LV ENGINE

Overview of existing standards and engineering recommendations relevant to LV Engine schemes with LVDC outputs

About Report

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Table of Contents

Glossary

Abbreviation	Term
AC	Alternating Current
CB	Circuit Breaker
DAB	Dual Active Bridge
DC	Direct Current
DCODE	Distribution Code
DER	Distributed Energy Resource
DNO	Distribution Network Operator
DOC	Distribution Operating Code
DPC	Distribution Planning and Connection Code
EMC	Electromagnetic Compatibility
ENA	Energy Networks Association
ER	Engineering Recommendation
ETR	Engineering Technical Report
ESQCR	Electricity Safety, Quality and Continuity Regulations
EV	Electrical Vehicle
GB	Great Britain
GSP	Grid Supply Unit
HV	High Voltage
IEC	International Electrotechnical Commission
IP	International Protection
IT	'I': No point is connected with earth (Isolation), except perhaps via a high impedance. 'T': Direct connection of a point with earth (Latin: Terra)
LCT	Low Carbon Technology
LV	Low Voltage
LVAC	Low Voltage Alternating Current whose nominal r.m.s. voltage ≤1kV
LVDC	Low Voltage Direct Current whose nominal voltage ≤1.5kV
MCCB	Moulded Case Circuit Breaker
PCC	Point of Common Coupling
PE	Protective Earthing
PFC	Prospective Fault Current
SPEN	SP Energy Networks
ST	Smart Transformer
TN	'T': Direct connection of a point with earth (Latin: **T**erra) 'N': Earth connection is supplied by the electricity supply **N**etwork
TN-C	TN with a **C**ombined PE conductor and an N conductor
TN-C-S	A **C**ombined PEN conductor occurs between the substation and the entry point into the customer installations, and earth and neutral are **S**eparated in the service head.
TN-S	PE and N are Separate conductors and connected together only at source
VLD	Voltage Limiting Device
VSC	Voltage Source Converter

Executive Summary

This report presents the outcomes of the University of Strathclyde LV Engine Task 2 work on review of existing standards and engineering recommendations which can be considered to support the trailing phase of SP Energy Networks LV Engine schemes with low voltage direct current (LVDC) outputs. The SP Energy Networks LV Engine project aims to design and trial the deployment of an electronic smart transformer (ST) within power distribution secondary substations. The ST deployment will be trialled within five different schemes, two of which will provide LVDC supply, and the remaining three will provide conventional 0.4kV alternating current (AC) supply with different network configurations.

Smart transformer deployment with LVDC distribution has the potential to provide a reasonable platform for implementing smart controls and configurable/modular interface design which can be scaled when more power capacity is required. LVDC distribution systems with higher voltages (i.e. >0.4kV) can also provide increased power transfer capacity to supply more loads (e.g. accommodate future growth in transport and heat demand).

However, the ST technology and its associated LVDC systems are not mature technologies. There is still a shortage of experience, appropriate standards and technical guidance on how to design, test, optimise, operate, and protect such new systems. Therefore, this report collates and reviews the available standards, technical guidance, code of practices, and engineering recommendations that are required for LV Engine LVDC solutions to comply with and validated against during the design, testing and deployment phases. The report also discusses the readiness level of the current Great Britain (GB) Distribution Code (DCODE) for accepting ST and LVDC technologies. The focus of the report review is limited to the supply terminals side of the LVDC and does not cover installations on DC customers' side.

The report has identified six land-based LVDC application areas. These include LVDC in buildings, LVDC for street lighting and EV charging, LVDC for last mile distribution, LVDC for telecommunication systems, LVDC for data centres, and LVDC for traction and rail systems. Among these areas, only LVDC for telecommunication systems and DC traction systems are considered as mature technologies and covered well by standards. DC traction system is obviously more relevant application to the LV Engine LVDC schemes. This is because DC traction systems are normally supplied by AC-DC rectifiers or controlled converters located at secondary substations, and also operate at DC voltages close to the range that will be considered for LV Engine LVDC schemes (600 < V <1500 V DC). Therefore, and in addition to other relevant LVDC international standards published by International Electrotechnical Commission (IEC), the report has reviewed existing DC traction systems British standards that are relevant to installation of power-electronic convertors at secondary substations, and discussed their adequacy for ST-based substations with LVDC outputs. The report key findings are listed as follows:

- The introduction of ST and LVDC distribution systems brings radical changes to the way that: HVAC grid supply is interfaced to LV networks; electricity is distributed and protected; and end-users are connected. Such changes will inevitably make existing standards and other important documents such as GB Distribution Code (DCODE), engineering recommendations and other associated technical guidance and code of practices to be subject to changes and new updates for accommodating ST and LVDC systems.

- Updating engineering recommendations, DCODE, and other technical guidance for considering LVDC distribution systems urgently require a definition of nominal operating LVDC voltage(s) which such documents can be harmonised at. The EU LV Directive (LVD) 2006/95/EC and the IEC 60038 have defined the LVDC supply range to be =<1500 V. The IEC 60038 has divided the LV in DC systems into two bands. From 120-1500 V is defined as an LVDC band and <120 V is an Extra LVDC (ELVDC) band. All the physiological impact of DC current electric shocks on humans and livestock across these two bands are well understood and covered by IEC 60479. But no standard operating voltage(s) for utility-owned LVDC public distribution networks has been defined yet by any existing standard.

- For DC rail and traction systems, the IEC 60038 and BS EN 50163 have recommended three DC nominal voltages 600 V DC, 750 V DC, and 1500 V DC. These voltages are widely adopted in UK traction systems, and 750 V DC voltage is the most common nominal voltage example used by UK rail systems. 750 V DC has also been implemented by utility-owned public LVDC distribution networks pilot projects in Finland and South Korea.

- The report has concluded that during the LV Engine LVDC trials phase, most of the key operating and testing requirements of power-electronic converters intended to be installed at a distribution substation for DC traction systems and covered by BS EN 50328 can be applicable for design, test, and install ST-based substation with LVDC outputs. These include: ***electrical service conditions*** such as safety, earthing, and DC protection requirements; ***environmental conditions*** such as converter operating temperature, converter storage and transport, humidity level, pollution degrees and etc.; ***mechanical characteristics*** such as protection degree of converters enclosures, mechanical vibration levels, and clearance distance; ***converter assembly testing specifications*** such as insulation test, load functional test, power loss determination, temperature-rise test, and supplementary testing related to checking of auxiliary devices, control equipment, protective devices, and short-time withstand current test. The BS EN 50328 also provides ***recommendations on information*** which can be exchanged between the converter unit purchaser and the suppliers.

- DC traction systems have relatively large DC voltage tolerances (i.e. +25% and -33% of nominal voltage) due to the homogenous electrical load and predictable load requirements. This cannot be applicable to utility-owned LVDC networks supplying public loads due to the requirement of tighter power quality tolerance. The only available standard which considers tighter voltage tolerance is IEC 60092 for electrical installations in ships. The standard defines steady-state DC voltage deviation limits to be no more than ±10% of the nominal voltage. This voltage variation limit is closer to voltage limits that existing LVAC distribution networks apply, and it has been also adopted by many studies in literature.

- Unlike AC systems, the unidirectional flow of DC current will increase the risk of electrolytic corrosion of earthed metalwork and structural steelwork in contact with the earth. When LV Engine LVDC schemes are trialled, corrosion prevention measures will be required. There is no technical guidance or standard on how to earth LVDC supply terminals for public networks and mitigate electrolytic corrosions. However, the BS EN 50122 and the ER G12 and based on DC traction experience have recommended neither of DC poles to be directly connected to the earth in order to minimise the risk of electrolytic corrosion of earthed equipment due to stray DC currents. Voltage limiting devices (VLD) standardised by EN 50526-2 are widely used for DC earthing in traction systems to meet such safety requirements. The adequacy of using VLD for LVDC public network may require further investigation and testing.

- Assuming that the LV Engine LVDC trials have achieved their objectives, and for the transition from the trials phase to the business as usual phase, the existing GB DCODE has to be updated to cover the technical requirements of electronic-based substations and DC distribution. For example, the Distribution Planning and Connection Code (DPC) of the DCODE needs to address the following questions. What DC connection voltage(s) should be provided to the customer? What are the configuration options of LVDC supply (e.g. 2-wire or 3-wire)? How reliable is ST-based substation and DC supply? How should DC DNO supply be interfaced to DC end-users' installation?

- For the LV Engine LVDC schemes, it is expected that the trial DC supply voltage to be higher than the maximum touch voltage that has been identified by IEC 60479. This will technically require DC-DC decoupling interface with galvanic isolation between the supply and the customer to meet the IEC 60479 safety requirements. Such an interface is new to the network and can bring new control capabilities such as bi-directional power flow, control of voltages on the customers' side, active energy management and etc. Such changes will require new operating procedures which currently are not covered by the existing Distribution Operating Code (DOC) of the GB DCODE. Relevant questions need to be answered in order to comply with the DCODE include: what type of information will be required and how can be communicated between the users and DNOs? How should the customer and supply be interacted when a new decoupling interface with active control capability takes place between the supply and the customer and who should own it?

- With current situation of LVDC distribution technologies, the Electricity Safety, Quality, and Continuity Regulation (ESQCR) (25) may not allow the connection of DC customers' installation to a public DNO DC supply due to the lack of BS standards on DC safety and protection for DC public networks. The current BS 7671 Wiring Regulations which have to be complied with to meet the ESQCR 25 do not cover the technical requirements of DC-DC interfaces between the supply and the customers' installation.

- To meet new connection requirements and to comply with ESQCR, the DNO also needs to provide the maximum prospective short circuit current at the supply terminals. Accurate DC fault level and DC short characterisations are still missing from ERs such as existing ER G74 and ER P25 (their focus is limited only to AC systems). The only available standard which has been used for characterising faulted DC auxiliary systems in power plant and substations is the IEC 61660. This standard provides a simplified method of calculation of prospective DC short-circuit current for rectifiers in 50Hz 3-phase AC bridge connection, stationary lead-acid batteries, smoothing capacitors, and DC motors. But, IEC 61660 may not be sufficient for DC fault characterisations of advance power-electronic interfaces such as modular ST with fault current management capability, where such features are covered by the standard.

- To enable GB DCODE for considering new technologies such as ST and LVDC systems to be integrated within the UK distribution networks, more work is needed by ENA for making key ERs such as ER G12, ER P2/6, ER P29 and P28, ER G74, ER P25, and ETRs such as 130 and 131 to consider LVDC technologies. Such requirements are currently challenged by the lack of LVDC standards at UK and at international level. The IEC has stated that there are over 30 IEC technical committees (TCs) need updating in order to add the standards requirements for DC into existing AC standards to cover planning, designing and implementation, communication, information exchange, control and systems security.

- These are in addition to the lack of skills geared towards LVDC in relation to designers, installers, and maintainers. The experience that will be extracted from the LV Engine LVDC schemes during the trials phase supported by the experience from DC traction systems and other LVDC applications will play an important role for filling the gaps in the skill sector required for advancing LVDC technologies and development of new associated standards.

List of figures

1. INTRODUCTION

1.1. Background

The growth of emerging low carbon technologies (LCTs) such as distributed renewables, and electrification of transport and heat demand, combined with energy efficiency requirements, have increased the need for enhancing the flexibility and controllability of existing secondary substations and their associated low voltage (LV) networks. In response to these, the SP Energy Networks (SPEN) LV Engine project has key objectives to design and trial the deployment of first electronic smart transformer (ST) within UK electric power distribution networks. The ST deployment will be trialled within five different schemes, three of which will provide conventional 0.4kV alternating current (AC) supply with different network configurations, while the remaining two will provide low voltage direct current (LVDC) and hybrid DC/AC supply.

LVDC distribution systems have the potential to provide more suitable infrastructures to integrate smart information and communication technology (ICT) systems, connect local generators with reduced voltage conversion stages, and provide different voltage levels with potential to increase LV power transfer capacity. The design and deployment of LVDC distribution networks has been considered as one of the key innovative parts of the LV Engine project.

The ST and the introduction of LVDC supply will present revolutionary changes in existing secondary substations. The deployment of ST will act as a decoupling interface between the high voltage (HV) AC distribution grid and the associated LV networks. This will obviously lead to new requirements for how to design, test, operate, and protect ST-based substations and their related DC supply terminals. To date, there is a shortage of experience, appropriate standards and technical guidance to address such new requirements. Therefore, this report reviews relevant existing standards and regulations, and evaluates their adequacy for supporting the design, testing, and implementing ST and LVDC solutions of the LV Engine schemes during the trial phase of the project.

1.2. Report scope and objectives

This report collates and reviews the available standards, technical guidance, GB Distribution Code, code of practices, engineering recommendations, and other regulations (e.g. the Electricity Safety, Quality and Continuity Regulations (ESQCR)) that are required for LV Engine LVDC solutions to comply with and validated against during the trials phase. The report focus is limited to the supply side of LVDC distribution networks and does not cover end-users' LVDC installation side.

The report is also aimed to identify the cases where the ST-based substation and LVDC developed solutions cannot be compliant with standards due to the lack of standards or due to the need for further modifications to existing standards.

1.3. Report structure

The report work is structures as follows:

- Section 2 provides a brief description of LV Engine LVDC schemes (4 & 5) which the review of this report is related to.
- Section 3 discusses key documents and ongoing international standards activities which are relent to DC-based substations and LVDC supply.
- Section 4 discusses in details key technical parameters and environmental conditions which can be considered during the trialing of LV Engine LVDC schemes.
- Section 5 outlines the key findings of the report review and the gaps in existing standards and GB DCODE which require further development for enabling the transition of LV Engine LVDC schemes from trialling phase to business as usual phase.
- Finally, the conclusions of the work are given in section 6.

2. LV ENGINE LVDC SCHEMES

The work of this report refers to LV Engine scheme 4 and 5 (i.e. with LVDC outputs). The schemes are described in detail in the main LV Engine project proposal [1] and are summarised as follows.

2.1. LV Engine Scheme 4

Scheme 4 is an LVDC supply scheme (see Figure 1) with the aim of demonstrating the requirements for design, installation and operation of an LVDC network using an ST.

2.2. LV Engine Scheme 5

Scheme 5 is shown in Figure 1 and provides hybrid AC/DC supply outputs from the ST. Scheme 5 will demonstrate optimal design, installation and operation of a hybrid LVDC and LVAC network.

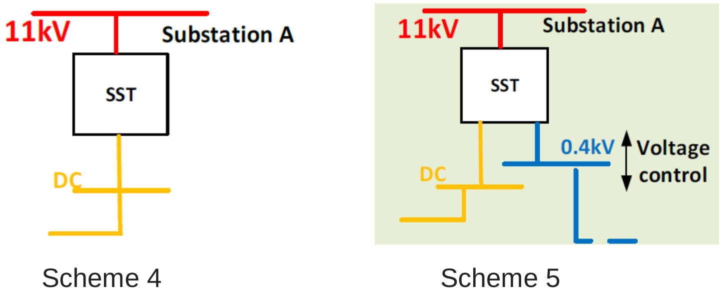

Figure 1: LV Engine scheme 4 and scheme 5 layout [1]

3. OVERVIEW OF EXISTING RELEVANT LVDC STANDARDS

It is important to understand the definition of LVDC supply in terms of voltage levels in order to identify the relevant standards and technical guidance which can be considered for trialling LV Engine schemes 4 and 5. The EU Low Voltage Directive (LVD) 2006/95/EC and the IEC 60038 define 1500 V as the maximum voltage to be considered as a low voltage DC compared to 1 kV for LV AC systems [2][3]. The IEC 60038 and IEC 61140 have divided LV in DC systems into two bands. From 120 V-1500 V is defined as an LVDC band and =<120 V is an Extra LVDC (ELVDC) band. Across these two bands and as presented in Figure 2, different LVDC applications have recently emerged or already been widely implemented. Examples include DC within buildings, DC for lighting and EV charging, DC for last mile distribution, DC for telecommunication systems, DC for data centres, and DC for traction and rail systems. Most of these LVDC applications are still at early stage of development, and the only two applications which can be considered as mature and covered well by existing standards are DC telecommunication systems and DC traction systems [4].

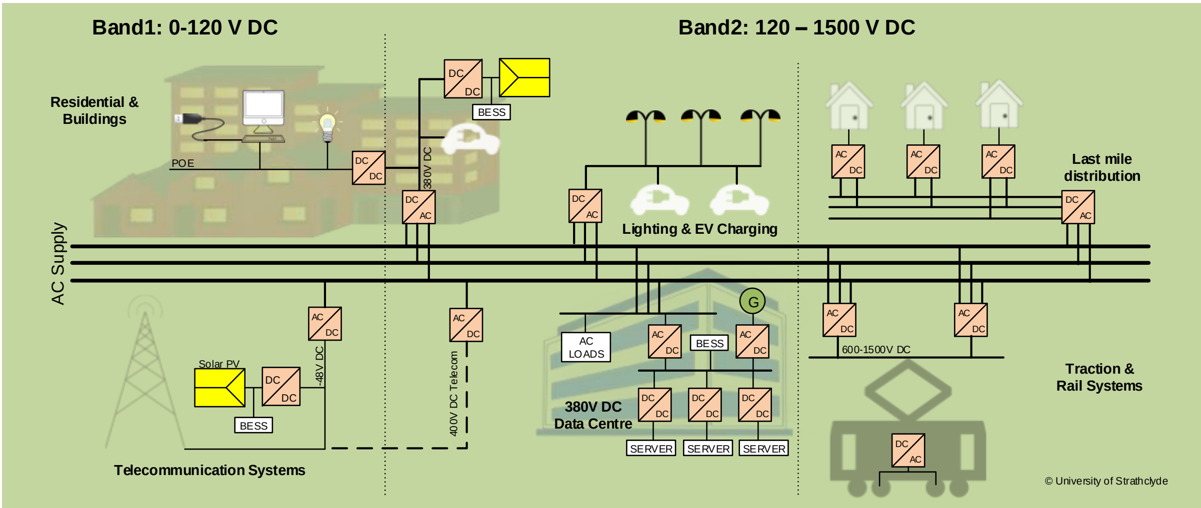

Figure 2: Overview of LVDC distribution systems applications [4]

Considering the DC supply voltage levels (see Figure 2), high power DC traction system is the most relevant application to ST-based substation with LVDC outputs. This is because DC traction systems are normally supplied by rectifiers/converters located at secondary substations, and also operate at DC voltages close to the range that will be considered by LV Engine project for LVDC supply (e.g. 600-1500 V DC). The IEC 60038 [3] and BS EN 50163 [5] have recommended three DC nominal voltages 600 V DC, 750 V DC, and 1500 V DC for DC traction systems within the LVDC voltage band (i.e. =<1500V). These voltages are widely adopted in UK traction systems. In addition to the experience from DC traction systems and their associated design and operating standards, there are also a number of ongoing international LVDC standards development activities which can provide useful input for supporting the design of LV Engine LVDC schemes. The key documents and international standard development activities which are considered by this report are discussed as follows.

3.1. Distribution Code of Great Britain

The Distribution Code (DCODE) (obligated by Ofgem Distribution Licence) is a core industry document that sets out the technical specifications for planning, designing, developing, and operating power distribution networks in Great Britain (GB) [6]. It also outlines the technical requirements for connecting equipment to the GB distribution networks, and helps existing and potential electricity users to understand what performance they can expect from distribution network operators (DNOs) and what is expected from them as users. The users that DCODE applies to as listed in [7] include demand customers, suppliers, embedded generators, other authorised distributors (i.e. Independent Distribution Network Operators (IDNOs) or private networks), and meter operators.

On the supply side and within the current version of the DCODE, the Distribution Planning and Connection Code (DPC) considers the technical design and operational criteria and procedures that are suitable only for AC distributions systems [7]. Electronic-based substations or DC distribution systems are not considered by the existing DCODE document.

On the users' installation side and as stated in the DCODE, user's installation connection or modification of connection can be accepted only if it complies with the principles identified in Regulation 25 of the Electricity Safety, Quality and Continuity Regulations (ESQCR). To meet the ESQCR requirements, the end-user's installation has to comply with BS requirements (e.g. the IET Wiring Regulation BS 7671) and to be designed, constructed, and protected in the way that operates safe. To date, the only available document for LVDC installations based on BS 7671 is the IET LVDC Code of Practice [8]. The scope of this document is limited only to LVDC wiring/rewiring for buildings to be connected to an AC supply, and it does not cover connection to DC supply or the interface requirements between the DNO supply and the end-user's installation.

Within existing DCODE, and once the customer is connected to the distribution network, the DNO requires certain information as specified in Distribution Operating Code (DOC) [7]. The DOC outlines the operating procedures at the interface between the DNO and the end-users. For the LV Engine LVDC schemes, it is proposed by the University of Strathclyde report on LVDC technical recommendation [9] that the DNO DC supply and the DC customers to be interfaced by a DC-DC converter with an isolation transformer. Such an interface is a new to the network and it has the capability to provide new local control functionalities (e.g. bi-directional power flow, control of voltage on the customer side, active energy management and etc.). This will require new operating procedures which currently are not considered by the existing DOC of the GB DCODE.

3.2. Engineering Recommendations

Table 1 lists the Energy Networks Association (ENA) Engineering Recommendations (ER) and Engineering Technical Reports (ETR) which are considered by this report, and are implemented or have an impact to the GB DCODE [6].

Table 1: List of relevant Energy Networks Association Engineering Recommendations and Technical Specifications to GB DCODE

ER code	Year of publication	Title
Engineering Recommendation (ER) G12	2015	Energy Networks Association, Requirements for the Application of Protective Multiple Earthing to Low Voltage Networks
Engineering Recommendation (ER) P2/6	2006	Security of supply
Engineering Recommendation (ER) P29	1990	Planning Limits for Voltage Unbalance in the United Kingdom
Engineering Recommendation (ER) P28	1989	Planning Limits for Voltage Fluctuations Caused by Industrial, Commercial and Domestic Equipment in the United Kingdom
Engineering Recommendation (ER) G74		Procedure to Meet the Requirements on IEC 909 for the Calculation of Short-Circuit Currents in Three-Phase AC Power Systems
Engineering Recommendation (ER) P25	2018	The short-circuit characteristics of single-phase and three-phase low voltage distribution networks
Engineering Technical Report (ETR) 130	2014	Application for assessing the capacity of networks containing distributed generation
Engineering Technical Report (ETR) 131	2012	Analysis package for assessing generation security capability – Users' guide

ER G12 (see Table 1) is the only current ENA ER document provides technical guidance on earthing and protection of DC systems based on DC traction systems requirements and in accordance to BS EN 50122.

3.3. Relevant standards for DC traction systems

The list of British standards of DC rail and traction systems as tabulated in Table 2 are cited by this report, and their adequacy for ST-based substation with LVDC outputs are discussed in more details in section 4. The Table 2 standards list covers general electrical service and environmental conditions in addition to mechanical characteristics requirements and recommendations for installing power-electronic rectifiers and controlled converters in UK secondary substations.

Table 2: List of relevant DC traction system standards and other associated BS standards cited by the report

Standard Code	Year of publication	Title
BS EN 50163	2007	Railway applications – Supply voltages of traction systems
BS EN 50328	2003	Railway applications – Fixed installations – Electronic power convertors for substations
EN 50121 Series	2000	Railway applications – Electromagnetic compatibility
BS EN 50122-1	2017	Railway applications – Fixed installations – Electrical safety, earthing and the return circuit
BS EN 50123-2	2003	Railway applications – Fixed installations – DC switchgear – Part 2: DC circuit breakers
BS EN 50123-7-1	2003	Railway applications – Fixed installations – DC switchgear Part 7-1: Measurement, control and protection devices for specific use in DC traction systems – Application guide
BS EN 50124-1	2001	Railway applications – Insulation coordination Part 1: Basic requirements – Clearances and creepage distances for all electrical and electronic equipment
BS EN 50526-2	2014	Railway applications – Fixed installations – DC surge arresters and voltage limiting devices Part 2: Voltage limiting devices
BS EN 50162	2004	Protection against corrosion by stray current from direct current systems
BS EN 50327	2003	Railway applications – Fixed installations – Harmonisation of the rated values for converter groups and tests on converter groups
BS EN 50529	1991	Degrees of protection provided by enclosures (IP Code)
BS EN 60721	Series	Classification of environmental conditions (IEC 60721 series)
BS EN 61869-15	2014	Instrument transformers- Part 15: Specific requirements for DC voltage transformers
BS EN 61869-14	2014	Instrument transformers- Part 14: Specific requirements for DC current transformers
BS EN 50160	2010	Voltage characteristics of electricity supplied by public electricity networks
BS EN 61000-4-30	2015	Electromagnetic compatibility (EMC). Testing and measurement techniques. Power quality measurement methods
BS EN 60664-1	2007	Insulation coordination for equipment within low-voltage systems. Principles, requirements and tests
BS 6423	2014	Code of practice for maintenance of low-voltage switchgear and controlgear

3.4. International Electrotechnical Commission LVDC standards

The International Electrotechnical Commission (IEC) has recognised the need for introducing new standards to enable secure and optimal integration of LVDC technologies within existing AC systems. In November 2014, the IEC established the Systems Evaluation Group (SEG4) to evaluate LVDC applications, distribution and safety for use in developed and developing economies. The final report from the IEC SEG4 has stated that “a very large number of publications, issued by over 30 IEC Technical Committees (TCs), are concerned and will need updating” in order to add the standards requirements for DC into existing AC standards [10]. In order to address such requirements, the IEC Standardization Management Board (SMB) approved in February 2017 the establishment of a new Systems Committee on LVDC systems. Recently (in May 2018), a new IEC Technical Committee Working Group (TC8/WG9) has been set up to conduct a preliminary work on assessment of standard voltages and power quality requirements for LVDC distribution, and to provide recommendations for future standards development [11].

Table 3 below lists a number of existing IEC standards which cover relevant certain aspects of LVDC for different applications, and considered for the detailed discussion in section 4 of this report.

Table 3: Key IEC standards relevant to LVDC distribution networks

Standard Code	Year of publication	Title
IEC 60038	2009	IEC standard voltages
IEC 60092-101	2015	Electrical Installations in Ships – Part 101: Definitions and general requirements
IEC 60479	2016	Effects of current on human beings and livestock-General aspects
IEC 60364-1	2005	Low-voltage electrical installations, Part1: Fundamental principles, assessment of general characteristics, definitions
IEC 60364-4	2005	Low-voltage electrical installations – Protection for safety
IEC 62578	2015	Power Electronics Systems and Equipment – Operation Conditions and Characteristics of Active Infeed Converter (AIC) Applications Including Design Recommendations for Their Emission Values Below 150 kHz, technical specification
IEC 61140	2016	Protection against electric shock – Common aspects for installation and equipment
IEC 60050-811	2017	International electrotechnical vocabulary – Part 811: Electric traction
IEC 60146-1	2009	Semiconductor converters - General requirements and line commutated converters

3.5. IET standards

In addition to amendment of the Institution of Engineering and Technology (IET) Wiring Regulations BS 7671 to include DC (e.g. DC protection, and other general characteristics of DC installations) [13], the IET has recently published two documents related to LVDC and Extra LVDC distribution standards. The IET Technical Committee (TC2.4) has developed the “Code of Practice for Low and Extra Low Voltage Direct Current Power Distribution in Buildings” and the accompanying technical briefing “Practical Considerations for DC Installations” [14][15].

4. ADEQUACY OF EXISTING STANDARDS FOR LV ENGINE LVDC SCHEMES

4.1. DC secondary substation layout

Smart transformer (ST) deployment at secondary substations will act as a decoupling interface between the HV grid supply and the associated LV distribution networks. To date, the only existing standard relevant to DC-based substation installation is the BS EN 50328 [17]. This standard specifies the requirements of fixed installations of power-electronic converters for substations in traction/railway applications. The traction supply power converters are classified in this standard as AC-DC conversion (diode rectifier or controlled rectifier), DC-AC conversion (controlled inverter), and AC-AC conversion (direct frequency converter or DC link frequency converter). The controlled converters have the capability of controlling a number of parameters such as frequency (including zero frequency), voltages, and flow of reactive power and real power [17].

Figure 3 presents the layout of a typical rectifier substation for a DC traction system in the UK in comparison to ST-based substation layout for LV Engine scheme 4 and 5. The DC traction rectifier substation is relatively different from the utility ST-based secondary substation. The DC traction substation consists of a conventional transformer and a rectifier to convert 0.4 kV AC to LVDC, whilst the ST-based substation interfaces HVAC (11 kV) to LV networks through a number of converter stages (e.g. HVAC-HVDC-LVDC). However, some experience from existing LVDC traction substations and their associated guidance on protection and safety, environmental conditions, marking, electrical connections, clearance and creepage, and etc. will still provide valuable sources of relevant information which can be considered by the LV Engine LVDC schemes during the trials phase. This is discussed in more details in the following subsections.

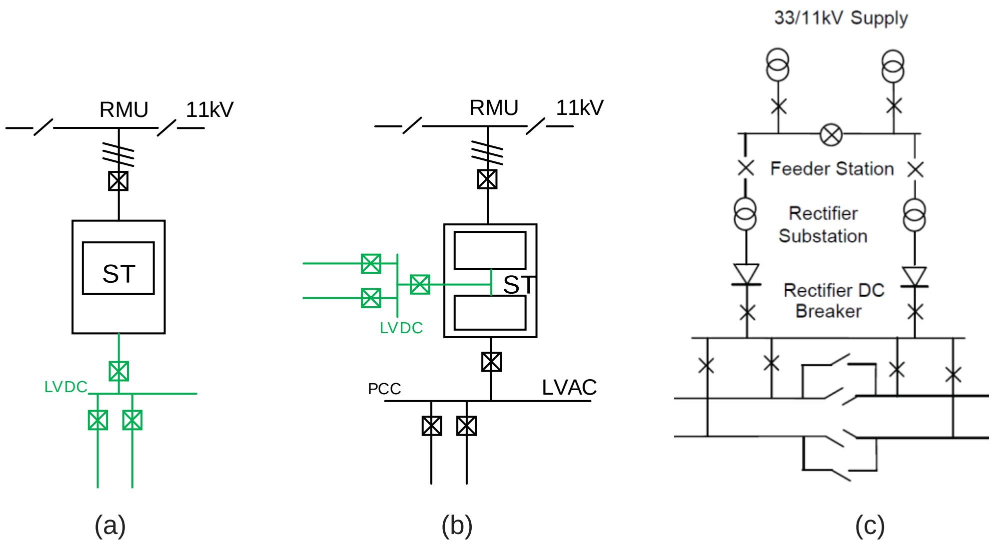

Figure 3: HV/LV secondary substation with DC supply: (a) smart transformer provides LVDC only, (b) smart transformer provides hybrid LVAC and LVDC, (c) transformer-rectifier unit in traction system [18]

4.2. Electrical service conditions

4.2.1. Security of supply

LV Engine LVDC schemes should be designed to comply with the Engineering Recommendation (ER) P2/6 [19] 'security of supply' standard, and deliver at least the level of security required for range of Group Demand up to 1 MW. ER P2/6 indicates that when a single transformer (e.g. single ST) with power rating 1 MVA is used to supply the demand, the Group Demand could be extended to include the transformer overload capacity.

During the trials phase, and according to [1] the LV Engine LVDC schemes are assumed not to connect any distributed generation (DG), and the potential EV chargers are treated as passive loads. But, in future if 'vehicle to grid' (V2G) technologies (enabling energy stored in vehicles batteries to be sent back to the network) or battery energy storage to be considered, the ER P2/6 may need to be updated. The current ER P2/6 does not include contribution afforded by battery energy storages to system's security of supply. The battery electrical storages (e.g. V2G) are not listed within the non-intermittent distributed generation in the ER P2/6 Table 2 [19]. ER P2/6 recommends that Engineering Technical Report (ETR) 130 [20] and ETR 131 [21] can be used to carry out detailed assessment and modelling programme to determine the security of supply contribution from particular DG plant. This might be suitable for considering battery storages connected to LVDC schemes if required in the future.

4.2.2. LVDC supply voltage

Nominal DC voltages

There is no international standard on nominal voltages for utility-owned public LVDC distribution systems. However, the IEC 60038 as discussed previously has recommended three DC nominal voltages for DC traction systems within the LVDC voltage band (i.e. =<1500 V). These include 600 V DC, 750 V DC, and 1500 V DC. Examples of UK traction systems which have adopted these voltages are listed in Table 4.

Table 4: Existing UK rail systems supplied by DC [22]

Name of the system	Blackpool Tramway	Edinburgh Trams	Manchester Metrolink	Nottingham Express transit	Midland Metro	Sheffield Supertram	South London Tramlink	Newcastle Tyne and Wear Metro
Power supply	600 V DC	750 V DC	750 V DC	750 V DC	750 V DC	750 V DC	750 V DC	1500 V DC

The 750 V DC voltage is the most common nominal voltage used by UK rail systems. 750 V DC has also been implemented in land-based utility-owned public LVDC distribution networks pilot projects in Finland and South Korea [23][24]. Further recommendations on DC voltage selection are discussed in [8].

Permissible DC voltage limits

For LVAC distribution systems, the IEC 60038 specifies the permissible voltage tolerances for 230 V single phase supply as +10% and -6% under normal operation [3]. Such specifications do not exist for LVDC distribution systems, but they are provided by other standards for other specific applications. For example, the British Standard BS EN 50328 and the European Regulation EN 50163 have defined the steady state voltage tolerance for LVDC traction systems to be +25% and -33% of the nominal DC voltage, and ±33% for short time operation < 5 sec [17][25]. Such limits meet the requirements of DC traction motor controls, but they may not be applicable for LVDC networks supplying public loads. This is because the power quality requirements in public networks impose the operation within relatively tighter voltage profile limits.

IEC 60092 standard on electrical installations in ships - Part 101 has defined the steady-state DC voltage deviation limits to be no more than ±10% [26]. For specific applications such as LVDC LED street lighting trials implemented in Netherlands, tighter voltage tolerance ±1.4% range has been considered. ±1.4% is selected as a design voltage drop which will ensure no high circulation current will flow in the earthing conductor when multiple earthing points are considered in the system.

Table 5 and Figure 4 summarise different voltage regulation standards for different applications. For the LV Engine LVDC schemes, ±10% can potentially be applicable to the DC supply, and tighter limits (e.g. ±1.4%) may be considered on the customer side after the DC-DC DAB converter.

Table 5: LVDC voltage tolerances

Application	Nominal Voltage	Permissible voltage tolerance	Standard
Marine/Ship	<1500 V	±10%	IEC 60092-101
Railway	600-1500 V	+20% and -33% ±33% for time operation (1-5 sec)	BS EN 50328 EN 50163
Public LVDC	<1500 V	Not defined yet	Not available

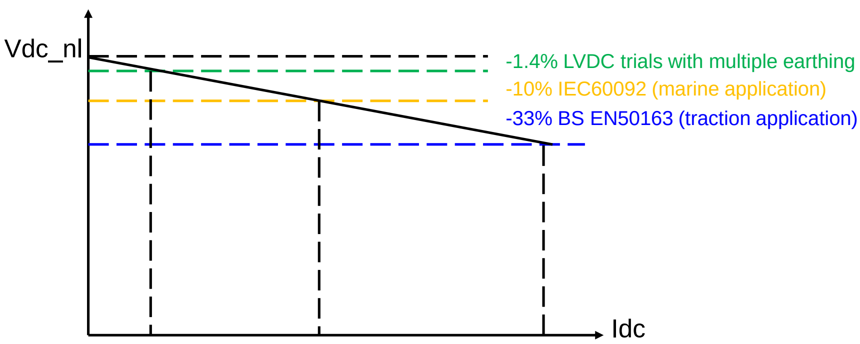

Figure 4: Allowed DC voltage drop for different LVDC applications

DC voltage unbalance

For AC distribution networks, the Engineering Recommendation P29 limits voltage unbalance which can be caused by customer installations to 1.3% at the point of common coupling (PCC) of an LV symmetrical supply and to 2% for no more than one minute [27]. Whilst the Engineering

Recommendation P28 limts the allowable voltage fluctuation magnitudes to maximum 3% caused by industrial, commercial, or domestic equipment [28].

Currently, there is no standard on DC voltage unbalance and power quality requirements for DC substations of public LVDC distribution networks. 2.86% is used as a voltage unbalance limit in existing LVDC pilot projects implemented in Netherlands [29]. This limit is based on practical experience and design, and not supported by international standards yet.

DC voltage dips/swells and transient overvoltage

With regards to voltage dips (caused by faults) and voltage swells (caused by load connection or switching operations), the BS EN 50160 defines for LVAC voltages of supply the dip threshold is 90 % of the nominal voltage and the threshold for swells is 110 % of the nominal voltage [30]. The BS EN 50160 indicates that voltage dips and swells need to be measured and detected in accordance to EN 61000-4-30 methods. Neither of BS EN 50160 or EN 61000 consider voltage dips/swells for DC supply of public electricity networks. Therefore, voltage dips/swells characterisations and classifications are required to be developed for LVDC supply of public network in future. This is the same requirement to be considered for transient DC over-voltages which can be caused by lighting or switching in the system. The cases that are provided by EN 60664-1 for LV end-users' to comply with in order to withstand over-voltages caused by lighting or switching do not cover LVDC supply.

4.2.3. Safety of DC substation

General safety requirements

The ESQCR Part III outlines the general substation physical protection (danger of unauthorised access) and safety sign requirements [33]. An example of the safety (warning) sign as specified in Schedule 1 of the ESQCR is presented in Figure 5(a). It has been stated that the safety sign could include additional text with the same colour and size specified in Schedule 1 of the ESQCR [33]. This may allow to add any recognised risk associated with DC terminals when LV Engine ST is deployed.

The BS EN 50122-1 which specifies the electrical safety and earthing for railway applications including DC systems, requires the use of warning sign as shown in Figure 5(b) and specified in ISO 3864-1:2002 and ISO 7010:2003+A1:2006. This warning sign is required 'where there is a serious risk of persons coming within the limits of live parts' [34]. The BS EN 50122-1 recommends that if required an appropriate supplementary sign may be used.

(a) (b)

Figure 5: Warning sign: (a) in accordance to ESQCR, and (b) in accordance to BS EN 50122-1

Guidance for earthing DC systems

In general, every substation has to be provided with an earthing installation designed to ensure no danger to persons arising from earth potential and avoid damage to equipment due excessive potential rise [35].

The ESQCR [33] has specified a number of general earthing requirements for LVAC supply. Extracted examples from the ESQCR include:

- the continuity of the supply neutral conductor

- no introduction of any protective device in any supply neutral conductor or any earthing connection of LV network
- the network does not become disconnected from earth in the event of any foreseeable current due to a fault
- no impedance is inserted in any connection with earth of an LV network other than that required for the operation of instruments or equipment for control and metering

ESQCR Regulation 10 specifies the requirements for earthing of metalwork which is not intended to serve as a live conductor and where necessary to prevent danger, connected with earth (see ESQCR 10 in [21] for more details) [33].

The IEC 60364-1 has identified five different types of DC system earthing arrangements. These include TN-S, TN-C, TN-C-S, TT, and IT. The standard has not yet covered the requirements for earthing methods to minimise the impact of stray DC currents.

Generally speaking, LVDC supply systems require special consideration to minimise the impact of stray DC currents on earthed metallic structures. Stray DC currents issue is well understood in traction systems, and it is defined by BS EN 50122-1 as '*part of the current caused by a DC traction system which follows paths other than the return circuit*' (see Figure 6). The flow of stray DC currents can be caused by parasitic capacitors which can be naturally formed between any earthed metallic surfaces and live parts.

As indicated in ER G12 [36] and BS EN 50122-2 [34], stray DC currents normally have relatively low electric energy, but they can cause a number of technical problems. These can include increased risk of progressive degradation of earthed metallic structures by corrosion issues, and increased risk of equipment overheating and arcing. Selected examples of listed equipment in BS EN 50122-2 which can potentially be effected by stray DC currents include: metallic pipe work, cables with metal armour or metal shield, metallic tanks and vessels, earthing installations, reinforced concrete structures, and buried metallic structures [34]. Figure 6 shows the flow of stray DC current in a metallic surface in a uni-polar LVDC system. The corrosion occurs where the stray current leaves the surface (see Figure 6).

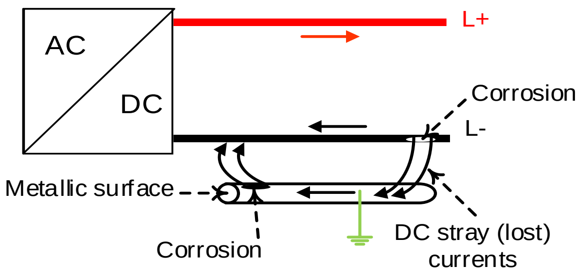

Figure 6: Stray currents in DC systems

The BS EN 50122 [34] and the ER G12 [36] provide a list of recommendations to minimise the risk of electrolytic corrosion of earthed equipment due to stray DC currents. These include:

- exposed conductive parts of traction and non-traction power supply not to be bonded directly to the return circuit (neither pole of the traction supply is directly connected to earth)
- the protective earthing (PE) conductor and all earthed metal parts to be segregated from all DC conductors by the maximum practicable distance, subjects to a minimum distance of 1 m

In DC traction systems, a voltage limiting device (VLD) is required between the PE conductor (including exposed surfaces) and the return conductor (negative pole) to make an open circuit between the two conductors under normal operation, and create a short-circuit path under faults to enable interruption of earth fault currents in a short time. When the applied voltage between the PE and the return circuit decreases below a specified level, the VLD acts as a short-circuit device and limits the voltage between the return circuit and the structure earth, preventing dangerous touch voltages. VLDs are already standardised by EN 50526-2 [39] and are commercially available.

Safety during maintenance work

BS 6423 [40] gives recommendations and guidance for the maintenance of LV switchgear and controlgear having a rated voltage up to 1000 V AC or 1500 V DC. The standard also provides recommendations on safety precautions for personnel carrying out maintenance.

To ensure safety during maintenance works and to comply with BS 6423, all parts of the main circuit to which access is required need to be capable of being earthed through suitable means [40]. In DC traction systems, 'earthing means either connection to earth or connection to the return circuit', depending on the implemented earthing arrangements [46].

The EN 50123-7 [46] indicates that the purchaser of AC-DC converter needs to specify in the enquiry how to earth the converter enclosure/frame. In accordance to clause 6.5.7 of EN 50123-7-1 [46], the metallic parts of the converter enclosures/frames have to be connected to a suitable earthing terminal, placed in an accessible position to allow the connection to the main earth system of the substation. The DC earthing terminal should be also suitably protected against corrosion [46].

Customer - DNO connection

The GB DCODE and as a part of approval to connect end-user's loads to the DNO supply, the user's installation must comply with the principles outlined in Regulation 25(2) (a) of the ESQCR [33]. One of the ESQCR requirement is to ensure that 'the connection itself will not be so constructed, installed, protected and used or arranged for use, so as to prevent as far as is reasonably practicable, danger or interruption of supply'. With the current standards, there is still a lack of knowledge on how to design compatible interface between DC customer and DC supply to avoid any possible safety risks. Also as discussed previously in subsection 3.1, the current Distribution Operating Code (DOC) of the GB DCODE which outlines the operating procedures at the interface between the DNOs and customers will need to be updated for considering LVDC supply in future. Within the trial stage of the LVDC Engine LVDC schemes, the type/topology of the interface between the DC supply and the end-users will be driven by the type of the LVDC application.

4.2.4. Protection requirements

DC fault characterisation

Regulation 28 of the ESQCR [33] requires that 'a distributor shall provide, in respect of any existing or proposed consumer's installation which is connected or is to be connected to his network, to any person who show a reasonable cause for requiring the information, a written statement of:

a) the maximum prospective short circuit current at the supply terminals
b) the type and rating of the distributor's protective device or devices nearest to the supply terminals'

Currently, the existing ER G74 [42] and the recent ER P25 [43] cover only short-circuit characteristics of AC power systems. The ER P25 has more specific scope on fault characterisation of LV distribution networks including renewable and storage converter-interfaced impacts on the AC fault current. The ER P25 indicates that if the short-circuit contribution from a generator interfaced by power electronics is greater than 1.2 times rated current, the contribution should not be neglected and assumed insignificant. Both ER G74 and ER P27 have been so far harmonised only to AC supply and do not consider DC fault current characteristics.

The IEC 61660 [44] is the most comprehensive DC protection standard that has been widely used for characterising faulted DC auxiliary systems in power plant and substations. The equipment considered within this standard and act as DC short-circuit sources include: rectifiers in 50Hz 3-phase AC bridge connection, stationary lead-acid batteries, smoothing capacitors, and DC motors. The IEC 61660 provides a conservative method of calculation of prospective DC short-circuit current for the aforementioned devices [44]. However, the method provided by this standard may not be applicable to all advance power-electronic interfaces such as smart transformer (ST) with fault current management capability. If the ST is a non-modular type, the IEC 61660 short-circuit calculation method should be sufficient to work out the maximum transient and steady state DC short circuit current on the LVDC supply side.

DC protection requirements

Regulation 6 of the ESQCR (electrical protection) imposes requirement for distributors to install adequate protective devices in their networks to 'prevent any current, including any leakage to earth, from flowing in any part of the network for such a period that part of the network can no longer carry that current without danger' [33]. To meet such requirements, the following DC protection recommendations are discussed.

Protection against direct contact in DC systems

According to IEC 60364-4-41 [45] and also as reported in BS EN 50122-1 [34], protection against direct contact is required for DC if the voltage is higher than 60 V. Direct contact protection can be provided by protection by clearance and protection by obstacles [34]. The BS EN 50122-1 indicates that 'the clearance to be observed for persons working near to energised contact line systems shall be defined in the operational specifications'.

Protection against faults and indirect contact in DC systems

Provisions for protection against indirect contact is normally required for exposed conductive part. BS EN 50123-7-1 [46] specifies protection requirements within substations with power-electronic converters (for DC traction systems). The following requirements are listed:

- DC protection to operate for all intended line feeding arrangements
  Examples given include: feeding only from one source, feeding from rectifiers in parallel at the substation, and dual end feeding.
- Discriminate between normal currents and fault currents
- Provision of operation in the shortest time
- Provision of discrimination between primary and back-up protection

DC electrical faults that require appropriate means of detection as specified in BS EN 50123 include:

- Positive pole to negative pole on the terminals
- Positive pole to earth fault within the substation, for example, on switchgear, converter, and etc.
- Positive and negative pole to earth fault (for systems with both poles insulated to earth)

BS EN 50123 indicates that consideration should also be given to detection of high resistive (arcing) faults between positive and negative poles (i.e. on DC terminals).

Recommendations on DC fault detection methods and protection devices

The BS EN 50123 recommends that DC line breakers can be equipped with some or all of the following protection functions:

- Inverse time overcurrent protection
- Inverse time overcurrent protection with thermal imaging
- Protection examining the wave shape of the current such as di/dt
  Rate of current rise (di/dt) characteristic can be embedded within DC line circuit breakers for detection of faults. The relay can have an adjustable range of di/dt settings, coupled with an adjustable range of time delay settings. The time delay is recommended to avoid unwanted tripping by starting currents which could have di/dt higher than the threshold setting point.
- Instantaneous direct acting or instantaneous direct acting with adjustable setting range
  Such protection functionality can be fitted on the rectifier/converter circuit breakers to provide protection in the event of faults on the rectifier/converter terminals (e.g. ST DC terminals).
- Under-voltage protection
  An under-voltage release element can be fitted within the DC line circuit breaker relay to protect against under-voltage faults. Nuisance tripping due to momentary drop in DC voltages can be prevented by having an associated time delay response. This time delay will be of short duration

for direct acting devices, not longer than 0.1 sec. Longer delays to prevent unnecessary tripping may be achieved with under-voltage relay fitted with time delay elements.

The above listed protection and fault detection methods have the potential to be considered in future utility-owned DC substations supplying public LVDC distribution networks.

In term of DC circuit breakers, IEC 60947 series [47] cover in details all the technical requirements of DC breakers that can be used with DC rated voltages up to 1500 V DC. The standard is limited to DC mechanical breakers and covers all the aspects that are required to be met by the manufactures of DC breakers. These include breaker ratings and short circuit breaking capabilities, testing requirements, associated control circuits (for closing and opening the breaker), marking and associated symbols to be shown on the breaker, mounting, transport and pollution degree, and etc. Examples of standardised and commercially available DC mechanical breakers are listed in Table 6.

Table 6: Examples of commercially available breakers

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

4.2.5. Instrument transformers in DC

BS EN 61869-14 and 61869-15 [48][49] are applicable standards to current and voltage transformers used for measuring, protection and control applications in DC systems with a voltage above 1 kV. No relevant standards are available for DC systems with voltages lower than 1 kV.

4.2.6. Electromagnetic compatibility (EMC)

ESQSR (Part I) imposes that distributor and meter operators to ensure their equipment is installed, protected, used and maintained as to prevent interference with or interruption of supply. The IEC 60364 [45] also requires all electrical equipment to be installed in the way that will not harm other equipment on the system or impair the supply during normal operation.

IEC 60364-4 [45] provides requirements of electromagnetic compatibility (EMC) and measures to minimise the impact of electromagnetic interference (EMI) in LVAC systems. But, in DC systems for public networks, there are no standards defining the EMI compatibility requirements for the range of 2-150 kHz frequency. For utility substations with implemented power-electronic converters for DC traction systems, the BS EN 50121 series [50] specify the requirements for EMC immunity. It is recommended by the BS EN 50121 that the immunity and emission tests of the converter group to be done only together and test the whole substation set [50].

4.3. Environmental conditions

4.3.1. Ambient air circulation

To comply with BS EN 50328 standard [17] and BS EN 60721 [37], substation equipment (converter) installed in a room needs to be connected to 'unlimited' supply of cooling medium. If the cooling air is taken from the ambient in the room, the heat needs to be extracted from the room, and this can be then considered as an intermediate heat-exchanger between the equipment and the outside air.

In accordance to BS EN 50328 standard [17], for converters mounted in an enclosure, the ambient for the converters (internal air of the cabinet) is to be considered as a heat transfer agent and not as a cooling medium. Also, the reflection from the cabinet walls should be taken into account. The standard also requires the compliance of cubicle or cabinet mounted assemblies with the overload conditions at maximum temperature of the outside air.

4.3.2. Normal service conditions

Storage and transport temperature

-25 ºC to +50 ºC temperature rang is recommended by the BS EN 50328 to be considered as storage and transport temperature limits for power electronics installed at substations for traction systems and with cooling liquid removed.

Normal operation temperature including off-load periods

Table 7 lists minimum and maximum temperature of cooling air for normal operation of a power-electronic converter implemented at secondary substation for supplying DC to a traction system. This includes off-load operation periods.

Table 7: Temperature of cooling air for power-electronic converters in DC traction systems substation [17]

Application	Minimum temperature	Maximum temperature
Extreme values	-5 ºC	+40 ºC
Daily average		+35 ºC
Yearly average		+25 ºC

Humidity level of the ambient air

The BS EN 50328 limits the minimum humidity level of the ambient air for power-electronic converter at secondary substation to 15 %. For the maximum humidity level, the converters should be designed for the case where no condensation can occur, and if condensation is expected, the installation needs to be treated as a special service condition (see subsection 4.3.3) [17].

Dust and solid particles content

Pollution degree (PD) 3A (as highlighted in Table 8) is assumed to be a normal level for indoor equipment (i.e. converter) [38]. For any condition exceeding PD 3A, it has to be specified by the purchaser as a special service condition [17].

Table 8: Pollution degree in accordance to BS EN 50124-1 [38]

Table A.4 — Definition of pollution degrees

	Dust deposit	Humidity
PD1	– no pollution – non–conductive – well protected	– dry – no condensation
PD2	– non–conductive – protected – temporary conductivity caused by condensation	– rare, short temporary condensation
PD3	– low conductivity (caused by condensation)	– frequent condensation
PD3A	– low conductivity	– damp – long time condensation
PD4	– occasionally conductive with periodic cleaning	– rain, snow, ice, fog
PD4A [a]	– occasionally conductive coming from heavy pollution	– rain, snow, ice, fog
PD4B [b]	– occasionally conductive coming from very heavy pollution	– rain, snow, ice, fog

[a] Fixed installations and track side equipment e.g. for signalling
[b] Fixed installations only
NOTE This table is cited in 4.4 and Table A.3

Altitude of the substation

BS EN 50328 specifies that for the use of air as a cooling medium or heat transfer agent, altitudes up to 1000 m are considered normal for a power-electronic converter. If the converter is to be used at an altitude higher than 1000 m, and it was originally tested at normal altitude, the current capability shall be decreased by 1 % for each 100 m for natural air-cooling, and by 1.5 % for forced air-cooling [17]. The dielectric properties of air can be considered as normal for altitudes up to 2 000 m [38].

Such parameters might be considered if the ST within the LV Engine schemes is deployed with trials located at relatively high altitude.

4.3.3. Special service condition

The following examples which are extracted from BS EN 50328 [17] present some of special service conditions that can be subject to a special agreement between the purchaser and the supplier:

- special mechanical stresses, for example mechanical shocks and vibrations
- foreign particles in the ambient air, for example abnormal dirt or dust
- salt air (for example proximity to the sea)
- high values of relative humidity and/or temperature similar to those associated with tropical climatic conditions
- other special service conditions not covered by this list or service conditions exceeding the specified limits of normal service conditions

4.4. Mechanical characteristics

4.4.1. General

The BS EN 50122 [34] indicates that power-electronic converters at a substation of DC traction system may be either enclosed or not enclosed. If frames and enclosures are used, they shall be metallic. DC converters and relevant enclosures need to be designed so that normal service, inspection and maintenance operations, replacement of diodes and fuses, earthing of cables or busbars and voltage tests can be carried out easily and safely [34].

The BS EN 50122 requires special attention to be paid to the materials of the converter enclosure ability to withstand moisture and fire. The selection of materials also needs to ensure corrosion due to atmospheric and electrolytic effects are minimised.

4.4.2. Classification of degrees of protection provided by enclosures of AC-DC converters

The EN 60529 provides a system for classifying the degrees of protection provided by the enclosures of electrical equipment. The protection degrees in the standard are applicable to most types of electrical equipment, but the standard has stated that it cannot be assumed that all listed degrees of protection are applicable to a particular type of equipment [51]. The EN 60529 indicates that equipment manufacturer (e.g. the ST) should be consulted to determine the degrees of protection available and the parts of equipment to which the stated degree of protection applies.

The BS EN 60529 defines the degrees of protection provided by enclosures of electrical equipment as:

- protection of persons against access to hazardous parts inside the enclosure
- protection of equipment inside the enclosure against ingress of solid foreign objects
- protection of the equipment inside the enclosure against harmful effects due to the ingress of water

The standard also provides the designations for these degree of protection, the requirements for each designation, and the tests to be performed to verify that the enclosure meets the requirements of this standard.

Measures to protect both the enclosure and the equipment inside the enclosure against external influences or conditions such as mechanical impacts, corrosion, corrosive solvents (e.g. cutting liquids), fungus, vermin, solar radiation, icing, moisture (e.g. produced by condensation), explosive atmospheres, and protection against contacts with hazardous moving parts (such as fans) are matters for the relevant product standard as stated by BS EN 60529 [51].

The BS EN 50122 [34] imposes that purchaser of power-electronic converter enclosures to specify the degree of protection in accordance to BS EN 60529 [51]. The BS EN 50122 also states that due to the specific requirements of converters for cooling and for connection of AC and DC cables or busbars, IP 00 (IP=International Protection, first '0'=non-protected against solid foreign objects, and the second '0'=non-protected against water) is considered as normal degree of protection for the bottom and the top of the enclosure.

4.4.3. Vibrations

To reduce the impact of limited vibration/shocks on the converter, the converter should be capable of operating satisfactorily when subjected to conventional sinusoidal vibrations at 10 Hz [17].

4.5. Clearance and creepage distance

See Table 13.

4.6. Marking of DC output terminals and labelling

4.6.1. Main circuit terminals

For LVDC circuit terminals, the IEC 60364-1 has identified the marking of positive pole as L+, the negative pole as L-, and the mid-point as M [23]. However, there is still no international agreement on the labelling and colour coding of DC cables.

The BS EN 50328 requires the expression of the polarity of DC output terminals at the DC substation of traction systems. This may be considered for marking LVDC output terminals of the ST since no other relevant standards are available for such application.

To avoid any possible confusion between DC and AC when existing AC cables are used for DC, the IET BS7671 has provided a guidance on DC cable colours as presented in Table 9.

Table 9: DC conductor marking and colours selection using existing AC wires

Function	Marking (IEC 60364-1 & IET BS 7671)	Colour (IET BS 7671)	
Positive of three-wire circuit	L+	Brown	
Mid-wire of three-wire circuit	M	Blue	
Negative of three-wire circuit	L-	Grey	

4.6.2. Rating plate

The BS EN 50328 indicates that each converter equipment delivered as an integrally assembled unit to include the markings presented in Table 10 on the rating plate:

Table 10: Converter assembly rating plate marking extracted from BS EN 50328 [17]

No	Markings indicated by BS EN 50328	Applicability to ST based substation
1	Manufacturer's or supplier's indication	Applicable to ST unit
2	Indication of the type of equipment (traction supply power converters type)	Type of the ST and converter stages
3	The number of the European Standard EN 50328:2003	May not be applicable, as this standard covers only power-electronic converters in railway substations.
4	Manufacturer's type designation	Applicable to ST unit
5	Serial number	Applicable to ST unit
6	Number of input phases or indication "DC"	Number of HVAC input phases to the ST unit, HVDC & LVDC number of conductors (e.g. 2-wire or 3-wire)
7	Number of output phases or indication "DC"	Number of LVAC output phases and number of LVDC output terminals (e.g. 2-wire or 3-wire)
8	Rated input voltage	Applicable to ST unit
9	Rated input frequency, if any	HV supply frequency, and may also require to add the frequency of HFT, and ST AC output frequency.
10	Rated output frequency, if any	Applicable to scheme 5 LVAC output terminals
11	Nominal DC voltage	Applicable to ST unit
12	Range of output voltage (for adjustable voltages)	Applicable to ST unit
13	Basic direct current	Applicable to ST unit
14	Duty class or designation of the load cycle	
15	Short circuit capability	Applicable to ST unit
16	Cooling method	Applicable to ST unit
17	Type of connection	Applicable to ST unit

Table 11 quotes from the BS EN 50328 additional items which may be considered if appropriate for marking ST rating plate.

Table 11: Additional markings indicated by BS EN 50328 [17]

No	Additional markings indicated by BS EN 50328
1	Cooling requirements (temperature, flow rate of cooling medium)
2	Overall weight, weight of cooling fluid, if any
3	Degree of protection (IP-Code)
4	Displacement factor under rated conditions
5	Output characteristic curve symbol

4.7. Testing requirements

4.7.1. General

The general terminology for testing procedures for power-electronic converters in secondary substations are provided by IEC 60050-811 standard [52].

To comply with the BS EN 50328, the converter unit tests whenever practicable need to be performed in electrical conditions equivalent to those in real service. If it is not practicable, the assemblies and equipment respectively need to be tested under such conditions as to allow the specified performance to be proven (components of the converter assumed to be tested separately) [17].

It is noted in BS EN 50328 that when 'the purchaser or his representative desires to witness factory tests, this shall be specified in the procurement specification'.

4.7.2. Test specifications

Table 12 is developed to present the key testing specifications and requirements for power-electronic converters installed at secondary substations in accordance to BS EN 50328. These include essential testing under normal operation and supplementary testing under faulted condition. Most of the listed test types in Table 12 could potentially be used as a check list to understand the performance of the ST unit for the LV Engine schemes.

Table 12: Test specifications required by BS EN 50328 [17]

<table>
<tr><th></th><th>Test type</th><th colspan="3">Description</th><th>BS EN 50328 clause for more details</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Insulation test</td><td colspan="3">Insulation tests shall be carried out to verify the correct state of insulation of a completely assembled unit. During insulation tests the main terminals of the converter, as well as the anode, cathode and gate terminals of all power semiconductor devices, shall be connected together.
Before the test and one minute after the test, the insulation resistance shall be measured by applying a direct voltage of at least 500 V. The insulation resistance shall be more than 1 000 Ω/V.</td><td>4.2.1.1</td></tr>
<tr><td>Insulation tests of converter equipment and assemblies arranged in a single enclosure</td><td colspan="2">Each circuit of the converter shall be subjected to an insulation test against the enclosure and against any other circuits which are electrically separate from the circuit section under test.
The test voltage shall be applied between the circuit under test and the frame or enclosure to which the terminals of any other circuits shall be connected for the purpose of this test.</td><td>4.2.1.2, 4.2.1.3</td></tr>
<tr><td>Test voltages, clearances and creepage distances</td><td colspan="2">Isolating distances shall be designed in accordance with the requirements for isolating distances specified in EN 50124-1. The insulation tests shall be performed with test voltages according to Table 13.</td><td>4.2.1.3.2</td></tr>
<tr><td>2</td><td>Light load functional test</td><td colspan="3">The light load functional test is carried out at a sufficient load to verify that all parts of the main circuit and the auxiliary circuits operate properly. For the routine test, the converter shall be connected to the rated supply voltage(s).</td><td>4.2.2</td></tr>
<tr><td>3</td><td>Load test</td><td colspan="3">The test is carried out to verify that the equipment will operate satisfactorily at basic current. The load test and the temperature-rise test can be combined.</td><td>4.2.3</td></tr>
<tr><td>4</td><td>Power loss determination</td><td colspan="3">If the power loss determination shall be done by measurement and not by calculation, the methods for power loss measurement given in section 4 of IEC 60146-1-2 may be used. The power efficiency may be determined by calculation of internal losses or by measurement of AC and DC power at basic load conditions. If the purchaser requires measurement of the losses this shall be mentioned in the procurement specification.</td><td>3.3.1, 4.2.4</td></tr>
<tr><td rowspan="5">5</td><td rowspan="5">Temperature-rise test</td><td colspan="3">The temperature-rise of the converter shall be determined under test conditions given for the load test
The temperatures of busbars, insulation material, cables and control and protection devices shall not exceed their admissible limits (absence of permanent damage).</td><td>4.2.5.1</td></tr>
<tr><td rowspan="4">Ambient air and cooling medium temperature</td><td>Ambient air temperature</td><td>The ambient air temperature shall be measured at half the distance from any neighbouring equipment, but not more than 300 mm distance from the enclosure, at middle height of the equipment, protected from direct heat radiation from the equipment.</td><td>4.2.5.2.1</td></tr>
<tr><td>Cooling medium temperature for air cooling</td><td>The average temperature shall be measured outside the equipment at points 50 mm from the inlet to the equipment.</td><td>4.2.5.2.2</td></tr>
<tr><td>Cooling medium temperature for liquid cooling</td><td>The temperature shall be measured in the liquid pipe 100 mm upstream from the liquid inlet.</td><td>4.2.5.2.3</td></tr>
<tr><td>Temperature of heat transfer agent</td><td>The heat transfer agent temperature shall be measured at a point to be specified by the manufacturer.</td><td>4.2.5.2.4</td></tr>
<tr><td>6</td><td>Checking of auxiliary devices</td><td colspan="3">The function of auxiliary devices such as contactors, pumps, sequencing equipment, fans, etc. shall be checked.</td><td>4.2.6</td></tr>
<tr><td>7</td><td>Checking of the properties of the control equipment</td><td colspan="3">It is not feasible to verify the properties of the control equipment under all those load conditions which can prevail in real operation. However, it is recommended that trigger equipment shall be checked under real load conditions as far as possible. When this cannot be done on the manufacturers' premises, it may be performed after installation by agreement with the user.
In type tests the function of the auxiliary circuits shall be tested at maximum and minimum values of the supply voltage.</td><td>4.2.7</td></tr>
<tr><td>8</td><td>Checking of the protective devices</td><td colspan="3">Checking of the protective devices shall be done as far as possible without stressing the components of the equipment above their rated values. Due to the wide variety of protective devices and their combinations, it is not possible to state any general rules for the checking of these devices. However, if a system control equipment is designed to protect the converter from overloads, its ability in this respect shall be checked.</td><td>4.2.8</td></tr>
<tr><td>9</td><td>Short-time withstand current test</td><td colspan="3">The short-time withstand current test is a supplementary test. The test is carried out to verify the short-time withstand current carrying capability of the converter for the specified current and duration</td><td>3.7.2.4, 4.2.9</td></tr>
<tr><td>10</td><td>Additional tests</td><td colspan="3">Specifications and procedures for any additional tests, for example vibration, voltage drift, and audible noise shall be agreed between purchaser and supplier.</td><td>4.2.10</td></tr>
</table>

Table 13: Insulation levels for AC/DC converters (minimum clearances between DC pole and earth) [17]

Nominal DC Voltage	Rated insulation voltage	Power frequency withstand voltage	Impulse voltage 1.2µs/50µs	Clearance
0.6 kV	0.9 kV	2.8 kV	not applicable	10 mm
0.75 kV	1.2 kV	3.6 kV	not applicable	14 mm
0.75 kV	1.8 kV	4.6 kV	not applicable	18 mm
1.5 kV	2.3 kV	5.5 kV	not applicable	22 mm
1.5 kV	3.0 kV	9.2 kV	not applicable	36 mm

BS EN 50328 allows impulse voltage test to be substituted by power frequency withstand voltage test if the converter purchaser and the supplier agreed to do so. In this test the voltage needs to be applied for 5 sec [17].

4.8. Information required

BS EN 50328 Annex A provides a summary of information which should be exchanged between purchaser and supplier of power-electronic converters for DC traction systems application (rectifier and controlled converters). This section of this report extracts only information that is related to controlled converters and inverters as detailed in Annex A3 of the BS EN 50328. It is assumed that the controlled converter can be supplied only as a whole converter group including transformer and filters under the overall responsibility of the converter supplier [17].

The information available in this section can potentially be adopted for the ST as a whole unit including its associated parts (e.g. filters and etc.). The BS EN 50328 also allows if there is any specific and special service conditions (different from those defined in the standard) to be mentioned in the purchaser specification.

4.8.1. Procurement specification

The following items is required by BS EN 50328 to be included, where applicable, within the specification issued by the purchaser in order to provide technical requirements for the performance of the converter.

Table 14: Information required to be included in the purchaser specification of converters for DC substations in accordance to BS EN 50328

No	Characteristics and functional requirements	Mechanical requirements
1	Type of equipment	IP code (degrees of enclosure protection) in accordance to EN 60529
2	Nominal DC voltage	Arrangement of AC and DC connections
3	Rated insulation voltage	Padlocking requirements
4	Insulation requirements differing from those defined as normal	Earthing and bonding facilities
5	Rated AC voltage on the supply side	Earthing method of the enclosure or frame of the converter
6	Conventional no-load voltage	Maximum dimensions of the converter at site
7	Rated direct voltage	Details of arrangement for transport and delivery to site
8	Basic direct current	
9	Duty class or designation of a load cycle	
10	Requirements for current limiting	
11	DC power	
12	Requirements concerning AC and DC harmonic content	
13	Rated voltage of auxiliary circuits	
14	Cooling method	
15	Safety related interlocks	

4.8.2. Supplier's tender specification

Table 15, Table 16, and Table 17 in accordance to BS EN 50328 list information and date to be given by the supplier during the delivery phase of the equipment.

Table 15: Required information relevant to AC-DC converter supplier's identification

No	Identification
1	Name of the manufacturer or trademark
2	Type of equipment
3	Type designation
4	Reference to the National Standard corresponding with this European Standard, which the manufacturer declares compliance with.

Table 16: Required information with regard to characteristics and functional requirements of controlled converter unit

No	Characteristics
1	Nominal voltage
2	Basic direct current
3	Duty class or suitability of the converter for a specified load cycle
4	Overcurrent curve
5	Losses
6	Power efficiency
7	Cooling method
8	Dimensions of the converter assembly
9	Space requirements for maintenance
10	Necessity of rear access
11	Weight of the complete assembly
12	Confirmation of compliance with the purchaser's requirements and a list of any non-compliances
13	Requirement of special tools for repair or maintenance

Table 17: Information and data to be given by the supplier during the delivery stage

No	Required information
1	Circuit and schematic diagrams of all circuits
2	Demand of cooling medium (e.g. air)
3	Method of fixing of the converter assembly to floor
4	Operation and maintenance manuals

5. EXISTING STANDARDS OPPORTUNITIES, ISSUES AND LEARNED LESSONS

The report has considered both the review of relevant existing standard and regulations to evaluate their adequacy for smart transformer (ST) and LVDC deployment during the trials phase of the LV Engine LVDC schemes as well as discussion on the cases where ST and LVDC emerging solutions cannot be compliant due to the gaps in standards, DCODE, and other relevant Engineering Recommendations (ERs). This section is aimed at summarising the key outcomes of the report review as follows:

- The introduction of ST and its associated LVDC distribution systems brings new changes to the way that HVAC grid supply is interfaced to LV networks, and to how the electricity is distributed, controlled and protected. Such changes will inevitably make existing standards in addition to other important documents such as GB Distribution Code (DCODE), engineering recommendations and other associated technical guidance and code of practices to be subject to changes and new updates in order to be ready for accepting ST and LVDC technologies.

- Updating standards, DCODE, and other technical guidance for considering LVDC systems will require a nominal DC voltage which such documents can be harmonised at. The EU LV Directive (LVD) 2006/95/EC and the IEC 60038 have defined the LVDC supply range to be =<1500 V, but no standard operating voltage(s) for utility-owned LVDC public distribution networks has been defined yet by any existing standard. The IEC 60038 has divided the LV in DC systems into two bands. From 120-1500 V is defined as an LVDC band and <120 V is an Extra LVDC (ELVDC) band. All the physiological impact of DC current electric shocks on humans and livestock across these two bands are well understood and covered by IEC 60479.

- The report has outlined a number of LVDC applications across the LVDC and ELVDC bands. These included LVDC in buildings, LVDC for street lighting and EV charging, LVDC for telecommunication systems, LVDC for data centres, LVDC last mile distribution, and LVDC for traction systems. It was found that the only mature applications in terms of the market size and standardisation are DC for telecommunication and DC for traction systems. The DC traction system application has been found as the most relevant application to ST-based substation and LVDC supply. DC traction systems are normally supplied from a substation with AC-DC rectifier or controlled converter, and the experience from such a DC application in respect to electric and environmental service conditions has provided valuable information which can be used for supporting the trials phase of the LV Engine LVDC schemes.

- The IEC 60038 and BS EN 50163 have recommended three DC nominal voltages 600 V DC, 750 V DC, and 1500 V DC for DC traction systems, and these voltages are widely adopted in UK traction systems. 750 V DC voltage is the most common nominal voltage example used by UK rail systems, and it has been also implemented by utility-owned public LVDC distribution networks pilot projects in Finland and South Korea.

- The report has concluded that during the LV Engine LVDC trials phase, most of the key operating and testing requirements of power-electronic converters intended to be installed at a distribution substation for DC traction systems and covered by BS EN 50328 and other associated BS standards (listed previously in Table 2) can be applicable for design, test, and install ST-based substation with LVDC outputs. Standardised areas covered by BS EN 50328 and can potentially be considered for trialling ST with LVDC supply include:
    - Electrical service conditions – such as supply voltage, safety, earthing, DC protection requirements, and etc.
    - Environmental conditions – such as converter operating temperature, converter storage and transport, humidity level, pollution degrees and etc.
    - Mechanical characteristics – such as protection degree of converters enclosures, mechanical vibration levels, clearance distance and etc.
    - Converter assembly testing specifications – such as essential testing under normal operation (insulation test, load functional test, power loss determination, temperature-rise test), and supplementary testing under faulted condition (checking of auxiliary devices, control equipment, protective devices, short-time withstand current test)
    - Recommendations on information which can be exchanged between the converter unit purchaser and the suppliers.

- DC traction systems have relatively large DC voltage tolerances (i.e. +25% and -33% of nominal voltage) due to the homogenous electrical load and predictable load requirements. This cannot be applicable to utility-owned LVDC networks supplying public loads due to the requirement of tighter power quality tolerance. The only available standard which considers tighter voltage tolerance is IEC 60092 for electrical installations in ships. The standard defines steady-state DC voltage deviation limits to be no more than ±10% of the nominal voltage. This voltage variation limit is closer to the voltage limits that existing LVAC distribution networks apply and also has been adopted by number of studies in literature.

- Unlike AC systems, the unidirectional flow of DC current will increase the risk of electrolytic corrosion of earthed metalwork and structural steelwork in contact with the earth. When LV Engine LVDC schemes are trialled, corrosion prevention measures will be required. There is no technical guidance or standard on how to earth LVDC supply terminals for public networks and mitigate electrolytic corrosions. However, the BS EN 50122 and the ER G12 and based on DC traction experience have recommended that in order to minimise the risk of electrolytic corrosion of earthed equipment and exposed conductive parts due to stray DC currents, they should not be bonded directly to the earth (i.e. neither of DC poles are directly connected to earth). Voltage limiting devices (VLD) standardised by EN 50526-2 are widely used for DC earthing in traction systems to prevent electrolytic corrosion problems.

Building on the experience from the limited number of IEC LVDC standards and DC traction standards and to verify the credibility of ST deployment and LVDC systems, further work is needed to improve existing GB DCODE, ESQCR, BS 7671, ERs, ETRs, and other international standards. Only then optimal and secure design of ST and LVDC systems can be assured, and their compatibility requirements with existing distribution grids can be identified. A number of cases when ST and LVDC deployment cannot comply with existing standards and regulations are summarised as follows.

- Starting with GB DCODE, the current version of this document has been developed to outline the technical requirements for connecting equipment to AC distribution networks only, and electronic-based substations or DC distribution systems are not covered. For enabling the transition of the deployment of ST and LVDC from trial phase to business as usual phase, there are still a number of remaining questions which need to be addressed by the Distribution Planning and Connection Code (DPC) of the DCODE. These include: what DC connection voltage(s) should be provided to the customer? What are the configuration options of LVDC supply (e.g. 2-wire or 3-wire) and their implications on the supply and end-users load operation? How reliable is ST-based substation and DC supply? How DC DNO supply should be interfaced to DC end-users' installation?

- For the user's installation to be connected to the DNO supply, it has to comply with the principles identified by ESQCR Regulation 25. One of the key criteria to meet the ESQCR 25 requirements is to comply with BS standard requirements (e.g. BS 7671). On the end-user's side, the only available document for LVDC installations (based on BS 7671) is the IET LVDC Code of Practice (CoP). The scope of this CoP is limited only to LVDC wiring in buildings, and it does not cover the interface requirements between the supply and the end-user's installation. The CoP also does not provide any information on earthing methods of DC for minimising the risk of electrolytic corrosion issues.

- LV Engine LVDC schemes are expected to supply ≥700V DC voltage. This is based on the recommendations made by the University of Strathclyde report on LVDC technical recommendations [9]. This voltage range is higher than what has been identified by IEC 60479 as a maximum touch voltage, leading to the need for DC-DC decoupling interface with galvanic isolation between the supply and the customer to meet the IEC 60479 safety requirements. Such an interface is new to the network and it has the capability to provide new local control functionality (e.g. bi-directional power flow, control of the voltage on the customer side, active energy management and etc.). These new changes will in turn require new operating procedures which currently are not covered by the existing Distribution Operating Code (DOC) of the GB DCODE. Relevant questions need to be answered in order to comply with the DCODE include: what type of information will be required and how can be communicated between the end-users and the DNOs? How should the customer and supply be interacted when a new decoupling interface with active control capability is introduced?

- To comply with ESQCR in order to meet new connection requirements, the DNO needs to provide the maximum prospective short circuit current at the supply terminals. The existing engineering recommendations such as ER G74 and ER P25 cover only short-circuit characteristics of AC power systems. For AC distribution, the ER P25 indicates that if the short-circuit from a generator interfaced by a power-electronic converter is less than 1.2 times of its rated current, the contribution can be assumed insignificant and neglected. This may not be the case for LVDC systems where high transient fault current can be dissipated in the system even if the steady state fault current is limited to 1.2 times of its rated current. Therefore, more accurate DC fault level and short characterisations are still missing from existing ERs and standards. The only available standard which has been used for characterising faulted DC auxiliary systems in power plant and substations is the IEC 61660. The standard provides a simplified method of calculation of prospective DC short-circuit current for rectifiers in 50Hz 3-

phase AC bridge connection, stationary lead-acid batteries, smoothing capacitors, and DC motors, but may not be applicable to advance power-electronic interfaces such as modular ST with fault current management capability.

- At international level, the IEC has stated that there are over 30 IEC technical committees (TCs) need updating in order to add the standards requirements for DC into existing AC standards to cover planning, designing and implementation, communication, information exchange, control and systems security.

6. CONCLUSIONS

The report has reviewed the current key British and international standards that are relevant to LVDC distribution systems, and investigated their adequacy for supporting the potential trials of LV Engine LVDC schemes. The report has also discussed the readiness of the Great Britain (GB) Distribution Code (DCODE) and ESQCR for accepting LVDC and smart transformer technologies to be deployed within existing UK distribution networks.

It has been concluded that there is a significant lack of standards for designing, installing, and operating smart transformers and LVDC distribution in public networks. The only areas covered by standards in this specific application are the definition of LVDC (i.e. ≤1500 V), the physiological impact of DC current electric shocks on humans and livestock, and standards on DC mechanical breakers. Standard nominal operating voltage(s) for utility-owned LVDC and supplying public loads are still missing.

The report has outlined a number of different existing LVDC applications, and has found that high power LVDC traction systems are the most mature LVDC technologies with the experience which can provide valuable information for enabling the trials of the LV Engine LVDC schemes. Important information from this sector which can be adopted by smart transformer-based substations with LVDC supply terminals includes electrical service conditions (e.g. safety, earthing, DC protection requirements); environmental conditions (e.g. converter operating temperature, converter storage and transport, humidity level, pollution degrees); mechanical characteristics (e.g. protection degree of converters enclosures, mechanical vibration levels, clearance distance); and general testing specifications.

In contrast, and due to the homogenous electrical load requirements and the flexibility of DC motors in DC traction systems, their DC voltage tolerance ranges (up to ±33%) cannot be considered for public LVDC distribution networks. Tighter power quality tolerance is required for the public LVDC networks, and the report has recommended ±10% to be considered for the LV Engine LVDC schemes. This was cited from a relevant standard to LVDC for marine application.

For LV Engine LVDC schemes to move from trial to business as usual phase, further work is required to update existing GB DCODE, ESQCR, ENA Engineering Recommendations (ERs) and other associated technical guidance. Only then, safe, secure, and optimal operation of ST and LVDC systems and compatible performance with existing networks can be assured. Because of the innovative nature of LVDC technologies, the update of the ENA ERs to consider LVDC is challenged by the significant lack of British standards and international standards and the limited skills and experience geared towards LVDC and electronic-based substations so far.

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