Overview paper on: low voltage direct current (LVDC) distribution system standards

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Abstract: Low-voltage direct current (LVDC) systems have recently been recognised as one of the key enabling technologies that can facilitate the connection of more distributed renewables with improved efficiency and enhanced controllability. However, there is still a shortage of mature experience and practical technical solutions that can support the uptake of such systems and increase commercial interest. One of the barriers is the lack of standards necessary to increase industry confidence. Recently, new standard activities at national and international levels have begun to cover specific LVDC applications. However, it is still not clear whether these activities, in addition to existing standards, are sufficient and comprehensive to provide the necessary tools for best practice system design. This paper therefore reviews and evaluates the available LVDC standards within the context of the established AC distribution system to determine where future work is required.

Keywords: distribution systems; low voltage direct current; standards.

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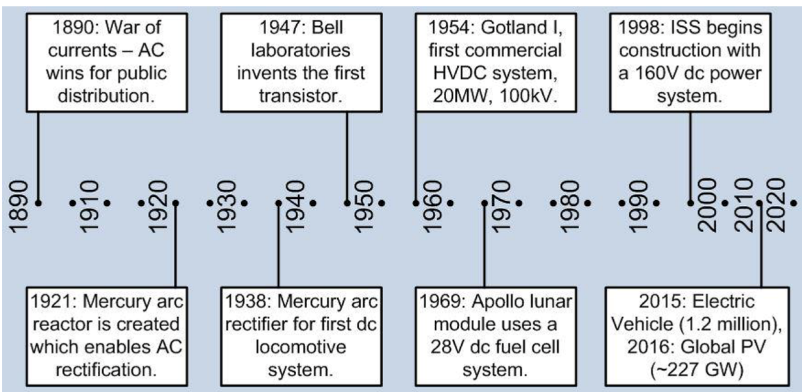
1 Introduction

The use of direct current (DC) power distribution is not new. In fact, it was the first standard electrical distribution system at the end of the 19th century (Lobenstein and Sulzberger, 2008). However, at the time, the inability to transform DC voltages limited the use of DC to local power stations close to electrical loads. The introduction of alternating current (AC) in 1880s and the invention of transformers facilitated the transmission of power over long distances; AC systems have since become fundamental to the operation of modern, highly interconnected power systems. The growth of public AC power networks quickly relegated the use of DC to specific applications such as trams, elevator motors and battery-operated systems. But, as shown in Figure 1, the development of industrial power electronics such as the mercury arc valve in 1902 and the transistor in 1947 has allowed DC systems to evolve over the past century and we now see DC power used in high voltage transmission lines, consumer electronics and industrial variable speed drives (Tiku, 2014). However, these modern applications for DC power distribution remain in isolated systems with limited networking and load heterogeneity.

Figure 1 A brief history of DC power distribution (see online version for colours)



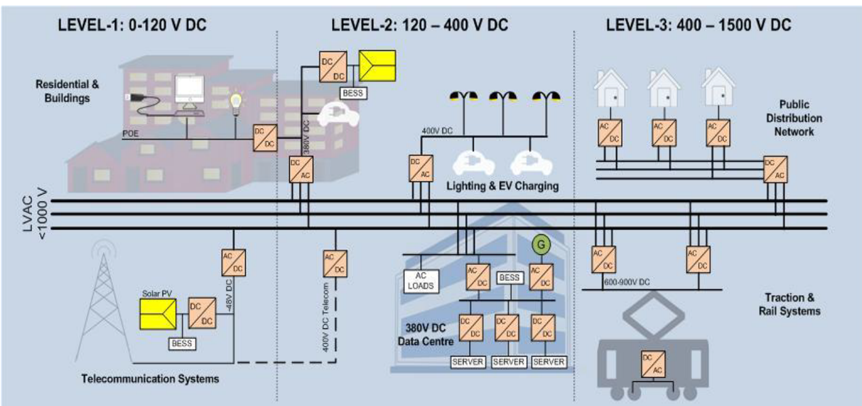
More recently, the increased understanding and concern about the effects of centralised fossil fuelled power stations on the environment has initiated a clean power revolution that is starting to challenge the 100-year old power system paradigm. Modern, renewable power generators are geographically distributed and either produce DC power natively or utilise DC to regulate the power generation from variable speed generators, such as wind turbines. Furthermore, the technical advancement in lithium ion batteries since the turn of the millennium has seen the cost reduction and energy density reach a level where electric vehicles are becoming a real proposition for mainstream consumers (International Energy Agency, 2016). This increasing volume of DC generators, modern electronic loads and energy storage systems raises the question as to whether DC distribution would be a more efficient and economical public power distribution medium. If DC power is to challenge the predominance of AC in low voltage public distribution networks, a new set of technical standards are required to facilitate harmonised voltages and power quality, suitable protection solutions and new safety regulations.

This paper seeks to assess the current state of LVDC standards and to highlight the work that is required to reach a similar level of standardisation compared to existing LVAC public distribution systems. Research papers (Elsayed et al., 2015; Monadi et al., 2015; Dragicevic, T. et al., 2015 & 2016) present excellent overviews of LVDC distribution and protection options. However, this article is the first review that has collated and evaluated the available LVDC system standards to assess the status of LVDC applications and the gaps that may limit the development of LVDC distribution systems. This is presented as an introduction to the active organisations currently developing LVDC standards, followed by a focused review on the power quality, protection and safety requirements for LVDC applications and future public distribution networks.

2 Applications and standards development

The LVDC systems under consideration in this paper are depicted in Figure 2 and a growing number of international standards organisations are developing requirements for the design and safe implementation of these LVDC applications. Most of the standards reviewed within this paper are outputs from the following organisations:

Figure 2 Overview of LVDC distribution systems (see online version for colours)



2.1 International Electrotechnical Commission

The International Electrotechnical Commission (IEC) has recognised the need for introducing new standards that can enable the integration of LVDC technologies within existing AC systems in a secure and optimised way. 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 (Fachot, 2015). The final report from the IEC SEG4 (IEC SEG4, 2016) 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. 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 & LVDC for Electricity Access (IEC, 2017).

2.2 IEEE Standards Association

The IEEE Standards Association has a number of working groups focused on the use of DC distribution for specific applications. The most general working group is WG 946 - DC System Design which is in the process of developing P946 - Recommended Practice for the Design of DC Power Systems for Stationary Applications. Further to this, the Distribution Resource Integration working group has developed P2030.10 - Standard for DC Micro-grids for Rural and Remote Electricity Access Applications (IEEE, 2016). Meanwhile, WG 1709 exists for the development of standards for DC power systems on ships and a series of working groups exist focused on the safe design of DC traction systems for transportation which includes protection, insulation and corrosion design standards. Furthermore, in 2013, an IEEE working group was established to investigate the required standards for 'DC in the home', and the research topics included sockets, safety equipment and breakers (Wiebe, 2013).

2.3 IET standards

The Institution of Engineering and Technology (IET) has recently published two documents related to LV and Extra LV DC 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" (IET, 2015c).

2.4 EMerge Alliance

The organisation, EMerge Alliance, exists for the specific purpose of developing cross-industry standards for the adoption of building level and data centre DC distribution systems. The organisation has published two standards: the Occupied Space Standard and Data/Telecom Standard. EMerge Alliance is currently leading the development of DC distribution systems with a broad consortium of industry and academic partners. They maintain a registry of products that conform to the EMerge Alliance standards and have a vision to develop standards for occupied spaces, residential buildings, data centres, outdoor spaces and building services (EMerge Alliance, 2016).

2.5 Cigre

Working group B4 of Cigre focuses on HVDC and Power Electronic research for distribution networks. Working group C6.31 Medium Voltage Direct Current (MVDC) Grid Feasibility Study is a new group that is considering the prospect of future MVDC distribution systems. As yet, there does not appear to be a working group for LVDC within Cigre.

2.6 National standards

The design of residential and building level DC distribution systems is governed by BS7671 in the UK and the National Electric Code (NEC) regulations in the US. To date, BS7671 contains guidance for the DC connections and cabling requirements with respect to solar PV installations as well as requirements on RCD clearance times according to earthing arrangements but does not make specific recommendations on DC distribution voltage levels or the protection requirements for more complex DC systems (IET, 2015a). In the 2017 NEC edition, there are sections dedicated to the implementation of DC micro-grids (712), solar PV (690), energy storage (706) and direct current bonding (250). Other national standards such as the Indian National Electric Code define a DC distribution voltage level as 220/440 V_{DC} and provide guidelines on cable colours, fault current calculations and solar PV recommendations (Bureau of Indian Standards, 2011). Japan specifies the upper limit of low voltage DC at 750 V_{DC} and China currently has national standards in the area of DC-powered telecom installations (IEC SEG4, 2016).

2.7 Bespoke installations and research projects

International research and commercial pilot projects are advancing the understanding and capabilities of public DC distribution systems that will ultimately inform future national and international standards. A summary of recent LVDC projects are presented in Table 1, collectively, these research themes are advancing the development of technically and economically viable DC distribution networks.

Table 1 Selected existing LVDC pilot projects and research themes

Project	*Application*	*Reference*
DC Smart	DC distribution smart grids	TU Delft (2016)
dcProject	Building level LVDC	Alliance for Sustainable Colorado (2016)
DCC+G	Building level LVDC	Wunder et al. (2014)
Bosch-Honda Micro-grid	Industrial/Factory LVDC	Ravula (2015)
LUT, Elenia, ABB	LVDC for MVAC networks	Nuutinen (2015)
University of Strathclyde	Protection of DC systems	Emhemed and Burt (2014)
University of Aalborg	Control strategies for DC micro-grids	Dragicevic et al. (2015)
Purdue University	Stability of DC systems	Purdue University (n.d.)

3 DC voltage level and power quality requirements

The following section introduces the existing and emerging LVDC applications according to their operating voltage ranges. The most appropriate standards that relate to these applications were reviewed to determine the adequacy of existing guidelines and to identify any gaps that might limit the safe and cost-effective development of these applications and future public DC distribution systems.

3.1 Operating voltage levels

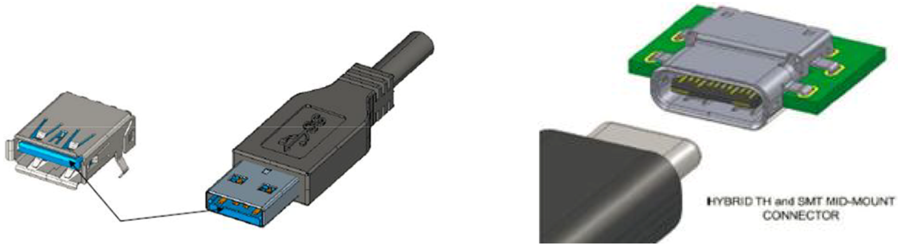
The European Union Low Voltage directive (LVD 72/23/EEC) states that low voltage equipment can possess voltage ranges of 40–1000 V_{AC} and between 75 and 1500 V_{DC} (The European Parliament and the Council of the European Union, 2006). This range sets the boundaries for LVDC; however, further voltage classification can occur within this range. This paper defines three voltage levels, which are depicted in Figure 2 in order to examine the protection and safety standards for applications with similar operating characteristics.

3.1.1 Level-1 applications (<120 V_{DC})

In this paper, Level 1 is considered to be <120 V, which represents the extra-low voltage range of LVDC according to IET (2015b). At this voltage level, the primary design concern is cable insulation thermal degradation caused by excessive currents, which can lead to insulation faults and electric shock. In addition, voltage drops are a significant design consideration and therefore cable lengths are limited at these voltage levels.

The Universal Serial Bus (USB) is the lowest voltage level considered in this review and is a widely used DC system, which has a safe operating voltage of 5 V that is common throughout the USB standard; this includes USB 2.0, USB 3.0 and USB type C as depicted in Figure 3. Both USB-IF and IEC have standardised the recommendations for USB (Hewlett-Packard et al., 2013; USB 3.0 Promoter Group, 2014). USB cables often interface with personal computers whose power supply requires a rectifier to transform the AC power to DC. The standard DC output voltage for a desktop computer is 12 V as specified by ATX12V 2.01 (Intel, 2004). Furthermore, with the introduction of 100 W USB power transfer capabilities, the opportunity for bi-directional power flow through the USB port becomes a real possibility (Intel & DisplayLink, 2016).

Figure 3 USB 3.0 port and connector (left) has the same structure as USB 2.0 but possess 9 pins rather than 4 pins. USB Type C (right) (see online version for colours)



Source: Hewlett-Packard et al., 2016

Within occupied spaces, there has been a rapid adoption of LED lights due to their higher energy efficiency and quick payback period (Yamada and Stober, 2015). To date, most LED bulbs are operated from the AC power network, with their own internal converter. However, DC LEDs can operate on a dedicated DC network and are proven to be more efficient and can provide higher lighting quality with greater resilience to voltage fluctuations (IET, 2013). BS EN 62560 and BS EN 62384 state that the maximum voltage for lamp controlgear should be within 250 V_{DC}, and the typical output voltage is 12/24 V for feeding the DC LED lights (IET, 2013). EMerge Alliance has standardised occupied space lighting systems at 24 V_{DC} and this requires a room-level converter to step-down the voltage to a safe distribution level (EMerge Alliance, 2016).

The emergence of Power over Ethernet (PoE) has occurred concurrently with the development of LED lighting systems and there appears to be a convergence between LVDC lighting systems and PoE to create intelligent, controllable and efficient building-level lighting systems. In 2003, the IEEE 802.3af standard was published which outlined a transmission power of 15.4 W at 44 V over conventional ethernet cables, and this represented the beginning of PoE. In 2009, the standard was upgraded to IEEE 802.3at to meet the demand of higher power applications such as combined power and data cameras, this standard enabled up to 30 W of transferable power at 44–57 V. The newest standard is currently under development and is scheduled for release in 2016 with a power transfer capability of 95 W which utilises four paired conductors within the CAT-5 cable (UL, 2015).

The –48 V_{DC} telecom standard utilises an earthed positive pole to create a negative voltage distribution system that offers cathodic protection to surrounding metal work. The voltage level is sufficient for low power telecom systems; however, ETSI (European Telecom Standards Institute) has since introduced a 400 V_{DC} standard for higher power and more efficient systems. The ETSI 300 132-2 standard for –48 V_{DC} systems offers detailed specifications for product suppliers and system designers. It states the voltage ranges for normal operations to be –40.5 to –57 V_{DC} and an expectation that there should be no degradation in system performance within this voltage range.

3.1.2 Level-2 Applications (120–400 V_{DC})

The applications presented in this section have been grouped in the voltage range of 120–400 V_{DC}, which represents the upper-end of extra-low voltage DC and the emerging voltage standard for occupied space, data centres and electric vehicle charging (BSI, 2014). In some situations, the applications presented here may also utilise Level-1 or Level-3 voltages which reflects the on-going challenge that standards organisations have in classifying and harmonising DC voltage levels.

The need for higher power services and the growing use of renewable generators has led ETSI to increase the operating voltage of telecom systems from –48 V_{DC} to 400 V_{DC} (European Telecommunications Standards Institute, 2011). Furthermore, the rapid increase in data consumption has seen steady growth in the construction of data centres, where the energy demand from these facilities currently amounts to 1.8% (Shehabi et al., 2016) of national electricity demand in the US. A number of LVDC data centre projects have highlighted significant capital and energy efficiency cost improvements that can be realised using a 380 V_{DC} distribution system compared to a traditional 208 V_{AC} and even 400 V_{AC} (Ailee and Tschudi, 2012).

With respect to EV charging, 'fast' off-board DC chargers are believed to offer the most practical public charging system based on time to charge and the potential to offer higher efficiencies compared to an on-board charger (Genovese et al., 2015). LVDC distribution can be applied in the form of dedicated EV charging networks where cable costs can be reduced, utilisation rates of a centralised DC charger increased and the integration of DERs can be easily accommodated (Tabari and Yazdani, 2013; Smith K.A. et al., 2016). The performances of these DC charging systems are standardised in BS EN 61851-23:2014 (BSI, 2014) which outlines the protection, power quality and safety requirements.

3.1.3 Level 3 (400–1500 V_{DC})

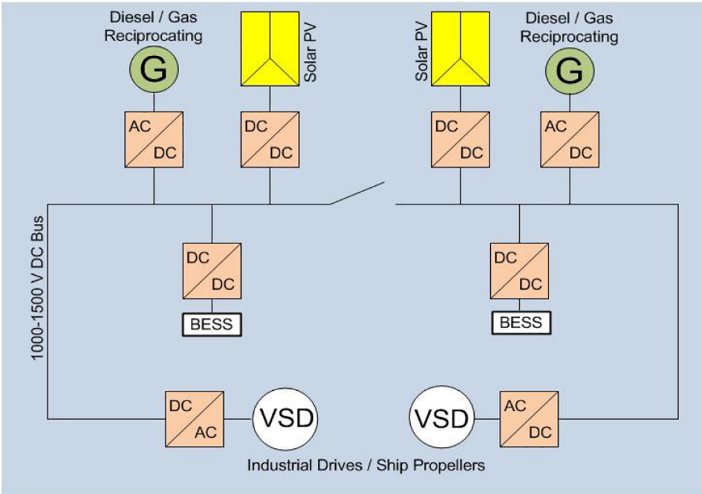
The final voltage classification has the largest voltage range which includes traction systems, solar PV, higher power micro-grids and public distribution systems. Traction systems for public transportation are well developed, and there are many examples of DC railway applications such as commuter trains and inner-city trams (TOSHIBA, 2014). Using DC infrastructure takes advantage of lower voltage losses compared to AC systems (Pires et al., 2009). BS EN 50163-1 specifies the recommended voltage levels for traction systems (600 V_{DC}, 750 V_{DC} and 1500 V_{DC}). Most commonly, 600–1000 V_{DC} is used for metros, light rail transit, suburban railways, and 1500 V_{DC} is used for overhead lines, which is the most economical solution for heavy metros (Goodman, 2006).

Solar PV has been widely implemented as a competitive and ubiquitous renewable energy source. The generated DC power from these systems can be stored in a complementary Battery Energy Storage System (BESS) or exported to the AC feeder by a DC/AC inverter as shown in Figure 2 (Mahela and Shaik, 2016; Adefarati and Bansal, 2016). BS EN 62548 recommends the voltage for PV systems to be within 1000 V_{DC} for buildings without restricted access; however, voltages over 1000 V_{DC} are permitted if the entire solar array and associated electrical equipment are restricted to the public.

Utility-level LVDC distribution networks are arguably the least developed concept compared to the other DC applications discussed in this paper. These DC networks are capable of interconnecting renewables and advanced electronic applications with reduced conversion and distribution losses (Elsayed et al., 2015) while potentially enhancing the power carrying capabilities of existing cable assets (Antoniou et al., 2013). Figure 2 of Section 2 highlights a trial public LVDC network deployed in Finland with a bi-polar voltage of ±750 V_{DC} (Nuutinen et al., 2014).

Figure 4 depicts an islanded DC micro-grid with multiple generating sources connected to a common DC bus and DC/AC inverters to power variable speed drives at optimum efficiency. This topology can be applied to a ship-based power system as demonstrated in ABB's DC on-board project, but it could equally be applied to industrial applications such as mining sites, waste water treatment and manufacturing factories (Hebner et al., 2015). In Germanischer Lloyd SE (2016), it states that the marine power system DC voltage should be within 1500 V_{DC} and as such the ABB DC ship on-board system uses a 1000 V_{DC} distribution voltage. This marine DC micro-grid has demonstrated a reduction in the electrical equipment footprint and weight reductions of up to 30%, which yields fuel and emission savings of up to 20% (ABB, 2014).

Figure 4 Islanded DC micro-grids for ships and industrial power systems, (see online version for colours)



Source: adapted from ABB (2014)

3.2 Voltage tolerances

For LVAC public distribution systems, IEC 60038 specifies the expected voltage and tolerances for standard appliance sockets as 230 V_{AC} +10 and –6% (IEC, 2009). This level of harmonisation does not yet exist for public LVDC distribution systems except for specific applications.

The available power quality standards relating to USB systems contain normal operating voltage ranges and acceptable voltage drops that are summarised in Table 2. With respect to voltage drops, the standards specify the following voltage drop limitations on the ground line to be: USB 2.0 (125 mV), USB 3.0 (171 mV) and USB type-C (250 mV).

The tolerances for electric vehicle charging infrastructure are detailed in BSI (2014), where the DC charging voltage range should be within ±5% of the required level with a voltage ripple that is no more than ±5 V. It also states that the charging system should reach the required charging voltage with a slew rate of 20 V/ms and must be able to reduce the system voltage at a slew rate of at least 250 V/ms.

In research conducted by Kaipia et al. (2016), it is suggested that consumer end inverters on a public LVDC distribution networks possess the ability to withstand +10 and –25% voltage variations. This is similar to the allowable supply voltage variation for railway applications.

Table 2 DC voltage tolerances

Application	*Nominal voltage*	*Min voltage*	*Max voltage*	*Voltage ripple*	*Standard*
USB 2.0	5 V	4.4	5.25	-	IEC 62680-2-1
USB 3.0	5 V	4.45	5.25	-	IEC 62680-2-1
USB Type-C	5 V		5.5	-	IEC 62680-2-1
Desk computer	12 V	–5%	+5%	<120 mV	ATX 2.01
LED lighting	12–24 V	–10%	+10%	-	BS EN 62384
EV charging	200–500 V	–5%	+5%	±5 V	BSI 2014
Marine/Ship	24 V+	–25%	+30%	±10%	IEC 60092-101
Railway	400 V+	–33%	+25%	-	BS EN 50328

3.3 Transient disturbances

Both telecom and traction system standards have well-defined transient disturbance requirements. The ESTI EN 300 132-2 telecom standard makes specific references to low voltage ride-through criteria and normal operating voltage ranges with error margins. Furthermore, EMC requirements for telecom systems are presented in ETSI EN 300 386.

Voltage dips on traction system contact lines are permissible up to 50% of normal voltage and should not last longer than 1 s. The duration of short interruptions caused by circuit breakers and auto reclosing should be less than 10 s. Finally, BS EN 50121 series provides the electromagnetic compatibility standards for railway systems.

It is clear that each LVDC application has its own unique voltage performance characteristics and this is largely possible due to the known nature of the loads and expected performance of each system. However, in more complex public LVDC networks, a more harmonised approach to voltage standards is required to ensure compatibility between a variety of electrical products and energy sources.

4 Protection requirements

4.1 Protection challenges

The protection of DC systems is a key research theme for the development of safe and economical LVDC distribution. The challenges relate to DC arc dissipation, due to the absence of a zero crossing-point on the current signal, the speed of protection due to aggression of DC arc (which requires longer time to be quenched) and the rapid DC fault propagation which can lead to tripping of converters and substandard selectivity issues. These challenges are summarised in Emhemed et al. (2016) and the authors suggest improvements to IEC61660 (International Electrotechnical Commission (IEC), 2000) to more accurately characterise short circuit current in complex DC distribution systems (Emhemed and Burt, 2013).

These characteristics are reflected in the existing protection guidelines, but it is arguable that further standardisation is required in the area of ‘complex’ LVDC distribution networks, where multiple devices, with varying operating characteristics are connected and therefore selectively isolating only faulted sections of the network enhances power system reliability.

4.2 Performance guidelines

For the USB, USB-IF (USB power delivery specification 3.0) and BS EN 62680-2-1 have specified that the power source connected to the USB should implement overcurrent protection and over temperature protection to prevent damage from excessive current and thermal effects (BSI, 2015). IEC 62700 recommends that the short circuit current protection for notebooks comply with IEC 60950. Furthermore, ATX12V specifies that short circuit protection and overvoltage protection should be applied to protect the power supply of desktop computers.

The controlgear for LED lighting systems requires short circuit and overload protection according to BS EN 61347-1. Also, BS EN 61347 2-13 standardises the maximum values of temperature rises under short circuit or overload conditions. Moreover, IET (2013) mentions that fuses and miniature circuit breakers can be utilised at the input of the driver to protect the running of the LED system. For power limited circuits such as LED lighting and POE systems, the NEC725 code presents Class 1, 2 and 3 circuits which specifies the power, voltage and protection requirements for these circuits (National Fire Protection Association, 2017).

In more complex DC distribution, systems such as data centres, fuses and circuit breakers are required to isolate the faulted section of the network. Although BICSI 002-2014 and TIA-942-A exist to support data centre design, these established standards do not yet incorporate DC electrical specifications. IEC/TC 64 is tasked with evaluating and standardising the DC electrical content for BS EN 50600-2-2:2014 and will be releasing recommendations in due course. However, ETSI EN 300 132-3-1 specifies expected voltage ranges and protection requirements for telecom systems, radio base stations and data communication equipment, which may be extrapolated for data centres with a distribution voltage less than 400 V_{DC}.

The protection of telecom infrastructure occurs at what is termed the A3 interface, this is where the generators connect to the Information Communication Technology (ICT). The acceptable voltage range at this interface is between 260 and 400 V_{DC} which represents the charge/discharge voltage characteristics of a connected Battery Energy Storage System (BESS). The standard states that the circuit should be protected with either fuses or circuit breakers which meet the requirements of IEC/EN 60269-1, IEC/EN 60947-2 and IEC/EN 60898-2. On start-up of the power system, the in-rush current must be minimised to avoid triggering the over current protection. The protection design should take into consideration system’s T_{50} metric; this describes the duration at which the in-rush current is 50% of the peak in-rush current (I_p) and the energy content (E) of the inrush current can be approximated using $E = I_p^2 \times T_{50}$ (European Telecommunications Standards Institute, 2011).

The DC protection requirements for traction systems are well defined with several protection options described in standards. BS EN 50123-7-1 relates to the DC switchgear for traction systems and establishes the requirements rate of change of current, inverse time overcurrent protection, inverse time overcurrent with thermal imaging as well as under voltage protection. Furthermore, BS EN 50123-1 specifies the recommendations for current limiting circuit breakers for the protection of traction systems at the station locations. This includes the high-speed current limiting breaker (with a total breaking time of <20 ms), very high-speed current limiting circuit breaker (total break time <4 ms) and semi-high-speed circuit breaker (total breaker time <30 ms).

There appears to be limited information relating to protection requirements for integrated solar PV DC distribution systems and electrical loads. At present, the majority of standards relate to solar PV systems that connect directly to the AC network. Therefore, the protection solutions presented here relate to the protection of PV pannel strings and arrays. In BS EN 50123-1:2003, the PV fuse link is specified to 1.45 times normal operating current. Also, BS EN 60269 (BSI 2012) and UL 2579 (Lyons, 2011) have stated the fuse link requirements for protecting the PV system. Furthermore, overcurrent protection is recommended in BS EN 62548-1:2015. Finally, IEC 60364 7-712 states the requirements for the overload and earth fault protection.

Overcurrent protection is also capable of protecting marine power systems. The electrical installation standard for small vessels, IEC 60092-507, recommends DC fuses operate with 1.45 times the lowest current carrying capacity of the conductors in the circuit. Also, IEC 60092-202 provides recommendations on the undervoltage protection for DC generators and DC motors. For personal water-craft, the American Boat & Yacht Council (ABYC) E11 has specified the overcurrent protection and ground fault protection for <50 V DC electrical systems. However, for larger, more powerful DC marine or land-based micro-grids, the circuit protection requirements are not fully covered in the existing standards and still require further development. Both 1000 V_{DC} marine power system and a ±750 V_{DC} public distribution system have been deployed by ABB and the Finish Distribution Network Operator Elenia Oy, which suggests practical protection solutions are available for these higher power distribution systems.

With respect to DC moulded case circuit breakers (MCCB), IEC 60947-2 has specified the standards for DC MCCB, where products are available commercially. However, mechanical-based breakers do not offer the required speed to prevent damage to sensitive power electronics, and this requires more expensive, higher-rated, devices to withstand the fault current. Therefore, significantly faster hybrid solid-state circuit breakers (SSCB) offer a promising solution for LVDC networks; however, this technology is still at the research stage without standard guidelines (Meyer and Rufer, 2006; Shen et al., 2015). Table 3 provides an overview of the commercially available DC fault interruption devices.

Table 3 Examples of standardised LVDC fault interruption devices (see online version for colours)

Miniature Circuit Breaker		
Brand	 Schneider Electric Acti 9 (Schneider 2017)	 ABB S280 (ABB 2007)
Operational Voltage	250 V DC (1P)/500 V DC (2P)	220VDC (1P)/440VDC (2P-4P)
Trip Units	Thermal-magnetic	Thermal-magnetic
Standards	IEC 60947-2;	IEC 60947-2;
Breaking Capacity	6000 A at 250 V DC/500 V DC	6000 A at 220 V DC/440 V DC
Moulded-Case Circuit Breaker		
Brand	 Eaton Series G-JG (Eaton 2016)	 ABB Tmax, T4 (ABB 2007)
Operational Voltage	250 V DC	125 V DC, 500 V DC, 750 V DC
Trip Units	Fix/Adjustable, thermal/magnetic	Thermal/Magnetic, Electronic
Standards	IEC 60947-2	IEC 60947-2
Breaking Capacity	Up to 50 kA at 250 V DC	Up to 150 kA at 250 V DC
Fuse		
Brand	 Eaton (Bussmann series) (Eaton 2015)	 Littlefuse (i.e. Class L-KLLU) (Littelfuse, 2012)
Operational Voltage	500 V DC	300 V DC
Trip Units	Thermal	Thermal
Standards	IEC/self-certified	Littlefuse self-certified;
Breaking Capacity	50 kA Max	20 kA

5 Safety

With the introduction of LVDC distribution systems into traditional AC networks, a number of additional safety requirements should be considered. These include the impact of running both AC and DC cables alongside one another; the effect of corrosion from DC earthing on adjacent metal work; an increased risk of fire due to DC arcing and the risk of stored circuit energy prior to maintenance activities. This section summarises the available safety standards with respect to mitigating the risk of electric shock, corrosion effects and fire safety.

5.1 Risk of shock

5.1.1 Basic protection

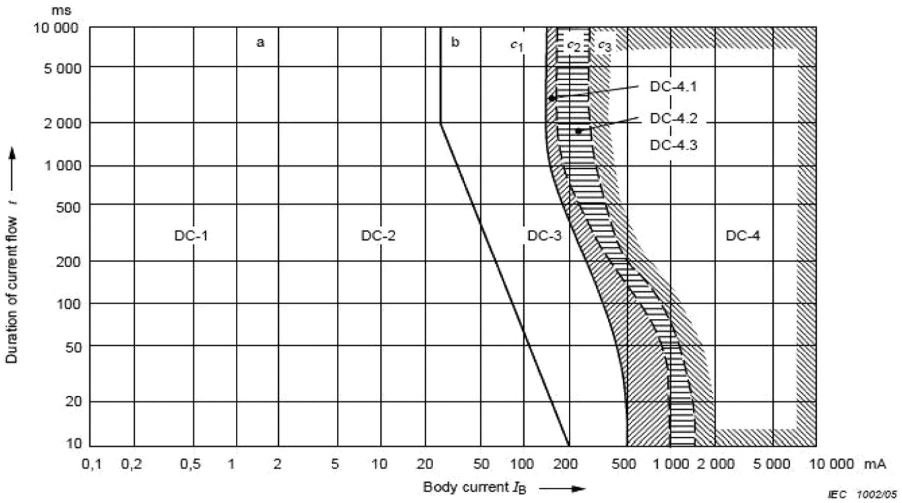
Basic protection refers to the measures that are in place to safeguard the public and livestock from electric shock during normal operating conditions. In the UK, BS7671 and EN BS 61140:2016 present basic protection and standard safety requirements for electrical circuits. The same approach to basic protection can be applied to both AC and DC systems; however, additional considerations are required when AC and DC circuits are mixed within the same installation. There are no specific recommendations on the mixing of DC and AC circuits within the same distribution channels or conduits. However, both BS7671 and NEC.725 state that different classes of distribution voltages can be mixed as long as all cables are insulated to the highest voltage rating in the shared distribution channel. Furthermore, the use of warning signs and suitable circuit identification should be considered. Chapter 51 of BS 7671 provides recommendations on the use of warning signs and the convention for labelling AC and DC circuits; however, further categorisation should be considered to identify different DC voltage levels within an installation.

As more complex DC distribution networks become technically and economically viable, there will be a requirement to maintain and operate these networks safely. These power systems are likely to contain a large number of power converters which can possess stored energy within capacitors that must either be isolated or discharged before performing maintenance work on the network. Therefore, recommendations on the safest approach to isolating and de-energising DC distribution networks should be considered in future standards.

5.1.2 Fault protection

The risk of an electric shock can occur in faulted electrical systems where exposed conductive parts become 'live'. To mitigate this risk requires an effective earthing and/or fault detection system that can rapidly resolve the fault before harm is caused to the public or livestock. IEC 60479 documents the effects of current on humans in Figure 5. The level of current flowing through an organic body depends on its impedance and the touch voltage of the live device. Four threshold current ratings are highlighted, these include: DC-1, where minor sensations are felt, DC-2 where muscles may involuntary contract, DC-3 strong muscle contractions and adverse heart effects are experienced, DC-4 irreversible damage can be done which can result in death depending on exposure to the current.

Figure 5 Effects of current on human beings and livestock



Source: IEC, 2005

It is therefore important to select DC voltage levels and protection such as residual current devices (RCDs) that limit exposure to body currents. It is suggested in Schneider (2013) that voltages under 50 V_{DC} do not present danger to humans, this assumes a body impedance of 1 kΩ and a threshold current of 50 mA. However, other standards prefer a more conservative design such as solar PV systems, where BS EN 62109 specifies that the limitation of current through protective impedance should not exceed 10 mA DC to prevent risk of shock (BSI, 2010).

Within occupied spaces, IEC 60598 specifies the provisions for protection against electric shock for LED lighting systems. It states that the control gear voltage should exceed 60 V_{DC}, and then touch current should be within 2.0 mA. Furthermore, IEC 61347-1 states the provisions for insulation between circuits and accessible conductive parts. With respect to personal computers and USB connections, BS EN 60950-1 states the provisions of protection from hazards for desktop computers. For example, without an overcurrent protection device, output current should be within 8 A when output DC voltage is less than 30 V. The USB-IF standard (Universal Serial Bus 2.0, 3.0 and type-C Specification) and BS EN 62690-2-1 offer recommendations and guidance on grounding safety.

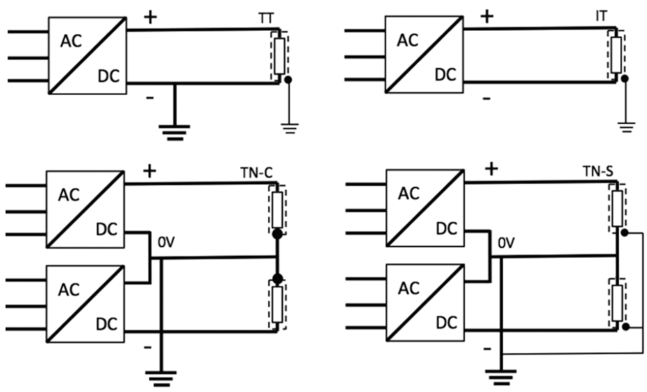
In larger DC power systems, IEC 60092-507 has standardised protection provision against electric shock, such as maximum breaking time of a protective device (e.g. U >400 V_{DC}, max time is 0.1 s), the residual current device operating time should not exceed 40 ms at a residual current of 150 mA for marine electrical installations. Whereas BS EN 50328 and BS EN 50633 describe the safety requirements for traction systems, and this includes the fault clearance and withstand time for the converter which is specified as 0.15 s.

IEC 60755 presents three classifications of RCDs: Type AC, Type A and Type B (IEC, 2008). RCDs measure the residual AC current through a coil; however, DC residual currents can cause the coil to saturate and therefore lead to inaccurate readings. Type B RCDs are designed to function with DC residual currents exceeding 6 mA and are therefore suitable for applications such as PV, EVs and variable speed drives (Kumar &

Eichner n.d.). Alternative earth leakage protection solutions include insulation monitoring devices (IMD) that can detect circuit insulation faults and send an alarm to the circuit controller (IEC, 2014). Finally, selecting an extra low voltage DC distribution level can mitigate the safety hazard of residual currents.

Four different earthing configurations are described in BS7671 and depicted in Figure 6: TN-C, TN-S, TT, IT. Each arrangement offers different benefits to LVDC systems; however, BS7671 advises against IT earthing due to the lack of practical experience with these systems. This represents a challenge as recent research suggests that IT systems offer several advantages over traditional earthing arrangements for new LVDC distribution systems, this includes enhanced redundancy and fast touch-voltage reduction (Kaipia et al., 2015). Further research is required to assess the optimum earthing arrangements for specific LVDC applications and this should be reflected in updated wiring codes. Within the NEC, code 250 relates to earthing and bonding of electrical installations and specific recommendations are stated for the sizing of the DC grounding electrode, the requirement for ground fault detection in ungrounded systems and the requirement for labelling the type of grounding configuration at the source of the DC system.

Figure 6 Possible LVDC earthing configurations: all earthing solutions are suitable in either a 2-wire or 3-wire DC distribution system



ETSI EN 301 605 describes the relevant earthing configurations for 400 V_{DC} data and telecom equipment. This standard concludes that TN-S and IT earthing arrangements are most suitable for this application as the PE arrangement can be managed within the telecom or data centre installation and therefore TT earthing can be disregarded (ETSI, 2011). The IT system offers an additional element of redundancy as it can continue to operate after a single pole to ground fault. The fault current in the IT system is limited by a high impedance earth connection, but this system can introduce additional complexity and cost compared to the more traditional TN-S system which is widely used in AC power systems and is most familiar to electrical installers.

An EV charging station may operate as an isolated DC system or a non-isolated system. In the isolated case, a protective conductor between the DC EV charging station and the vehicle is monitored for loss of electrical continuity. Should a loss occur, the charging station is required to shut-down within 10 s of detection. For non-isolated systems, the earth conductor is monitored for continuity and the charging station must shut-down within 5 s of detecting a loss of protective earth. A DC EV charging station is required to shut-down in the event of a short circuit, earth leakage, CPU (Central Processing Unit) failure or high system temperatures (BSI, 2014). Any ECP (Exposed Conductive Part) should have a voltage less than 60 V within 1 second of disconnecting the EV from the electrical supply and the stored energy should be less than 20 J.

5.2 Corrosion effects

None of the application-based standards specifically mention or offer recommendations towards the mitigation of electrolytic corrosion effects. However, the IET's "Practical Considerations for DC Distribution" suggests the IT earthing arrangement naturally limits the earth current during faults and therefore is more protective of adjacent metalwork (IET, 2015c).

IEC 50162 provides detailed guidance for the protection against corrosion by stray currents from direct current systems. However, this standard refers to the more traditional uses of DC power and perhaps requires an update that incorporates the recent developments in public LVDC distribution applications such as building level distribution and micro-grids.

The –48 V telecom standard uses an earthed positive pole to mitigate against electrolytic corrosion; however, this creates an earth to circuit current flow through human/livestock where contact to a live circuit occurs. The flow of fault current in this direction can cause ventricular fibrillation at half the current value in the circuit to earth direction and is therefore considered a more dangerous distribution configuration and unlikely to be adopted at higher voltage levels (Hirose et al., 2011).

5.3 Fire safety

Much of the fire risk associated with DC distribution is similar to AC systems and is mitigated with standard design and protection measures according to national wiring regulations as well as health and safety requirements. However, electrical arcing of DC systems is more severe compared to AC and therefore additional basic protection requirements may be necessary to avoid exposure to flammable gasses and to ensure appropriate separation between electrical equipment and building material fabric.

Recently, the introduction of DC power sources, such as solar PV, into public distribution systems and buildings has caused increased fire and safety risk to property and personnel responding to fires (Allianz Global Corporate & Specialty, 2012). The severe arcing of a rooftop solar PV installation under faulted conditions can ignite a fire; therefore, careful installation of solar PV systems and protective equipment is essential. It is also important that personnel responding to a building fire, with a solar PV installation, possess the means to isolate the solar panels and understand when it is safe to apply water to the fire without the risk of electrocution. The American wiring code, NEC 690, presents clear guidelines for the automated shut-down of solar PV systems under faulted conditions. In addition, detailed research into this fire safety risk has been conducted by Underwriters Laboratory and the findings are presented in Backstrom and Dini (2011). These fire safety requirements must also be considered in more complex DC distribution systems which may contain additional DC sources such as battery energy storage and fuel cells.

6 Discussion

This LVDC standards review has focused on civilian technical standards with a particular emphasis on the protection requirements, power quality and safety for existing and emerging LVDC systems. The available LVDC standards discussed in this paper are presented in Table 1 according to application and voltage range. From this presentation, it becomes clearer where standards are lacking for certain applications. The adequacy of existing standards and opportunities for future development can be summarised according to each of the voltage-level categories.

The <120 V_{DC} applications are all commercially available and possess well-defined technical standards with limited barriers to future development. However, the area of residential and occupied space LVDC distribution is complex with many electrical products that require different supply voltages. The use of a universal DC distribution system for occupied spaces requires consideration of the optimum appliance voltage level. We have seen from this review that USB connections operate at 5 V, computers at 12 V and lighting at 24 V with some telecom and PoE systems at 48 V. These voltage levels may be suitable for distribution systems up to 1 kW but in order to avoid converter efficiency losses, room-level DC voltages should be harmonised to a single level that is capable of supplying the diverse electrical appliances. Furthermore, the connection of AC appliances to a DC supply can cause overheating, risk of fire and permanent damage to the AC product, so it is therefore necessary to design power outlets that accept only AC or DC appliances.

The applications presented in the 120–400 V_{DC} category are less developed compared to those in the lower voltage range; however, the 400 V_{DC} telecom standards provide sufficient information to enable standardised voltage levels and the development of commercial products for these systems. The introduction of the EMerge Alliance 380 V_{DC} data centre standard further supports the development of this DC distribution voltage level in building environments. A common theme between these application standards was a lack of preference or guidance towards the most appropriate earthing arrangement. This remains an area of active research that requires a solution offering safety, optimum system performance and reduces the risk of electrolytic corrosion to structural steel within buildings and underground pipes. These applications may span power levels from the tens of kilowatts to hundreds, with either uni-polar or bi-polar converter configurations.

The use of LVDC in utility-level distribution networks such as islanded DC micro-grids, hybrid AC/DC micro-grids and last mile DC distribution requires further standardisation. Little experience exists with these larger LVDC networks and as such the optimum design configurations are still an area of research. These networks may draw experience from high power DC traction systems; however, traction systems have large power quality tolerances due to the homogenous electrical load and predictable load requirements. A utility-level LVDC network may have multiple generator types and varying electrical loads that will require tighter power quality tolerances and more sophisticated protection solutions. These networks have the potential to distribute power at the megawatt level and thus far have adopted a bi-polar ±750 V_{DC} distribution configuration for the maximum power delivery efficiency. This distribution voltage level also facilitates the separation of 750 V_{DC} line into ±375 V_{DC} for lower power applications in the Level 2 voltage range.

In order to recognise the potential environmental and cost benefits that LVDC can bring, it will be necessary to demonstrate an equivalent or higher level of safety compared to AC systems. Further investigation and standardisation are required in the area of fire prevention from DC arcs both within enclosed areas that contain potential flammable gases and with respect to proximity to building fabric materials, especially electrical appliances and power plugs. Furthermore, the performance of maintenance on complex LVDC networks requires careful consideration of the isolation and de-energisation of connected converters on the network prior to commencing work.

Table 4 Available LVDC standards

	Application	*Protection criteria*	*Safety*	*Power quality*	*Earthing & Bonding*
LEVEL 1: <120 V	USB	USB-IF (2.0, 3.0, Type-C) BS EN 62680-2-1	USB-IF (2.0, 3.0, Type-C) BS EN 62680-2-1	USB-IF (2.0, 3.0, Type-C) BS EN 62680-2-1	USB-IF (2.0, 3.0, Type-C) BS EN 62680-2-1
	Telecom (48V)	ETSI EN 300 132-2TR 100 283	ETSI EN 300 132-2	ETSI EN 300 132-2	ETSI EN 301 605
	LED Lighting	BS EN 61347 2-13 BS EN 61347-1	IEC 60598-1 IEC 61347-1	BS EN 62384	IEC 61347-1
	PoE	NEC.725	-	IEEE 802.3at	-
EVEL 2: 120-400 V	Residential	-	BS7671 NEC	-	BS7671 NEC
	Building	-	BS7671 NEC	-	BS7671 NEC.250
	Telecom (120 - 400V)	ETSI 300 132-3-1 ITU-TL.12(00-05)	ITU-TL.12(00-05)	ETSI 300 132-3-1 YD/T2378-2011 YD/T2089-2016	ETSI EN 301 605 ITU-TL.12(00-05)
	EV Charging	BS EN 61851-23:2014	BS EN 61851-23:2014	BS EN 61851-23:2014	-
	Data Centre	BS EN 50600-2-2:2014	BS EN 50600-2-2:2014 IEC62040-5-1	BS EN 50600-2-2:2014	ETSI EN 301 605
LEVEL 3: 400-1500 V	Traction	BS EN 50123-7-1 BS EN 50123-1	BS EN 50328 BS EN 50633	BS EN 50328 BS EN 50163	IEC 62128 IEC 60364-4-41
	Public Networks	-	P2030.10 NEC.712	-	NEC.250
	Ship Power	IEC 60092-507 ABYC E11	IEC 60092-507	IEC 60092-101	-
	Solar PV	BS EN 60269-6 BS EN 62548-1	BS EN 62109-1 EC 60364-4-41	BS EN 62109-1	IEC 60364-7-712

7 Conclusion

This LVDC standards review has highlighted the international organisations that are actively developing design recommendations for LVDC systems and it has presented the available standards with respect to each application's protection requirements, power quality and safety. From this review, it has become clear that stand-alone DC applications have well-defined technical standards, but the technical specifications for more complex, integrated networks that will be found within the built environment and public distribution systems are still evolving. Opportunities therefore exist for academics and industry to assist in the formation of the following standards:

- Voltage harmonisation: standard public distribution voltages are required for street-level, commercial and residential spaces with consideration to allowable voltage tolerances. From this review, it is suggested that ±750 V_{DC} is considered for street-level distribution, ±200 V_{DC} (380–400 V_{DC}) is used for building level distribution and a 48 V_{DC} room-level voltage is established to offer the most likely compatibility with electrical devices while maintaining a safe voltage level.
- Safety: the physiological effects of current on humans are well understood but greater standardisation of allowable touch voltages and acceptable exposure times should be considered. A better understanding of the optimum (safe and economical) earthing configurations for DC distributions systems is required.
- Protection: the provision of performance guidelines for SSCB and DC RCDs is required for the protection of physical assets and life. Special consideration should be given to the interference of power converters and fault current levels on existing building-level protection systems. Furthermore, the operation of protection systems and its impact on fire safety should be considered with respect to stored energy in converters and batteries.

Once these areas are addressed, product manufacturers and electrical system designers will have the confidence to implement public LVDC distribution and the benefits afforded by LVDC can be recognised.

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