LVDC RULES – TECHNICAL SPECIFICATIONS FOR PUBLIC LVDC DISTRIBUTION NETWORK

Pasi NUUTINEN[1] Tero KAIPIA[1] Janne KARPPANEN[1] Aleksi MATTSSON[1] Andrey LANA[1]
Antti PINOMAA[1] Pasi PELTONIEMI[1] Jarmo PARTANEN[1] Mika LUUKKANEN[2] Tomi HAKALA[3]

[1] Lappeenranta University of Technology (LUT), Finland, firstname.lastname@lut.fi
[2] Ensto Finland Oy, Finland, mika.luukkanen@ensto.com
[3] Elenia Oy, Finland, tomi.hakala@elenia.fi

ABSTRACT

When a low-voltage DC distribution system installation is realised in a public power distribution network, an extensive specification is required to ensure electrical and equipment safety and compatibility between the existing grids and customer-end installations. The goal of the paper is to give to a reader an understanding what is required for safe and reliable operation of the LVDC distribution in an actual distribution environment. The paper discusses the mechanical and electro-technical aspects of the pilot installation. The focus is on the common system and power electronics specifications.

INTRODUCTION

A three-year research project, LVDC RULES, was launched in 2015 and is conducted in collaboration between Lappeenranta University of Technology, Elenia Oy, and Ensto Finland Oy. The concrete result of the work will be a pilot installation realised in the distribution network of Elenia Oy [1]. In LVDC RULES, the aim is to take the final steps towards the industrial-scale low-voltage DC (LVDC) distribution. In the two previous utility-scale LVDC installations in Finland, the goal in the first one was to realise a flexible research platform with custom-built converters [2], while in the second one the approach was to use modified commercial components [3]. LVDC distribution network combines DC distribution, power electronics, and information and communications technology (ICT) system, which are the key enablers for smart grid services and functionalities. The specification aims to ensure flawless operation and compatibility within the system and with the surrounding environment.

COMMON ELECTRICAL SPECIFICATIONS

The smartness of the system and requirements for various ancillary functionalities are not the only aspects that need to be taken into account in the design process. The most important requirement is still safe and reliable power transmission between the grid and the customer, throughout the lifetime of the entire distribution system. Hence, the main focus in this paper is on the discussion of the electrical and mechanical specifications concerning the entire LVDC distribution system and power electronics.

Nominal voltage levels

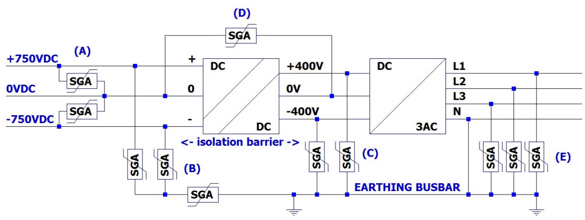
One of the main advantages of the LVDC distribution system is the notably higher power transmission capacity if compared to the low-voltage AC (LVAC) distribution system. Hence, the LVDC distribution system can be used to replace the existing LVAC network and partially lateral medium-voltage (MV) AC line branch [4]. To gain the advantage, the highest allowed DC voltage level of 1500 VDC is used. In this application, bipolar ±750 VDC system structure was selected, because 1500 VDC unipolar solution requires switches with a high rated voltage, if two-level power electronics topologies are used [5]. The nominal operation voltage is ±750 VDC +10%/-20% and the bipolar distribution grid includes middle conductor, thus a unipolar connection of the converters is allowed.

Earthing system

Earthing system of a public LVDC distribution includes utility network earthing system and earthing system used in customers' private installations. It comprises protective and functional earthing arrangements. LVDC distribution system can be realised as earthed and earth isolated. Functionally earthed system requires earthing resistance preferably less than 1 Ω but in Finland, the soil resistivity is high (2300 Ωm in average) and it is more feasible to select IT earthing system [6] than enhance the earthing, although the required insulation monitoring device (IMD) adds some costs to the system [7]. Customer-end installations are realised with functional earthing, i.e. with TN-S [6] earthing system. Use of functionally earthed customer-end network with unearthed DC network requires galvanic isolation between the networks.

Voltage withstand and insulation

Overvoltage protection is important in LVDC network composed of power electronics that are significantly more sensitive to climatic overvoltages, if compared with traditional AC distribution components. The protection has to cover both overvoltages between lines and against earth. Fig. 1 introduces the protection scheme. Because all equipment are energised directly from the supplying grid and the system is a part of public distribution network, the overvoltage category is IV. Consequently, the rated impulse voltage for the equipment and components is at least 15 kV, short-term ($t \leq 5$ s) temporary overvoltage is $U_n + 1200$ V and long-term ($t > 5$ s) temporary overvoltage is U_n + 250 V, where U_n is the nominal voltage of the system [8]. Under any circumstances, the potential difference seen by power electronics module should not exceed 900 VDC in normal operation. Special attention is paid to the component and connection selection since even moderate level leakage current may trigger the insulation monitoring device and result in system shutdown.



(A) Floating voltage limitation between LVDC lines
(B) Potential binding for LVDC network
(C) Potential binding for intermediate circuit rails
(D) Potential difference limitation between middle conductors
(E) Customer-end network surge arresters

Fig. 1. Overvoltage protection in LVDC distribution grid.

Protection

The fault protection of the public LVDC network is based on IMDs. The insulation level is continuously monitored compared with pre-set limits of warning and trip. In an insulation failure, the Finnish standardisation for utility low-voltage distribution (SFS 6000-8-801) requires disconnecting the supply within 5 seconds [9]. This is to minimise the risks due to double faults. However, with the permit of the operations manager, longer tripping times may be applied. Operation in short-circuit is a major difference in LVDC application, if compared to existing AC systems. Typical overcurrent protection scheme of a converter is tripping on an overcurrent event. In LVDC distribution, shutting down the converters is not applicable solution, but a selective protection system is needed. DC network short-circuit protection of the LVDC mains is implemented using DC-rated circuit breakers. These are located after the rectifier and before every inverter unit. The AC side of the rectifier is protected using fuses. Similar protection scheme is used in [2]. The required switch-off time depends from the ratings of the components and the selectivity of the protection.

The fault and overcurrent protection in the customers' installations is based on fuses or today more commonly on miniature circuit breakers with electromagnetic trip units. Residual current devices (RCDs), with operating current of 30 mA, are used to provide additional protection. In a customer-end network protected with 3x25 A main fuses, type C16 circuit breaker is the most demanding protection device, that has to trip in 0.4 s time required by SFS 6000-4-41 [9]. With type-C trip curve, current of 5–10 times the rated current results in requirement of 160 A, at minimum. DC/AC inverters are compatible with the existing protection devices, and the supply of controlled short-circuit current is guaranteed in every condition. Short-circuit protection of a converter-fed customer-end network is discussed in more detail in [10].

According to SFS 6000-8-801 [9], the recommended minimum single-phase short-circuit current in the connection point of customers' installations is 250 A. This is partly based on the need to ensure supply voltage quality in AC distribution. As in this case the only aim is to ensure operation of the protection devices, 165 A current has been considered adequate. This is the situation with individual DC/AC inverters feeding every customer [2]. In the case of the 17 kVA inverter, the required power can be 38 kW in the worst-case situation, where a high-impedance single-phase short circuit occurs and the inverter output voltage is the nominal 230 V and the current is 165 A. This is the maximum power of the DC/AC inverter module and the power is supplied from the DC network through the DC/DC converter. Hence, the maximum current being 165 A per phase during a three-phase short circuit, the maximum short-circuit impedance is 1/3 of the single-phase impedance, resulting 38 kW three-phase power. Special attention has to be paid on the protection of the service lines that supply several customers, or in the case of point-to-point structure [3]. In this situation, DC/AC inverter with a higher current rating is used.

Electromagnetic compatibility and voltage quality

Electromagnetic compatibility (EMC) deals with the supply voltage and load current quality at the electrical interfaces, common-mode conducting interferences, and radiating interferences. The specifications are divided to emissions caused by and immunity of the equipment, especially the converters. If standard requirements do not exist, specifications have been derived based on applicable compatibility levels for this environment. The EMC issues of the equipment have to be taken into account according to best knowledge. If required, electromagnetic interference (EMI) mitigation measures have to be taken. If the system is considered from MV network point of view, the LVDC distribution appears as an electronic load. Currently, there are no standards defining electromagnetic interference (EMI) in the DC network in the frequency range from 2 to 150 kHz. IEC TS 62578:2015 [11] discusses the emission values below 150 kHz, but it does not define the limits for the emission. EMI issues in the previous installation [2] are discussed in two previous publications [12], [13].

Basically, the voltage quality in the DC is not a limiting factor because the customer-end voltage quality is maintained with the DC/AC inverter. However, the LVDC system should not disturb customers of the AC network, connected to the MV network. The DC network is implemented as an IT system and there are no end-user equipment directly connected to the DC network. Hence, the disturbances in the DC network have no effect on electrical or equipment safety, but they could generate radiating interferences and hinder the use of power line communication (PLC) [12], [13]. EMI issues could arise especially in aerial networks, that are normally constructed by using aerial bundled cables (AC) manufactured and installed according to HD 626-5D S1 [14]. This is not discussed in any publication, but on-site measurements will be conducted and the results will be analysed in future

Table 1. Emission limits and voltage quality requirements for 230/400 VAC customer-end networks.

Property	Limit
Conducted RF-emissions, 0.15–30 MHz, Group 1	Class A
Radiated emissions, 30–1000 MHz, Group 1	Class A
Voltage fluctuations and rapid voltage changes	$\leq$ 3 % of U_N
Flicker, short-term, 10 minutes period	$P_{st} = 1$
Flicker, long term, 2 hours period	$P_{lt} = 0{,}8$
Harmonics, long term	THD = 8%
Harmonics, short term	THD = 11%
Frequency	50 Hz ±1% (99.5%[1]) 50 Hz +4%, -6% (100%[2])
Variation	±10% (95%[3]) -15%, +10% (100%[4])

1) Of 10 s mean values of a year
2) Of 10 s mean values of a year
3) Of 10 min mean RMS values during each one-week period
4) Of 10 min mean RMS values of supply voltage

It was said that the use of functionally earthed customer-end network with unearthed DC network requires galvanic isolation between the networks. This is realised using isolating DC/DC converter instead of the solution with 50 Hz transformer [2]. This could increase the magnitudes of the disturbances and has to be taken into account in the design process. Measurements will be conducted to ensure that the power electronics modules comply with the available standards. In Table 1, emission limits and voltage quality requirements for the customer-end supply are shown. Voltage quality requirements are set in the standard SFS-EN 50610 [15]. In the case of LVDC, the voltage quality of the customers is maintained with the DC/AC inverters, if they are supplied with individual inverters [2]. In this case, better quality than the standard requirement can be achieved. In the point-to-point structure [3] or in the case of a single DC/AC inverter supplying multiple customers, the voltage quality in the supply point is kept constant.

Cables, overhead lines and labelling

Cable types allowed to be used in DC distribution according to HD 603 [16], HD 626 [14] and national standardisation, are utilised. These are the same cable types that are used in most of the public AC networks in Europe today. It is essential to label every part of LVDC grid clearly to prevent any possibilities for mixing AC and DC conductors. In the unit cabinets, the connection voltage should be marked on the outer surface of protective cover/casing. In Table 2, colours of the underground cable conductors and coding of aerial bundled cable (ABC) conductors are shown. With ABC, a specific sign near to each pylon is used and if the same pylon is used for several lines with different voltages, LVDC should have notification stripe marking around the pole. These are shown in Fig. 2.

Table 2. Colours and coding of underground cables and ABCs, respectively as used in Finland. Available conductors depend on cable type [16] and their use in AC network of the applied earthing system.

Underground cable color (a.c)	DC
Brown (L1)	Positive pole (+DC)
Black (L2)	Middle pole (M)
Gray (L3)	Negative pole (-DC)
Blue (N), if available	Not used
Yellow-green (PE), if available	Protective earth (PE)
Sheath (N or PE or PEN), if available	Protective earth (PE)
ABC coding (a.c)	**DC**
Two-ridge (L1)	Positive pole (+DC)
Three-ridge (L2)	Middle pole (M)
Four-ridge (L3)	Negative pole (-DC)
Suspension wire (PEN or PE)	Protective earth (PE)

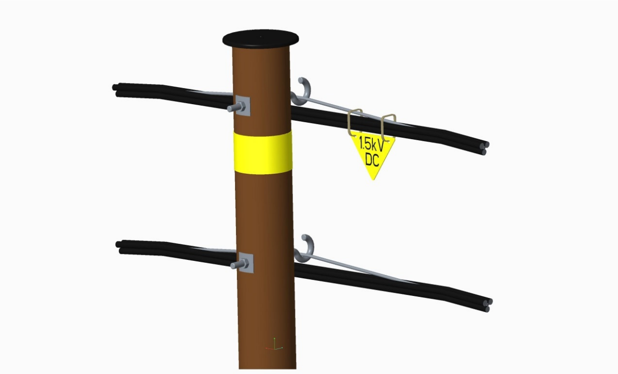


Fig. 2. Sign for overhead line installations and yellow notification stripe between lines connected to different voltage levels.

COMMON MECHANICAL SPECIFICATIONS

In addition to the electrical specifications, mechanical aspects have to be considered to ensure reliable operation in all conditions. Also, the maintenance has to be taken into account. Lifetime of the components in traditional AC distribution solution is 40 years and above, and the system is inspected in every five years, but there is no scheduled maintenance program for the network components, which would facilitate the maintenance of the system. It is clear that by adding power electronics to electricity distribution, the need for maintenance will increase. Therefore, the design and structure of the LVDC components has to enable development of a feasible maintenance program. In Table 3, typical lifetime targets in different power electronics applications are shown. It can be seen that there is a huge difference in correlations between years and operating hours. In LVDC application, the converter is designed to operate 8760 hours a year, which results in 15 years using the maximum operating hours in a photovoltaic application. Therefore, power electronics have to be replaced 2–3 times in 40 years period and the maintenance is important design criteria of the units. Maintenance usually requires either customer-end or DC network interruption, the number and duration of which have to be minimised. Hence, a research question is raised: what kind of maintenance program and related processes the life-cycle management requires?

Table 3. Typical lifetime target in different power electronics application. [17]

Application	Typical design target of lifetime
Aircraft	24 a (100 000 h flight operation)
Automotive	15 a (10 000 operating hours, 300 000 km)
Industry motor drives	5–20 a (60 000 h with full load)
Railway	20–30 a (73 000 – 110 000 h)
Wind turbines	20 a (120 000 h)
Photovoltaic plants	30 a (90 000 – 130 000 h)

Environmental factors and cooling

All units are installed into outdoor cabinets which are placed on ground level. Environmental conditions, shown in Table 4, are given as specified in SFS 6000-5-51 [9]. The system should be capable of starting the operation even after a long term power interruption under high moisture environment. In the LVDC application, nominal powers of the units, especially DC/AC inverters, are rarely used i.e. the peak operating time is low. Also, the highest power demand in Finnish operating environment occurs usually during the winter time when the temperature is low, which results to easier and physically smaller cooling design. Primary cooling of the power electronics units is based on free air convection, but forced air cooling is also enabled under high-power and/or high-temperature conditions.

Table 4. Environmental conditions [9].

Factor	Classification	Range
Temperature	AA8	- 50 … +40 °C
Altitude	AC1	≤ 2000 m
Water tightness	AD3	Rain
Objects	AE2	2,5 mm
Corrosion	AF2	Climatic
Vegetation	AK2	Danger
Animals	AL2	Danger
Lightnings	AQ2	Indirect exposure

POWER ELECTRONICS SPECIFICATIONS

The LVDC distribution system includes at least one AC/DC rectifier unit and several DC/AC inverter units. To reduce the number of different power electronics modules, only one type of DC/AC and DC/DC modules are designed. The rectifier unit is based on the DC/AC inverter modules, and the DC/AC inverter unit includes galvanically isolating DC/DC converter module and DC/AC inverter module, or several modules, depending on the required power (Fig. 3). Bidirectional power transmission is enabled in both module types.

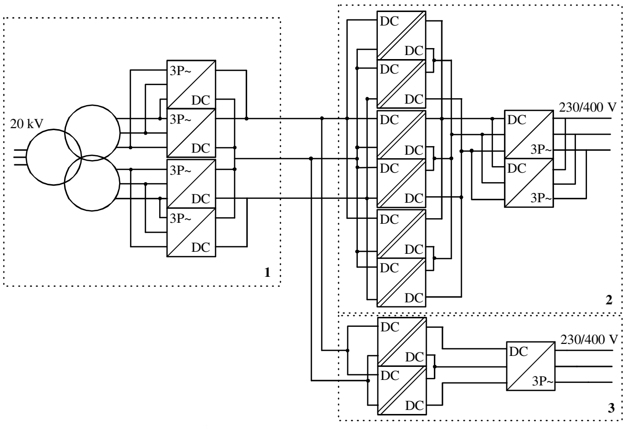


Fig. 3. Overview of the power electronics in the LVDC distribution system.

DC/AC inverter units

The DC/AC inverter unit consists of isolating DC/DC converter and DC/AC inverter modules. Two inverter units are designed: 17 kVA with one DC/AC module and 50 kVA with two modules (3 and 2 in Fig. 3, respectively). The DC/AC module is capable of supplying higher power than the required 17 kVA, but the thermal design is based on 17 kVA power. The unit is designed for a single customer having 3x25 A main fuses or for a group of customers having low-power consumption profile. The module enables three-phase customer supply with neutral connection. Because of the customer load behaviour, the inverter is designed to be able to supply three-phase loads with high phase asymmetry, and pure single-phase loads. The 50 kVA unit is utilised in supply of high-power (3x63A) loads or group of customers through 400 V public LVAC network. In the latter case, any number of customers with different consumption profiles can be connected to it as long as the power capacity is not exceeded and the voltage quality can be maintained.

The minimum short-circuit current arising from the requirements for short-circuit protection of the customer-end installations is 160 A. The DC/AC module is designed to be able to feed at least 165 A current for 5 s time period to ensure safe operation. The 5 s time is enough for the 25 A type gG main fuse operation with the 165 A current.

The 50 kVA inverter feeds at least 320 A current for 5 s during short circuit. With this rating, 0.4 s trip requirement can be guaranteed with 32 A type C circuit breaker, and 63 A type gG main fuse blows within 5 s.

DC/DC converter module

Inverter units include DC/DC converter modules: two modules in 17 kVA unit and six in 50 kVA one (Fig. 3). The module is designed to operate on DC network voltage range of 600–900 VDC. The maximum power of the module is 10 kW. The outputs of the DC/DC modules are connected in series to constitute two voltage rails and 0 V rail that is connected to the customer-end PEN (Fig. 3). The module has two main functions: 1) it constitutes galvanic isolation between the DC and the customer-end AC networks and 2) it steps down 750 VDC to 400 VDC for the inverter unit. The module is capable of supplying short-term overcurrent; the maximum current is 95 A with 400 VDC output voltage, resulting required 38 kW.

AC/DC rectifier unit and supply transformer

The rectifier unit (number 1 in Fig. 3) is supplied directly from the 20 kV MV network through a 100 kVA double-tier transformer. Two secondary windings (50+50 kVA) are required with series-connected rectifier units for constructing the bipolar DC network structure. The rectifier unit is based on two 50 kVA DC/AC inverter modules and it enables full control over DC network voltages. The DC/AC module cannot control the short-circuit current when operating as AC/DC rectifier, and the short-circuit protection of the DC network is based only on external protection devices.

CONCLUSIONS

In this paper, common system specifications and power electronics specifications for an LVDC distribution network were introduced. The paper discussed the main aspects of an LVDC distribution system installation that will be realised in LVDC RULES research project during year 2017, and addressed the main features that have to be taken into account when a bipolar ±750 VDC LVDC distribution is applied in a public electricity distribution network. For instance, customer-end short-circuit protection was considered as crucial requirement that complicates the power electronics design. Demanding operation environment calls for proper surge protection, and converter mechanics has to enable maintenance program and life-cycle management. EMI in large-scale installation, despite the previous studies, requires attention. Hence, despite the smart grid functionalities and services that LVDC enables, the main priority still is to realise safe and reliable power transmission between the grid and the customer.

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