ST trial.

7 From Trials to Business As Usual

Although these LVDC trials focus on relatively simple LVDC applications such as street lighting and EV charging, there are an increasing number of new DC-based electrical customers that may benefit from a public LVDC supply such as: data centres, commercial office spaces and even residential households. The use of LVDC distribution has primarily been considered at an academic and research level to date but LV Engine offers the opportunity to test the application of public LVDC distribution in real networks.

These trials will quantify the benefits of LVDC over traditional LVAC networks and will work towards establishing the public distribution standards for LVDC connections.

In terms of a development trajectory, the strategy outlined in this document takes a measured approach to applying LVDC to low-power/low-risk applications first with new cable infrastructure and then, with the lessons learned from these initial deployments, more complex trials can be attempted. The use of LED street lighting is growing within the UK and internationally and it seems logical to offer a dedicated DC supply to these homogenous and isolated networks. However, not all street lighting systems possess their own dedicated cable network and many lighting columns are individually supplied from the main DNO LVAC cable distribution system. It may therefore be worth attempting to quantify the number of independent street lighting networks in the UK, their cable configurations and whether they would be suitable for a LVDC supply.

All technical, social, political and economic indicators demonstrate that EV adoption is on the precipice of exponential growth. Many Local Authorities are already struggling to meet the demand for urban EV charging infrastructure, therefore any opportunity to facilitate the cost-effective connection of charging infrastructure will be welcomed. In this trial project, the implementation of a High Power Charger should perhaps be undertaken in conjunction with a local authority or city that is simultaneously introducing electric taxis or buses, therefore a high utilisation rate of the charger will be expected during the trial phase.

The prospect of integrating EV charging into the street lighting network is appealing as it will increase the utilisation of existing electrical distribution assets and reduce the presence of ‘street furniture’. However, further consideration is required with respect to street-lighting columns that are setback from the curbside of the pavement. The City of Oxford EV trial project is testing an in-ground charging pillar by Urban Electric that retracts underground when not in use [27] and this may also be appropriate for integrated LVDC street lighting and EV charging, where existing lamp-posts are set-back from the curbside (for new street-lighting installations, with EV charging, it is highly recommend that the lighting columns are positioned at the curbside of the pavement). Further EV and smart street-lighting trial projects are on-going in the City of Glasgow through the EU funded Ruggedised Project, which may welcome the incorporation of LVDC distribution.

8 Conclusions

This report has reviewed the options available for testing the application of public LVDC distribution in conjunction with a ST. It is assumed that the aim for LV Engine is to identify a standard ST specification that will deliver LVDC power efficiently to a variety of future customers. The following points summarise the main design recommendations and topics for further discussion:

- The public LVDC supply should arguably be delivered at the highest voltage available within the standards to minimise losses and maximise future power transfer capacity. It is therefore recommended that +/-700V_{dc} voltage be adopted which allows for a voltage rise of +50V_{dc} while remaining within the LVDC IEC standards. However, this may be reconsidered if the ST design can be optimised for cost and efficiency at a lower voltage or with a uni-polar output.
- For new and/or conversion of existing public distribution cables, both 3-core and 4-core cable with concentric earthing sheath have been successfully used in prior international LVDC trials. The 4-core cable will optimise power transfer under a bi-polar distribution regime but questions remain as to whether the earthed sheath has the capacity to support load imbalances. It is therefore recommended that within these trials, a dedicated core for mid-point return is used in either the 3-core or 4-core cable configurations.
- The system boundary between the public LVDC supply and the customer’s LVDC application requires further discussion but it is suggested that the boundary is located before the customer’s DC/DC converter. This would require the DNO to be responsible for a fixed voltage power supply with standard voltage drop and droop characteristics, allowing potential

customers to design their LVDC network/application to conform with the standard, public LVDC supply from SPEN.

- For the LVDC distribution system, a TN-S earthing system is required to minimise the effects of corrosion but the LVAC system may utilise a standard TN-C-S earthing configuration. Considering the limitations on fault current from the ST, it is suggested that either LVDC mechanical breakers with Definitive Time Over-current relays are used, or alternatively mechanical or solid-state breakers equipped with a microprocessor and specialised protection algorithms may also prove suitable if they become commercially available.

It is recommended that this document is updated in an iterative process once the following information is obtained:

- Existing cable specifications for street lighting networks that may be considered for this trial project. This varies between local authorities; each authority currently sets their own street lighting design specifications in terms of cable type and wiring configuration.
- Further communication is required with DC product suppliers to create a confidential spreadsheet with each manufacturer's DC power supply requirements to ensure that the final LVDC Public Supply specifications are compatible with the early DC product manufacturers.
- An analysis between the ST cost for both a bi-polar and uni-polar DC output should be considered and evaluated against the power transfer capabilities in each regime.
- Risk management options for DC customers should be considered during the testing and trials of the ST: AC customers can be supplied through existing assets in the event of a fault to the ST but a back-up DC supply may be required for specific DC customers.

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