Protecting the last mile – enabling an LVDC distribution network

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Contents

Executive summary

Traditional distribution power systems are facing numbers of changes. The major aspects that may influence the shape of the changes include: the connection of small scale renewable and advanced distributed energy resources, the deployment of demand side controls, and the supply of more heat and transport demands. But, because distribution systems have been designed and operated with very limited automation and controllability especially at lower voltages, such changes will grow in impact and extent starting from the tail of the network and working upstream. Consequently the future grid's "last mile" to consumer premises will see significant pressure for the provision of significantly increased power flow capacity and the accommodation of decentralised controls. The last mile network benefits the least from load diversity due to the lower number of consumers that each asset serves, and therefore significantly increased power flow capacity will be required over and above the provision of smart controls. Only then can the anticipated growth in electric vehicle and heat pump deployments, for instance, be accommodated. Further constraints on the choices made in changing the last mile network stem from the scale and intrusive nature of the LV network – options where wholesale changes to cable assets involving significant numbers of disruptive streetworks can be avoided during the transition of the network are very attractive. There is therefore a need for a rethink of the new standard designs to be adopted in last mile network. Furthermore, since most of the decentralised devices generate/consume DC or require a DC intermediate stage, low voltage direct current (LVDC) distribution systems with help of smart controls have the potential to facilitate this transformation. LVDC systems can enable increased penetration of distributed renewables, support better control, accommodate new heat and transport demands, and reduce losses with advantages over the corresponding low voltage alternating current (LVAC) systems.

However, integrating LVDC systems within existing power grids will introduce a new complex arrangement of mixed AC and DC systems. In order to increase the feasibility of LVDC networks, and make LVDC distribution systems technically compatible with existing AC systems, this report has investigated the main challenges in doing so. It has also outlined a number of recommendations that can accelerate the implementation of LVDC systems. The report has in particular considered: the potential benefits of LVDC systems for future electricity grids, the possible topologies of LVDC last mile networks, the characteristic behaviour of an LVDC network under fault conditions, and the protection issues and options for protecting future LVDC distribution networks.

The report has outlined the potential benefits that LVDC distribution networks will bring to future smart grids. Overall cost and losses are expected to be reduced, and system efficiencies will be improved. The options for utilising existing grid assets in implementing future LVDC systems have been investigated in the second section of the report. Recommendations have been outlined for choosing the appropriate voltage levels, using existing LV cables with different connection arrangements for implementing LVDC networks, interfacing LVDC with AC systems, and choosing earthing arrangements for better LVDC performance. In section three of the report the behaviour of an LVDC network under fault conditions has been characterised in order to ascertain required measures of risk and resilience. Consideration has been given to using IEC61660 for characterising DC short-circuits for an LVDC last mile network, and this has been tested on a simplified unipolar LVDC network. The report has identified which corrective factors within IEC61660 require improvement before application to LVDC grids.

The effectiveness of using traditional LV protection with conventional interrupting components has been discussed in section four of the report. The results have shown that this type of protection is unlikely to ensure good performance in the LVDC networks under fault conditions. Slow protection operating times and greater fault impact can be experienced. LV conventional protection increases the risk of physical damage to the converters and other sensitive devices by exposing these components to high transient DC fault currents. Also, the rapid reduction of voltage at converter terminals increases the risk of them unnecessarily tripping for downstream faults, thus resulting in substandard protection selectivity. There is also a risk that local microgeneration fails to ride through remote transient disturbances. Therefore, the report has proposed an effective and more reliable protection scheme concept which can be developed further in order to significantly improve the protection speed and consequent LVDC performance. The

concept is based on the combination of AC protection on the AC side and fast acting electronic-based DC protection in addition to internal converter/inverter protection.

Other work reported elsewhere has focussed on the role that advanced LVAC distribution networks could fulfil and the changes to the last mile protection required to accommodate high penetrations of inverter connected resources. This report will not repeat this effort.

1. Introduction

Historically, the first distribution power systems were designed as DC, and then were changed by AC systems due to the AC advantages. Currently and because of advanced power electronics technologies, DC has been widely used particularly for long high voltages DC (HVDC) transmission lines. HVDC provides a cost effective solution with better power flow controllability and lower losses for transferring power for long distance (i.e. >600km) [1]. HVDC in addition, can be used as back-to-back station to connect two large AC systems with different frequencies. Due to such benefits, it is strongly believed that HVDC is more economical and environmentally friendly technologies that can help in building the “supergrid” to connect the whole Europe and North Africa to allow sharing of different renewable energy resources and power transfer across this area [1]. At distribution levels, DC distribution systems are not widely used yet, and their applications are limited to specific areas. For example, Low Voltage Direct Current (LVDC) distribution systems have been widely used in auxiliary installations in power plants and substations as well as providing power for emergency services such as emergency lightings and alarm services. LVDC systems are also considered a good solution for many transport applications such as electric traction systems (railway and underground) due to the wide usage of DC motors, and also as a good solution for aircraft power systems and electric ships due to the enhanced controllability of DC [2].

Recently, the interest toward using more power sources and energy storage devices generate DC outputs, and DC power consuming devices has been rapidly growing, and LVDC distribution systems have been used for new applications such as powering different sized data centres [3]. This is in the context of the U.S. Environmental Protection Agency (EPA) recommending that data centres’ growing energy consumption which was 1.5% of the total U.S. electricity consumption in 2006 (equivalent to 5.8 million average U.S households) needs to be addressed by using more efficient energy technologies [4]. According to this report, each 10% efficiency improvement in data centres’ energy usage will lead to a saving of 6 TWh of energy each year [3]. LVDC distribution systems have been considered as one of contributors to achieving this. Recent research conducted by the Electric Power Research Institute (EPRI) has concluded that using 380V LVDC to supply small and medium sized data centres instead of traditional distribution systems will improve their electrical efficiency by up to 15% and with 36% lower lifetime cost [4][5]. Also, ABB has reported that a recent 1MW 380V DC network built in 2012 to supply a medium sized data centre had 10% lower capital costs less than the equivalent AC system [4].

With the help of modern power electronics and advanced smart grid technologies, it is believed that LVDC power systems have the potential to be a valuable component of future smart grids. More intelligent monitoring and controls, and better generation and use of energy could be offered by LVDC systems [3]. The systems can support increased penetration of distributed renewables, electric vehicles, and heat pump systems, and better facilitate the connection of the explosive numbers of appliances run on DC current [6][7]. This will in turn help further cut CO2 emissions. A study commissioned by the UK Department of Trade and Industry (DTI) from the Energy Saving Trust has suggested that 30%-40% of the UK’s electricity demand should be met through microgeneration technologies connected to distribution networks by 2050 to meet the long term UK’s 2050 target (80% carbon reduction) [8].

However, the implementation of LVDC networks introduces new components that can make power systems more complex. A new complex arrangement of mixed AC and DC will emerge. Such a change presents significant challenges for operating and protecting the network, and to date there are no comprehensive standards for how to configure, operate, and protect future LVDC last mile networks optimally [3]. In order to make LVDC distribution systems technically feasible and to assess their compatibility with existing AC systems, an understanding of their behaviour under different operating conditions is necessary. For example, under disturbance conditions, and as the system becomes more complex new forms and types of faults will be introduced, and different system responses are anticipated [9]. This report presents the LVDC implementation challenges, and discusses the following main areas: (i) the potential benefits of LVDC systems for future electricity grids, (ii) the possible configurations of LVDC distribution networks, (iii) the characterisation of LVDC networks under fault conditions, and (iv) the protection issues and options for future LVDC distribution networks.

2. Potential benefits of implementing an LVDC distribution network

Due to the better efficiency and good level of controllability within power electronics technologies, and the possibility of implementing a higher voltage as allowed by EU (LVD) 2006/95/EC [10], an LVDC system has the potential to overcome some of the traditional LV power system constraints [6]. Using LVDC with a higher voltage will reduce the impact of thermal limits (reduce the losses), and increase the transmission power capacity of the networks [9]. This in turn will increase the possibility of expanding an existing system to supply a higher load without uprating the MV/LV transformer or adding new cables [11]. The results of the research in [12] have shown that with the same voltage drop and the same cables (as used for 3-phase AC), a unipolar 1.5kV LVDC system can transmit 16 times more power than a 0.4kV AC system. Bipolar configurations with ± 0.75kV LVDC can deliver up to 28 times more power than a traditional AC system [13]. The different type of connections of LV cables including unipolar and bipolar systems are discussed in more detail later in this report. The table below [13] shows how LVDC systems can increase the thermal and voltage drop limits in relation to that possible in traditional LV systems.

Cable (mm^2)	Limits	Traditional 0.4kV distribution system	Unipolar 1.5kV DC system		Bipolar 1.5kV DC System
			Two terminals	One terminal	
3x70x95	Voltage drop	1.00	3.94	2.17	4.33
	Thermal limit	1.00	14.80	7.73	28.13

Table 1: Normalised comparison of the performance of an LVDC and traditional LV system in regard to thermal and voltage drop limits [13]

In DC systems, the inductances have no effect on the voltages during normal operation, and thus the reactive current component which increases the magnitude of the current resulting in more losses, does not exist. In addition, the skin effect that is normally caused by opposing eddy currents induced by the changing magnetic field of AC currents and increases cable resistance in AC networks has no impact in DC cables. According to IEC 60228 [14], the difference between the DC and AC resistance for the same cable can be distinguished from the following equations [15].

DC resistance: $R_{dc} = R_{20} \times [L + \alpha(T - 20)] \quad \Omega$ (1)

Where, R_{dc} is the conductor DC resistance at an operating temperature, R_{20} is the conductor DC resistance at 20° C, L is the length of the cable, T is the operating temperature °C, and α is the resistance temperature coefficient and is equal to 0.00393 for copper and 0.00403 for aluminium.

AC resistance: $R_{ac} = R_{dc} \times \left[L + y_s + y_p\right] \quad \Omega$ (2)

Where R_{ac} is the conductor AC resistance at an operating temperature, y_s is the skin effect factor, and y_p is the proximity effect factor.

From (1) and (2), it can be clearly seen that the AC resistance is always larger than the DC resistance due to the skin effect issue.

Therefore, for new installations, all these points would increase the opportunity for using smaller cables with lower costs, and indirectly reduce the environmental impact of energy transmission and generation. A comparison between low voltage AC and DC power grids' properties is conducted in [16] and the conclusion is that up to about 20% cable cross section can be reduced in each conductor when the cable is used to deliver power by a DC grid instead of AC. Also the number of the cable conductors in DC is expected to be lower than in AC, where the power will be carried by two conductors for unipolar DC system and by three conductors for bipolar DC system instead of four or five conductors as used in low voltage AC. The same power capacity can therefore be achieved with lower investment in cable materials when compared to AC grids.

An LVDC distribution system will also facilitate in a better way the connection of renewable and highly efficient microgeneration and storage devices compared to traditional LV systems [17]. Most microgeneration and energy storage devices generate DC outputs or require a DC intermediate stage. These clean energy sources can be connected by DC/DC converters or directly to LVDC networks, avoiding the energy loss (typically 7-15% for converting from DC to AC) due to the conversion to AC [3]. For example, the connection of variable-speed microgeneration such as microwind turbines and micro gas turbines to an LVDC network will save one stage of conversion. Also, it is easier to connect multiple sources in parallel to DC systems than to AC systems, where frequency synchronisation for the connection is not required [18].

In addition, an LVDC network is also more suitable for the connection of large numbers of DC power consuming devices. Electronic domestic loads internally powered by DC dominate today more than AC loads. Electronic loads such as computers, fluorescent lamps, TVs, and others use bridge rectifiers to obtain DC from AC. The conversion from AC/DC introduces harmonics which lead to negative power quality issues [19]. Also, the need for using large numbers of adapters to convert 230V AC to lower voltages and then convert into DC, and the need for power factor correction, can be removed, resulting in reduced losses and saved cost [7]. The transformers used for the adaptors of consumer electronic equipment can cause considerable losses during stand-by mode. Different electronic devices will have different energy losses, but in general the amount of power lost during the conversion process is about 10-25%, and almost the same amount of power is lost when the converters are in stand-by mode [3]. According to the International Energy Agency (IEA), the total domestic consumption of electronic equipment in stand-by mode in the EU has been estimated to be more than 36 TWh/year [20][11]. Therefore, many conversion steps for sources and loads can be reduced, resulting in reduced losses and costs and saved energy in comparison to the equivalent AC system. LVDC distribution networks can also accommodate some AC loads. For example, all resistive loads such as heaters, and incandescent lamps run by AC can still be supplied by DC voltage if the DC voltage is equal to the AC RMS values, and the same power can be delivered [19]. However, some AC loads such as AC machines, and inductive loads cannot be supplied with DC voltage, and still require DC/AC conversions when they are supplied from an LVDC system.

It can be concluded from the above discussion that LVDC distribution systems have the potential to bring technical and economic benefits to future electricity grids. Overall cost and energy waste are expected to be reduced, and system efficiencies improved. Better utilisation of existing AC components such as MV/LV transformers and LV cables is anticipated. Also better accommodation and controllability of generation and use of energy can be offered, resulting in reducing the environmental impacts of energy usage and production. However, there are some disadvantages such as the lifetime of the electronic converter devices which will be shorter than traditional network components [12]. The devices also add some losses and generate voltage harmonic. But from the above discussion, the overall system losses still can be reduced and efficiency can be improved specially for networks with long feeders such as rural networks when energy efficiency is an issue. The investigation in [21] has considered a real test LVDC network, and it has concluded that the LVDC is more cost effective solution to the common rural 20/0.4kV AC networks when the AC feeders are over 1km [21]. As for urban networks, LVDC is still useful for facilitating the connection of high density of microgenerators due to its higher level of controllability compared to AC. In addition, high fault levels will not be an issue when urban networks are replaced with LVDC, and this is because the contribution to faults will be limited by the converters across the network. However, LVDC systems will add new components which can make the networks more complex compared to traditional LV networks, and this will lead to significant challenges for designing LVDC distribution networks and understanding their behaviour under different operating circumstances. LVDC is still a hot topic and there is lack of standards and recommendations for LVDC, and how it can be operated. The next section of the report discusses the challenges facing the design of LVDC last mile networks in terms of topology, voltage levels, and cable connections.

3. An LVDC last mile distribution network

Recommendations by network planners and designers for designing new supplies or refurbishing existing areas are intended to ensure the best use of existing assets and at the same time delivering reliability and integrity into the future [22]. Therefore, the design of future LVDC distribution systems must take account of the existing infrastructure of LV AC last mile networks in order to maximise the benefit from existing equipment and offer more efficient, reliable, and economic system solutions.

Taking typical UK traditional LV distribution systems as an example to be replaced with DC, an LVDC network will be supplied from the MV (11kV) network at secondary substations via 11/0.4kV Dy11 transformers with the neutral point of the secondary solidly earthed. An LVDC system will include power electronic converters to convert AC to DC voltages and DC links between these converters. However, there are still remaining issues in relation to the appropriate DC voltage levels, the possible DC cable connections, and general network topologies including the required grounding schemes. This section of the report discusses these key issues which are still facing the design of future LVDC networks. The discussion includes the possible options of LVDC structures, interfacing LVDC to AC grids, the potential voltage levels, the possible LV cables connections, and the most suitable earthing systems.

i- <u>LVDC network topologies</u>

Traditional LV distribution networks have different forms of topology depending on the required security of supply, the costs, and the prospective fault levels. For example an LV network can be relatively simple where the downstream loads are supplied by a single source as laid out in Figure 1-a. This type of network is a radial feeder configuration, and is widely used due to the low cost and low fault level [22][23]. But the configuration has the lowest level of supply security with no redundancy. To increase the reliability, an LV network can be connected to two transformers as given in Figure 1-b. If one transformer is tripped or disconnected for maintenance, the load may still be fed by the other transformer. Such configuration can also be sectionalised more as shown in Figure 1-c, to ensure the operation of more unfaulted lines. An LV distribution network can also supply a high density of important loads by a ring configuration. The loads in this case can be supplied by more than one transformer by using busbar trunking as illustrated in Figure 2. The level of redundancy in ring configuration is relatively high. When such configurations are replaced with LVDC networks, the new structures will be similar to the AC plus adding AC/DC conversion directly after the MV/LV transformers. The loads and local generators will be interfaced by DC/AC and/or DC/DC converters.

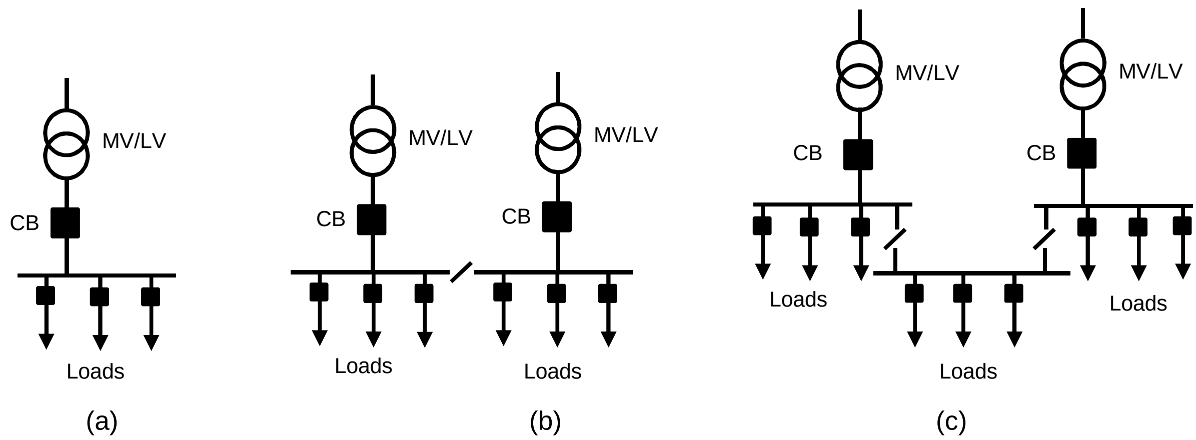


Figure 1: (a) radial single feeder configuration, (b) two-pole configuration, and (c) Interconnected switchboards [23]

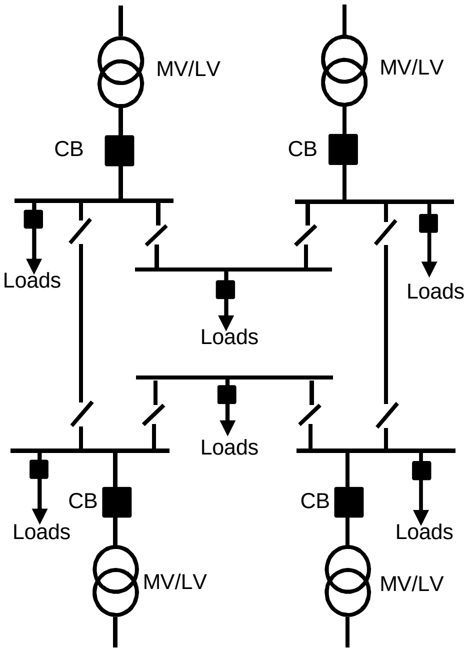


Figure 2: LV Ring configuration [23]

ii- <u>Interfacing an LVDC to AC grids</u>

The interface between AC and DC systems has an important role to play in relation to AC and DC systems performance. Different interface topologies have different control possibilities to control voltages and power flow between AC and DC systems. In general, there are different AC/DC interface technologies from uncontrolled devices such as diode rectifiers (i.e. the power flows only from AC to DC) to fully controlled such as voltage source converters (VSC) that are based on isolated gate bipolar transistor (IGBT). VSCs can be divided into three types; two level VSC, three level VSC, and VSC with DC/DC buck converter [19]. VSCs IGBT-based have the ability to control the voltages on the DC and allow the transfer of power in two directions between AC and LVDC systems. This will facilitate the increase of renewable energy resources across LVDC networks. The active and reactive power between AC and DC can be controlled independently when VSCs are used [19]. In addition, two level VSCs can be combined with galvanic isolation (GI) to offer decoupling between AC and DC systems [19]. This feature helps the converter to be more resilient, and helps the DC systems to reject AC grid disturbances to some level [24]. Due the advantages of a two level VSC IGBT-based, and its less complexity compared to other VSCs, it has been chosen with smoothing capacitor as shown in Figure 3 to interface the LVDC network example that has been proposed in this report.

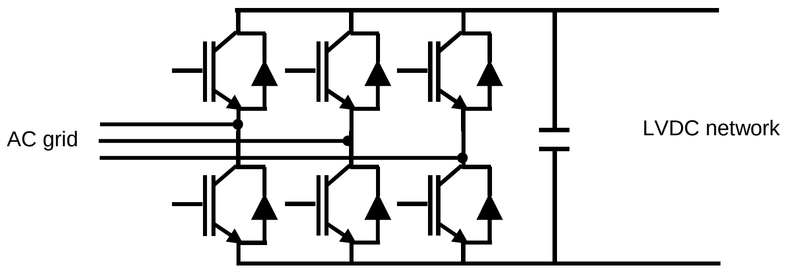


Figure 3: IGBT-based VSC interfacing an LVDC network to an AC grid

iii- LVDC Voltage levels

With respect to the voltage levels at low voltage distribution networks the EU Low Voltage Directive (LVD) 2006/95/EC as mentioned earlier allows the use of voltages up to 1kV in LV AC systems and up to 1.5kV in LV DC systems [10], and any voltage above these values cannot be considered as LV. The Finland national standard issued by Electro-technical standardization association (SESKO) which relies on LVD 2006/95/EC has recommended that the DC voltage level between two conductors of an LV cable should not be higher than 1.5kV, and between one conductor and the ground should not be more than 0.9kV [25]. These recommendations have identified the limits of DC voltages that can be used for LVDC networks, but the voltage level can differ in accordance with the operating requirements. For example, the new industry specification and the single worldwide standard of LVDC voltage level for powering data centres has been chosen to be 380Vdc [4]. This DC voltage level has been internationally adopted and validated for numbers of data centres across the world. It has been used for numbers of data centres in U.S., France, Sweden, China, South Korea, Japan, and Taiwan [4][26].The main reasons for choosing this value are stated to be low capital and operating cost [4]. The remaining question is, what will be the most appropriate voltage levels for future LVDC networks if existing LV cables are planned to be optionally utilised?

Traditional LV cables have various voltage ratings depending on their size and insulating materials. Larger LV cables are rated 600V/1kV (line-to-earth/line-to-line), and smaller power cables are rated within the range of 450V/750V (L-L/L-E) for single wire installation and up to 500V L-L and 300V L-E for multi-wire installations [19]. These ratings are specified as RMS operating values, and represent the amount of heat that AC voltage will produce compared to the equivalent DC voltages. This means the same power can be delivered by AC and DC as long as the RMS AC is equal to the equivalent DC.

However, the actual AC voltages that are normally applied on LV cables are the peak values. Thus, if an existing LV cable is used for a DC application, the DC voltage rating can be equal to the peak of the AC voltage instead of the AC RMS. Using a DC voltage level equals to the AC peak value (i.e. DC rating=$\sqrt{2}$ of the AC rating) gives the opportunity of delivering the same power with lower current. This can be very useful for reducing the thermal losses in LV feeders and significantly increase cables power capacity when they are used for LVDC networks. The remaining question is: can the cross sections and insulations of existing LV AC cables endure DC voltages equal to 1.4 of the AC ratings? Based on the following real LVDC application example, the answer to the above question is yes.

The design and operation of a real rural bipolar LVDC test network which is owned by Finnish Energy SSS Ltd and built as a part of Finnish national Smart Grids research programme has proved that existing LV AC cables can still be used for DC with voltages equal to the peak of AC voltage ratings without any damage to the cables [21]. A typical 1kV AC PVC insulated underground cable has been successfully used as a DC feeder for the LVDC Finnish test network. The cross section of 1kV AC cable was enough for the use of DC up to ±750 (1.5kV between plus and minus poles). The possibility of using existing LV cables for LVDC feeder in terms of voltage rating can be explained more as follows. The working voltages are usually equal to one third of the Dielectric Withstanding Voltages (DWV) [27]. The DWV is normally around 75% of the breakdown voltage [27]. Therefore, the rated RMS working voltage is equal to just one quarter of the breakdown voltage, and hence the operating DC voltage will be 35% of the breakdown voltage in case of the peak of the AC RMS having been chosen.

However, it is not necessary to use the highest available DC voltage to justify the adoption of LVDC and reduce network losses. Other options that increase the useful utilisation of existing equipment can be considered. Table 2 explains three LVDC voltage level options; option one is the use of the highest applicable DC voltage depending on the size of the used cable. This option as already discussed will provide the highest increase in the power capacity. Option two is by converting the existing AC 0.4kV into DC, and option three is by providing a DC voltage at consumer's side equals to the RMS AC 230V. The basis and the advantages and disadvantages of each choice are given in Table 2.

<table>
<tr><th colspan="2" rowspan="2">1- Existing AC low voltage cables</th><th colspan="2">AC voltage rating</th><th colspan="2">DC voltage options</th><th rowspan="2">Advantages and disadvantages</th></tr>
<tr><th>Line-Line</th><th>Line-ground</th><th>unipolar</th><th>bipolar</th></tr>
<tr><td rowspan="3">Based on the available capacity</td><td>Larger LV cables</td><td>1000V</td><td>580V</td><td>900V</td><td>±750V</td><td>Offering the highest power capacity, and reduced losses. But more DC/DC conversions are required to step the voltage down for connecting local loads and generation. This may increase the cost of system design.</td></tr>
<tr><td>Smaller LV cables (1-wire installation)</td><td>450V-750V</td><td>260V-433V</td><td>368V-613V</td><td>±368V-±613V</td><td>The power capacity provided by this voltage level is smaller than that provided by larger LV cables in the above example.</td></tr>
<tr><td>Smaller LV cables (multi-wire systems)</td><td>500V</td><td>300V</td><td>425V</td><td>±425V</td><td>It is suitable for small sized cables, but lower power capacity is expected in comparison to the above voltage levels.</td></tr>
<tr><td colspan="2">2- Considering existing UK typical LV 400V</td><td>400V</td><td>230V</td><td>326V</td><td>±326V</td><td>Many electronic devices have input rectifiers that give the peak of 230V AC which is equal to 326V DC. So all these devices can be directly connected to 326V DC if the rectifiers are removed. Thus, a large number of existing loads can still be supplied by this voltage level.

Less conversion stages and lower harmonics are experienced in this case.

The power capacity is less compared to the previous options with higher voltages.</td></tr>
<tr><td colspan="2">3- providing a DC voltage at consumer's side equals to the RMS AC 230V</td><td>400V</td><td>230V</td><td>230V</td><td>±230V</td><td>All resistive loads such as heaters run on rms 230V AC voltage can be directly connected to the DC without conversion.

Lowest power capacity is obtained by this lower voltage level compared to the above options.</td></tr>
</table>

Table 2: Voltage level options for an LVDC distribution network

iv- LVDC feeders connection arrangements

In terms of LVDC system connections, either unipolar and bipolar configurations can be implemented to any LVDC network regardless of the topology types [28]. In the unipolar system, only one voltage level, positive DC to neutral (or negative) is provided. In the bipolar system two voltage levels are offered, and the load can be connected between the live conductor and zero-voltage conductor, or directly between ± conductors. Bipolar connections therefore provide more voltage level options for load connections than unipolar.

If the existing LV cables of a traditional AC system are used for LVDC application, there will be numbers of possible connection solutions to meet the load demand. This is because existing LV networks have different cables with different numbers of conductors. Typically, traditional LV systems can supply their loads through 4-core separate neutral earth (SNE) cables. This type of cable has three conductors for phases, one conductor for neutral and one for the earth connection. Another common type of LV cable is the 3-core combined neutral earth (CNE), with three conductors for phases and one conductor for neutral and earth connections [29]. Based on the applications, the neutral and earth conductors of 4-core SNE and 3-core CNE cables can be identical to the phase conductors or different in shape and size. The cables can be designed with reduced neutral conductors and armoured waveform earth conductors. This is because the neutral and earth conductors of AC cables are not designed for carrying large current flows under normal circumstances. In AC systems in order to reduce power losses and the cable cost, the 3-phase system is designed to be symmetrically loaded. This permits the use of a smaller sized neutral and earth conductor, thus saving in conductor material can be achieved. During fault conditions, the earth conductor can carry fault currents but only for a very short time, and the fault currents will be very quickly cleared by protection devices. Also, since the line and phase voltages are not the same, the insulation thickness between the live conductor and the reduced neutral/earth conductor could be less than the insulation between two live conductors.

These factors require special considerations when 3-phase AC cables are planned to be used for LVDC systems. This is in order to avoid the use of two conductors within the same DC circuit with different cross sections, different insulations, and different thermal limits. Using conductors with different cross sections (i.e. live conductor and reduced neutral conductor are used in the same DC circuit) will make the power capacity to be limited by the thermal limits of the lower sized conductors. Tables 3-6 describe the possible unipolar and bipolar connection options when different LV AC cables are used for LVDC applications.

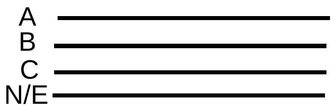
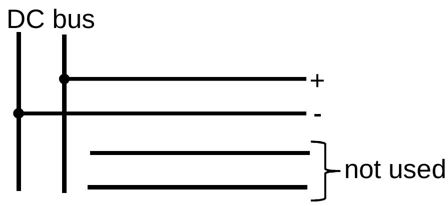
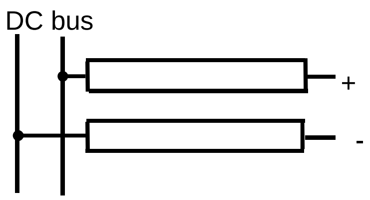
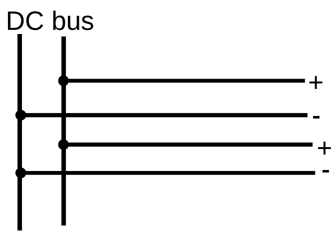
3-core combined neutral earth cables (CNE) - DC unipolar connection options	
Cable connection arrangement	Applications/advantages/disadvantages
 4-wire cable for 3-phase AC connection	3-core CNE cable used for LV AC applications with 3-ø conductors, and one CNE
 One terminal DC unipolar connection	- It is more suitable for 3-core reduced neutral or armoured waveform 3-core cables, where the earth wire has smaller size compared to live conductors (if reduced neutral is used with live conductors, the result will be two cables carrying the same current with different thermal limits, and this may not be desirable operation option). - It is less reliable compared to two terminal DC unipolar systems, and bipolar systems. - Two conductors are not used, resulting in reduced efficiency. But they can still be considered as standby conductors or used for earthing.
 One terminal DC unipolar connection with reduced equivalent impedance	- The equivalent impedance is less due to parallel connections, and hence less overall power and voltage losses. - It is more applicable to 3-core unarmoured cables which have identical conductors. - It is not ideal for 3-core reduced neutral or armoured waveform cables. - It is less reliable compared to bipolar configuration, and two terminal unipolar systems. - The short circuit level will be higher. - The DC load current could be higher than the AC current in AC 3-phase system for delivering the same power. This is because the same power is carried by two conductors instead of three. - No conductor for earthing will be available if required.
 Two terminal DC unipolar connection	- The transferred power is twice compared to one terminal DC unipolar configuration. - It is more reliable system in case of failure of one circuit. - It is more suitable for unarmoured 3-core SNE cables, where all conductors are identical. - No conductor for earthing will be available if required.

Table 3: 3-core combined neutral earth cables (CNE) - DC unipolar connection options

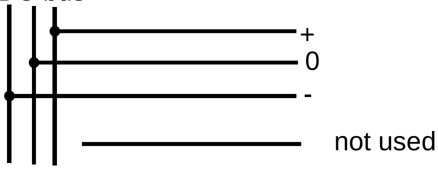
3-core combined neutral earth cables (CNE) - DC bipolar connection options	
Cable connection arrangement	Applications/advantages/disadvantages
DC bus  DC bipolar connection	- The power is carried by two conductors and one return path. - It provides larger power capacity compared to unipolar configurations. - It is more suitable for all types of LV cables (armoured and unarmoured). - All the DC conductors are identical with the same thermal limits. - It is more reliable compared to unipolar systems. - If the connected loads are not identical, an unbalanced condition will be introduced in the system - It is more expensive.

Table 4: 3-core combined neutral earth cables (CNE) - DC bipolar connection options

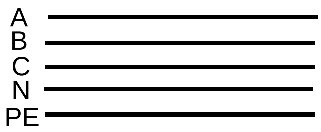
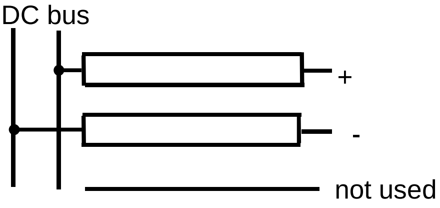
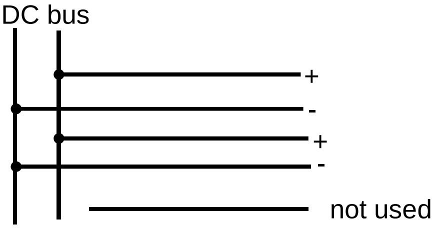
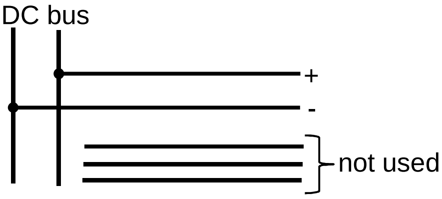
4-core separate earth (SNE) - DC unipolar connection options	
Cable connection arrangement	Applications/advantages/disadvantages
 4-core separate earth (SNE)	4-core SNE with 3-ø conductors, and one conductor for neutral, and one for the earth
DC bus  One terminal DC unipolar connection with reduced equivalent impedance	- Overall losses are reduced. - It will experience higher short circuit level. - It is more suitable for both armoured and unarmoured 4-core LV cables. - It is less reliable compared to two terminal unipolar and bipolar systems.
DC bus  Two terminal DC unipolar connection	- The power capacity is twice that of one terminal unipolar configuration. - It is more reliable compared to one terminal unipolar configuration. - It is suitable for all types of LV cables. - The currents are carried by two circuits instead of one.
DC bus  One terminal DC unipolar connection	- It is less efficient compared to two terminals unipolar and bipolar systems where three conductors are not used. - It is less reliable compared to two terminals DC unipolar systems, and bipolar systems.

Table 5: 4-core separate earth (SNE) - DC unipolar connection options

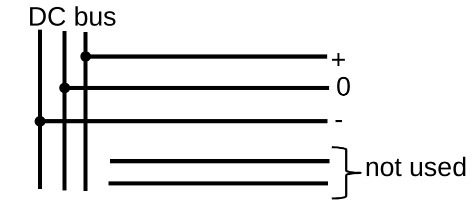
4-core separate earth (SNE) - DC bipolar connection options	
Cable connection arrangements	Applications/advantages/disadvantages
 DC Bipolar connection	- The power is twice compared to unipolar connections. - It is more suitable for all types of LV cables (armoured and unarmoured). - All the DC conductors are identical with the same thermal limits.

Table 6: 4-core separate earth (SNE) - DC bipolar connection options

The bipolar arrangements will offer more power capacity, but balancing the voltage across the load terminals can be an issue. This will require more control functions to be implemented within the converters, resulting in more cost. The unipolar is less complex, but the offered power capacity is less compared to bipolar. The unipolar systems can be one terminal or two terminal systems as given in Table 3 and Table 5 depending on the type of cable and required operation. One terminal DC unipolar connection can be configured by using any type of LV cable, but two terminal unipolar requires using unarmoured 3-core CNE or 4-core cables as given in Table 3 and Table 5. The bipolar connections require 3 conductors, so the two types armoured and unarmoured 3 and 4 cores cables can be used, and the remaining conductors can be used for earthing if an LVDC is an earthed type. The DC voltage levels that can be applied to DC cables are influenced by the size of the cables and other operating requirements as discussed earlier.

Figure 4 below shows a single line diagram of an LVDC example (unipolar and bipolar). The LVDC network is interfaced to the AC system by IGBT-based VSC located directly after the MV/LV transformer. As explained previously in Table 2, there are many electronic devices that have input rectifiers that give the peak of 230V AC. Therefore, the DC network can supply the downstream DC and AC loads via common 326V provided by DC/DC converter as shown as bus 3 in Figure 4. All the DC loads and microgeneration with DC outputs can be directly connected to this bus or interfaced by DC/DC converters. The AC loads and microgeneration with AC outputs can be connected to 326V DC bus by AC/DC converter. The other option of connecting the consumer's premises is by two separate converters DC/DC and AC/DC as shown in Figure 4 between bus 6 and 5 and bus 7 and 5. This configuration can be useful if one of the converters is faulted and disconnected, the other converter can still provide supply within the premises.

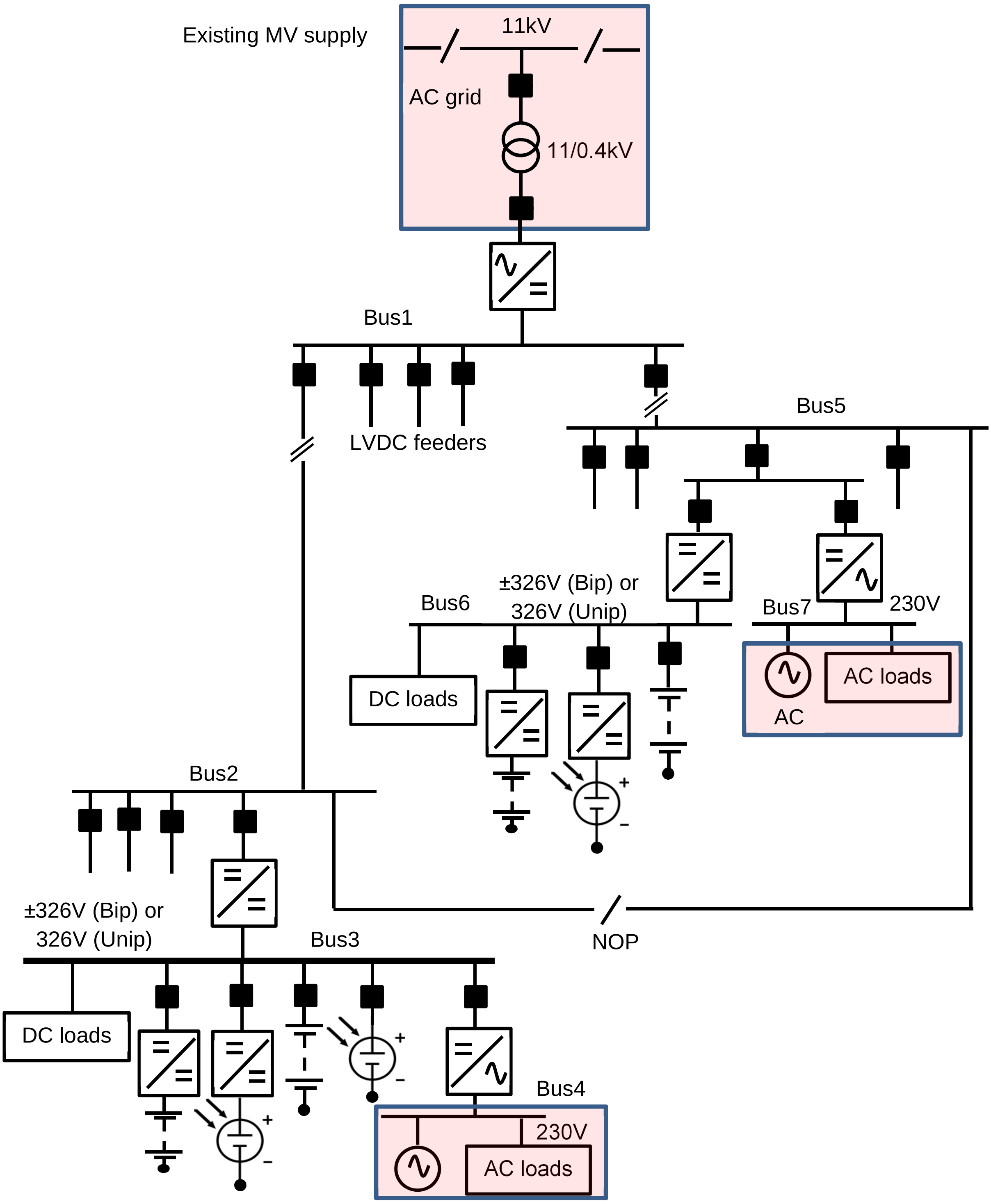


Figure 4: An LVDC network topology example

v- LVDC Earthing systems

Earthing techniques are normally used for earth fault detection and for safety of personal and equipment [18]. Existing AC cables have been designed in accordance with the required earthing arrangements. In general and according to BS7671 [30], LV systems can have five different types of earthing systems: TN-S, TN-C-S, TT, TN-C, and IT. The earthing system TN-S, TN-C-S protective multiple earthing (PME), or TT are allowed by Electricity Safety, Quality and Continuity Regulations (ESQCR) 2002 for UK LV networks [31]. Old urban homes in the UK have TN-S supplies, and the earth connection is provided by the lead sheath of the underground lead-and-paper cables [32]. The TN-C is very uncommon in the UK, and the IT grounding system (source not directly earthed) is not allowed for LV public networks in the UK [31]. In the UK and most modern houses in Europe, the earthed TN-C-S system (PME) is widely used, where the combined neutral-and-earth conductor is earthed at many locations in order to reduce the risk of broken neutrals [32]. In this case the neutral point of the secondary windings of Dy11 transformers is solidly earthed, and the neutral earthed conductor is separated to neutral and earth conductors at the consumers side [22].

With regard to DC distribution networks, the earthing system can be a complex issue. Different earthing systems result in different system performance. LVDC systems would have one of the following earthing systems; unearthed, high impedance earthed, or solidly/low impedance earthed. Low impedance earthing can be valuable for earth fault detection, but the transient voltages and short circuit currents are high, which in turn have a severe impact on electronic components [18]. High impedance earthed systems will reduce the impact of transient voltages and currents and provide additional protection to converters. However, it can be hard to detect a high resistance earth fault, and metal close to loads can thus be energised and unsafe.

The studies in [9], [12], and [13] have proposed that LVDC networks should be unearthed IT-systems. The earthing can be limited only to the metal bodies on the DC side, and the consumers' networks including AC loads are locally earthed. The main purpose of this option is to provide additional protection to the converters against high earth fault currents by not having a short-circuit path between the AC and DC systems through the earth. In this case the system will have earthing techniques similar to TT-system earthing. Furthermore, the secondary of the MV/LV transformer can still be earthed, and without a ground reference point on the DC side, while the protective earth connections of the consumers' appliances are provided locally. However, because the consumers' earth connections are independent from the grid earth, additional protection will be necessary to protect against earth faults. Residual current devices (RCD) will be required for earth fault protection on the consumers' side of unearthed LVDC systems [32]. This will result in extra cost for protection as well as the cost of adding earth electrodes at each premises. Also, it will be more difficult to keep the neutral current to zero in bipolar DC systems to keep the balance between plus and minus voltages if the LVDC network is unearthed.

Bipolar LVDC networks can be solidly earthed at the neutral conductor (mid-point), or via earth resistances of several ohms for additional converter protection and minimising the current flow through the neutral [25][33]. This will provide a DC offset point, and in the case of a system with well-designed controlled converter (i.e. three level VSC IGBT-based), it would be possible to use one line of bipolar LVDC to deliver half of the power if the other line is out of service. If decoupling between DC side and AC consumer networks is required to increase the resilience of the LVDC during AC grid faults, galvanic isolation (GI) transformers are needed to break the earth path between AC and DC sides [25]. However, having an LV transformer at consumer's side will not be desirable if energy efficiency is an issue.

Identifying the most appropriate earthing arrangements for LVDC distribution networks in terms of safety of personal and equipment, facilitating voltage controls, and fault detection and protection may require further study and research. This can identify whether existing earthing techniques allowed by Electricity Safety, Quality and Continuity Regulations 2002 for UK LV networks will be sufficient for future LVDC networks or these techniques need to be changed for better performance.

4. Fault characterisations of an LVDC last mile network

As it has been discussed previously, an LVDC last mile network will contain a new complex arrangement of mixed AC and DC. One danger is, as the system becomes more complex new forms and types of faults will be introduced, and different system responses are anticipated [9]. When an LVDC is faulted, the stored energy within smoothing capacitors and storage devices start feeding large discharging currents within very short transient time [18]. This will make DC fault currents to experience a transient discharge current with high frequency oscillations between the smoothing capacitors and system inductances plus steady-state short circuit current. The transient fault currents can cause extreme stress to DC systems performance and protection operation [18]. Consequently, characterising LVDC short-circuits is significantly important, as appropriate equipment ratings and correct protection settings and selectivity require accurate short-circuit characterisation. Therefore, this section of the report discusses numbers of factors that have an impact on DC fault current profiles and the nature response of an LVDC network under fault conditions. The discussion includes DC fault types, the nature of DC short circuit currents, and a mathematical model for LVDC short-circuit analysis. The effectiveness of using existing standards such as IEC61660 for characterising LVDC short circuits is also investigated.

i. Types of DC faults

Generally, the common causes of short circuit could be a component failure, lighting surges, high magnitude earth fault or line to line fault, external environmental stress (fires, and etc.), or due to insulation deterioration resulted from operating under an excessive temperature caused by overloading stress [24]. Within LVDC last mile networks, the converters such as VSCs IGBT-based are more durable to faults on the AC grid and more sensitive to faults on the DC side [24]. In general and from fault location perspective, two types of fault can occur on the DC side: one is an internal DC fault inside the main converter, and the other is an external DC fault on the converter terminals or at remote locations on downstream DC feeders. Internal faults are less frequent in comparison to external faults [24]. The most severe external DC fault is at the converter terminals. However, remote faults on DC feeders can also have a significant impact on the converter performance [24]. This impact will be discussed later in this section. The external DC faults are classified as follows.

Line-to-earth fault: this fault occurs when a positive or a negative DC pole is shorted to the earth. In such case, the voltage of the DC faulted line will drop down depending on the fault impedance.

Line-to-line fault: this type of fault will happen if the positive and the negative DC poles are shorted. The fault could be as result of DC cable insulation breakdown or direct short circuit between the poles.

ii. Characteristics of DC short-circuit currents

When an external DC fault is initiated in an LVDC network, the charged smoothing capacitor will immediately act as a significant DC fault source, and start feeding the fault. When the discharge current peak is reached, the capacitor is completely discharged and the DC terminal voltage will become very small or almost zero. Then the anti-parallel diodes of the converter will be forward biased, and the VSC will lose control and the IGBT switches will be blocked for self-protection. This will result in the anti-parallel diodes acting as a bridge rectifier and continuing to supply the fault during the transient. After the transient fault current is terminated, a steady state DC fault current will be supplied by the grid and local generation. This means, the profile of an external DC fault on the DC feeders can be divided into three periods [24]; the capacitor discharge period, the anti-parallel diodes period, and the grid current-fed period as shown in Figure 5 a, b, and c respectively.

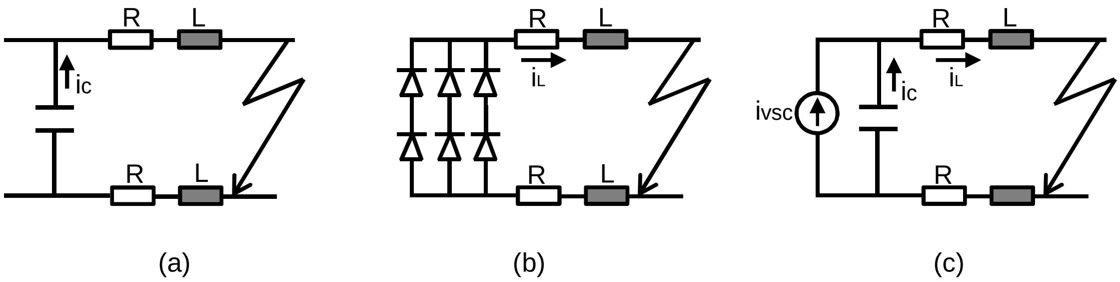


Figure 5: equivalent faulted circuits during transient and steady-state DC short circuit [24]: (a) capacitor discharge current contribution, (b) anti-parallel diodes fault current contribution, and (c) grid fault current contribution

The equivalent circuits of a DC power system during a DC fault are based on a nonlinear second order RLC circuit. The complete response of these circuits will give the fault current profile during transient and steady state periods. The damping factor and the resonant frequency of the RLC equivalent circuit which depend on the capacitor and the equivalent resistance and inductance from the converter to the fault point determine the type of the transient response of the discharge current. The derivatives of the analytical expressions of the DC fault currents and DC voltages are given in details in [24] and [34], and summarised as follows.

During smoothing capacitor discharge period:

$$V_c = \frac{V_0\omega_0}{\omega} e^{-\delta t} \sin(\omega t + \beta) - \frac{I_0}{\omega C} e^{-\delta t} sin\omega t \tag{3}$$

$$i_c = C\frac{dV_c}{dt} = -\frac{I_0\omega_0}{\omega} e^{-\delta t} \sin(\omega t - \beta) + \frac{V_0}{\omega L} e^{-\delta t} sin\omega t \tag{4}$$

Where, V_c and i_c are the voltage across the capacitor and the discharge current of the capacitor respectively. V_0 and I_0 are the initial voltage and current of the smoothing capacitor, and C is the capacitance value. $\delta = R/2L$, $\omega^2 = (1/LC) - (R/2L)^2$, $\omega_0 = \sqrt{\delta^2 + \omega^2}$ and $\beta = \arctan(\omega/\delta)$

The time for the capacitor voltage to drop to zero is $t_1 = t_0 + (\pi - \gamma)/\omega$

Where, $\gamma = \arctan(\frac{V_0\omega_0 Csin\beta}{V_0\omega_0 Ccos\beta - I_0})$

It can be clearly seen that the DC discharge fault current has a sinusoidal form decaying exponentially due to the nonlinear RLC circuit.

During anti-parallel diodes' conduction period:

From Figure 5-b, there is no impact from the smoothing capacitors during this period, and only cable inductance has an impact on the fault current. Therefore, the equivalent circuit in this case is a first-order circuit. The fault current of the inductor will be circulated in the diodes, and it can be calculated from the following equation:

$$i_L = I_0' e^{-(R/L)t} \tag{5}$$

Where I_0' is the initial current value of the inductor. *R* and *L* are the equivalent resistance and inductance from the fault location back to the DC voltage source.

Grid-fed fault current period:

The three-phase short circuit analysis can be used for calculating the short circuit contribution during this period. Each leg of the converter will pass one phase current, and the total contribution will be the sum of the three phases.

The grid voltage is $V_{ga} = V_m \sin(\omega_s + \alpha)$, where the ω_s is the synchronous angular frequency and α is the phase A voltage angle.

The phase A current therefore is $i_{ga} = I_m \sin(\omega_s t + \alpha - \varphi) + (I_{m0} \sin(\alpha - \varphi_0) - I_m \sin(\alpha - \varphi))e^{-t/\tau}$
(6)

Where $\varphi = tan^{-1}(\frac{\omega_s(L_g+L)}{R})$ and the time constant $\tau = \frac{(L_g+L)}{R}$.

I_{m0} and $\varphi_0$are the initial grid current amplitude and initial phase angle, and L_g is the grid inductance.

The total current contribution to the DC steady-state fault current supplied by the grid is the sum of the three phases a, b, and c currents i_{ga}, i_{gb}, and i_{gc}.

iii. Equivalent circuits of an LVDC for DC short-circuit analysis

Aside from the grid, an LVDC distribution network can have its own devices that can also contribute to the fault. Local microgeneration, storage units, and DC machines will also supply fault currents into the fault point. The short-circuit contributions from these devices will depend on the devices' size and penetration, and the total impedance between the devices and fault locations. In addition, in an LVDC network with a high penetration of local generation, the fault can be supplied from more than one direction. This phenomenon will have an impact on DC fault current profiles (particularly during the transient period) and on the protection performance. The network models used for characterising DC short-circuit currents in an LVDC should consider all these points with enough details of all fault sources. Also fault studies should be conducted under all possible system configurations. This is because different connection options (unipolar and bipolar) of an LVDC network will have different impacts on the equivalent impedance of the network during the fault.

The following diagrams in Figure 6 and Figure 7 show the equivalent circuits of the unipolar LVDC distribution networks given in Figure 4 in section 3 under line-to-line fault conditions. All the resistances, inductances, and capacitances of the network which are necessary for transient and steady-state fault current analysis are included. The model also considers all the fault sources such as grid-fed, local generation, and fault contribution from adjacent feeders.

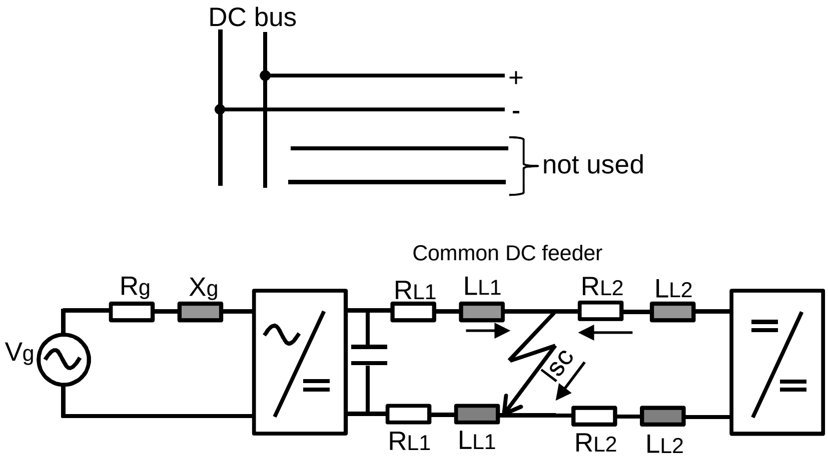


Figure 6: Equivalent circuit of faulted unipolar LVDC with one terminal

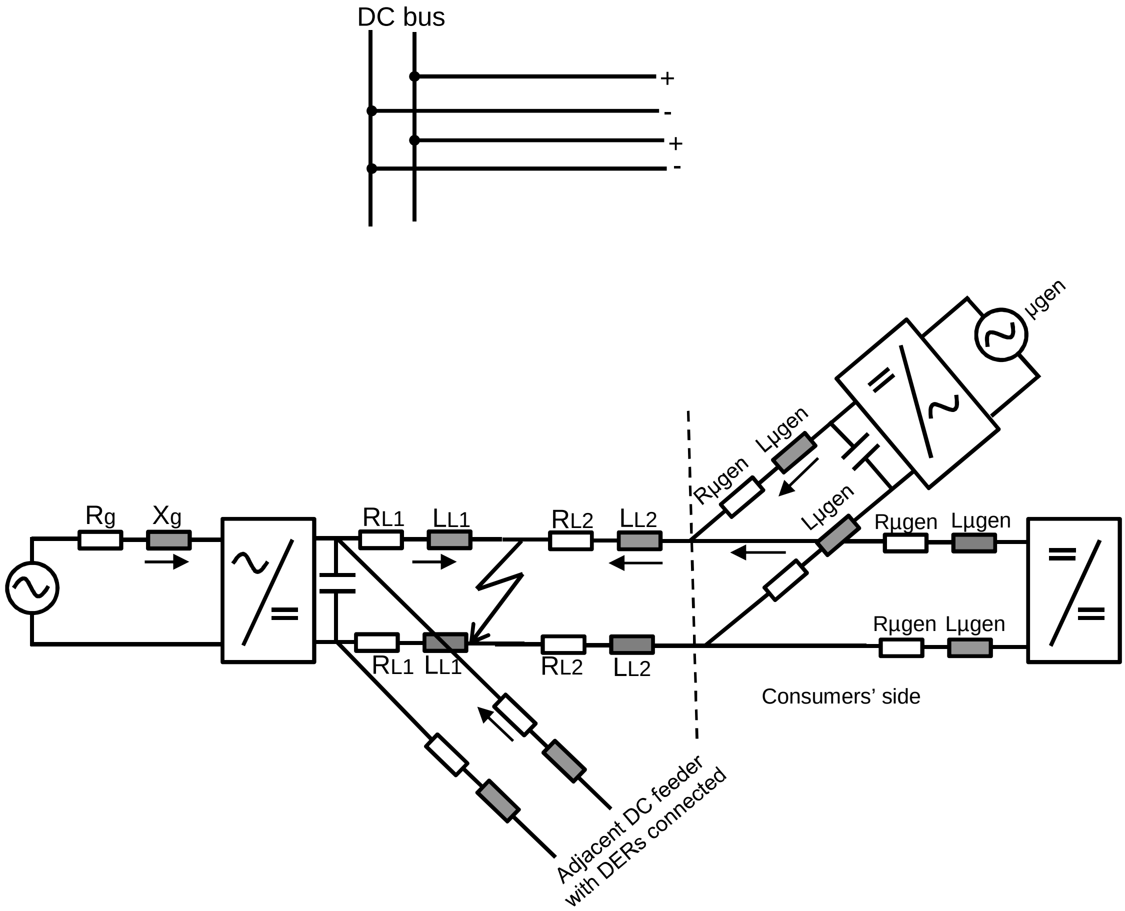


Figure 7: Equivalent circuit of faulted unipolar LVDC with two terminals

There are limited simplified generic mathematical models that have been used for characterising DC short circuit currents of different DC systems such as DC auxiliary systems of power plants and substations. The most known models are the static model, the models implemented in ANSI/IEEE guidelines, and the dynamic model represented by IEC61660 [35]. Compared to the other two, IEC61660 is the most comprehensive DC protection standard that has been most widely used for characterising faulted DC auxiliary systems [35]. This standard also counts the fault response of similar sources that can be found in LVDC networks. Therefore, and because there is no representative DC protection standard for an LVDC last mile network, the next section evaluates the possibilities and the limitations of using IEC61660 for better characterising short-circuits on an LVDC network.

iv. The effectiveness of using IEC 61660 for an LVDC short circuit characterisations

IEC61660 takes into account the following components as DC fault sources; rectifier bridge, stationary batteries, smoothing capacitors, and DC motors that can be connected to DC auxiliary systems [36]. All the sources are connected in parallel to the main DC bus as shown as single diagram of a DC auxiliary system in Figure 8. Since all the sources are connected in parallel, each source can be individually considered. Each DC source will supply a different fault current profile. However, IEC61660 has introduced a typical short circuit current form as given in equations (7) and (8) and shown in Figure 9 to represent approximate transient and steady-state courses of DC short-circuit current that could be supplied by all such sources [36].

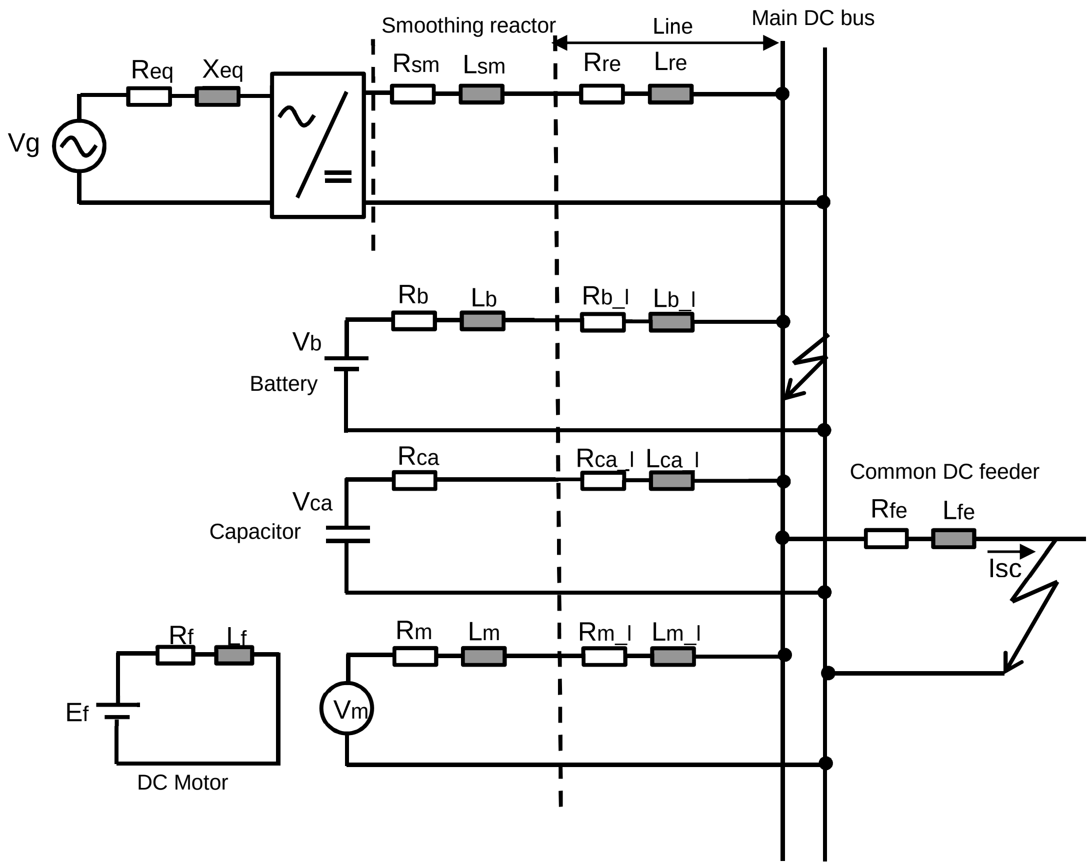


Figure 8: the mathematical model of IEC 61660 for DC short-circuit calculations [36]

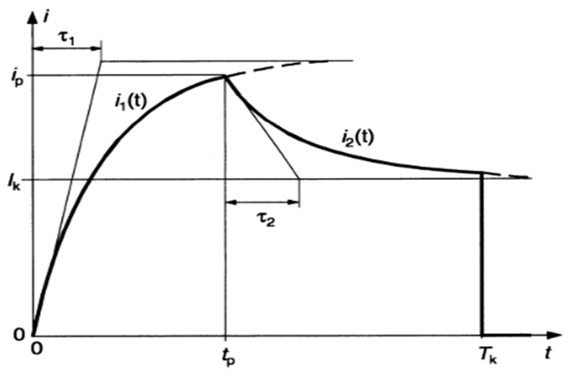


Figure 9: The IEC standard approximation of a DC fault current profile [36]

The DC fault current profile including the transient and steady state contributions can be described by the following equations as given in IEC61660:

$$i_1(t) = i_p \frac{1-e^{-t/\tau_1}}{1-e^{-t_p/\tau_1}} \qquad 0 \le t \le t_p \tag{7}$$

$$i_2(t) = i_p \left(1 - \frac{I_k}{i_p}\right) e^{-\frac{t-t_p}{\tau_2}} + \frac{I_k}{i_p} \qquad t \ge t_p \tag{8}$$

Where: I_k is the steady-steady-state short-circuit current, i_p is the peak current, t_p is the time to peak, and τ_1, τ_2 are the rise and decay time constants.

If a DC fault occurs on the main DC bus, the above equations can be directly used to identify the DC fault current supplied by each individual DC source. The total DC fault current is then the sum of the individual fault contributions. In case of downstream faults at remote locations on the common DC feeder as shown in Figure 8, the currents from all the sources will flow through the common feeder from the bus to the fault point. In this case in accordance with IEC 61660, the DC fault current from each source must be corrected by factors that have been examined on an experimental basis [36]. These correction factors are used to obtain an accurate DC short-circuit calculation, and more details on their influence on DC fault currents behaviour are given in [36].

IEC61660 has mentioned that special considerations are necessary for the correction factors if the test DC network is different from the installation scheme as given in Figure 8 [36].Therefore, the identification of new correction multiplicative factors may be necessary if the standard were used for LVDC short-circuit studies. This is because LVDC last mile networks are different from DC auxiliary systems in terms of cable lengths and configurations. For example, smoothing capacitors and inductive components of longer cables in the fault path in relative to short cables of auxiliary systems can make the DC fault current during transient region to be oscillatory. In this situation, the solution of DC short circuit current calculations is a second order equation, and using IEC61660 solutions as given in (7) and (8) may result less accurate fault calculations. Inaccurate short circuit estimation will have a negative impact on protection systems speed and coordination under fault conditions. Therefore, the effectiveness of IEC61660 is examined on a faulted LVDC last mile network under different fault scenarios. At each fault, the DC fault is characterised in accordance with the IEC61660 standard and by simulation studies, and a comparison is thus made. The studies are conducted as follows.

Test Network

An LVDC similar to the network developed in Figure 4 in section 3 is used as test network. A typical medium voltage (MV) distribution network based on actual data has been selected to supply the test network. The network data has been derived from information provided within distribution long term development statements (LTDS) by the distribution network operators and manufacturers of distribution equipment [22]. The AC MV 11kV network has been modelled using an ideal voltage source and impedance with X/R=5 scaled in accordance with IEC60909 [37] to provide a fault level of 156MVA at the ring main unit (RMU). An impedance of 4.5% and rating of 0.5MVA has been taken for the secondary substation transformer (11/0.433kV). The LVDC network is interfaced to the AC system by IGBT-based VSC with smoothing capacitor C=6750µF. The LVDC test network is assumed to be radial unipolar network providing 612V DC between the two poles, and the parameters of the used LV cables are Rdc=0.164Ω/km, and L=0.24mH/km.

A short-circuit fault between the two DC poles is applied at four different locations on the DC feeder. Fault1, shown as F1 in Figure 10, is applied at the terminals of the converter, and the other faults F2-F4 are applied at 500m, 1km, and 2km away from the converter terminals respectively. These fault scenarios provide different fault locations for IEC61660 suggests varying values for the correction.

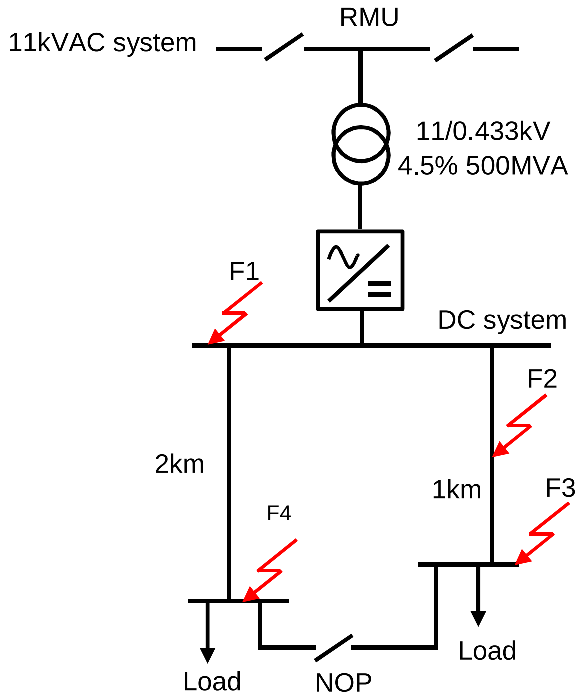


Figure 10: LVDC test network model

LVDC short-circuit characterisation in accordance with IEC 61660

The DC fault current contributions from the converter and the capacitor to each fault location as shown in Figure 10 are calculated individually by using equations (7) and (8) as follows.

Converter characterisation

By using the equivalent circuit diagram given as figure 6 in IEC61660, the DC steady-state fault current I_k supplied by the converter can be calculated from the following formula [36].

$$I_k = \lambda_D \frac{\sqrt{2}C_v V_n}{\sqrt{3}\sqrt{R_g^2 + X_g^2}} \quad (9)$$

R_g and X_g are the equivalent resistance and reactance of the upstream AC grid. V_n is the nominal rms AC L-L voltage, and C_v is the voltage factor. The voltage factor as explained in IEC61660 is used in accordance with IEC60909, and it is equal to 1.1 [37]. λ_D is a corrective factor that reflects the impact of DC resistance on the steady-state fault current. The value of λ_D at each fault location can be obtained from the curves of figure 7 in IEC61660 [36]. λ_D depends on the ratio between the equivalent resistance of the DC feeder within the fault path and the equivalent resistance of the AC grid (R_{dc}/R_g) and the AC equivalent resistance to reactance ration (R_g/X_g). From AC grid data R_g/X_g equals to 0.2, and R_{dc} changes in accordance with the fault location on the DC side. When $R_{dc} = 0$ for the fault F1 as shown in Figure 10, $\lambda_D = 1$, and for remote faults F2, F3, and F4 as the R_{dc} increases, the values of $\lambda_D < 1$. This will impact the value of I_k as given in (9). I_k is calculated from (9) for each value of λ_D. The peak short-circuit current supplied by the converter is obtained from the following formula.

$$i_p = K_D I_k \quad (10)$$

Where the factor K_D depends on L_{dc}/L_g, and the values of $\frac{R_g}{X_g}(1 + \frac{2R_{dc}}{3R_g})$ and can be obtained from the curves of figure 8 in IEC61660 [36]. Using the test network parameters, the values of K_D have been found for all the faults to be larger than one. If $K_D \geq 1.05$ and $L_{dc}/L_g < 1$ as mentioned in IEC61660, the time to the peak t_p can be calculated from equation (11).

$$t_p = (3k_D + 6)ms \tag{11}$$

Based on the K_D values, the peak current i_p for each fault location is calculated. The rise and decay times of the converter transient fault current have been calculated from the following equations [36]:

$$\tau_1 = 2 + (K_D - 0.9)\left(2.5 + 9\frac{L_{dc}}{L_g}\right) \quad ms \tag{12}$$

$$\tau_2 = 2/\left[(R_g/X_g)\,(0.6 + 0.9\,R_{dc}/R_g)\right] \ ms \tag{13}$$

Based on this information, the DC short-circuit current profile supplied by the converter has been calculated from equations (7) and (8).

Capacitor characterisation

The steady-state fault current of the capacitor $I_{kc} = 0$, and the capacitor peak fault current can be obtained from the equation below.

$$i_{pc} = K_C(V_C/R_{dc}) \tag{14}$$

Where V_C is the capacitor voltage before the fault. The factor K_C and the peak time of the capacitor fault current t_{pc} have been calculated from the curves of figure 12 and 13 in IEC61660 for each fault location, and i_{pc} has been determined. The rise and decay time constants can be calculated from the following formulas:

$$\tau_{1c} = K_{C1}t_{pc}, \tag{15}$$

$$\tau_{2c} = K_{C2}R_{dc}C \tag{16}$$

Where τ_{1c}, τ_{2c}, are the rise and decay time constants respectively. *C* is the capacitance value, and K_{C1} and K_{C2} have been obtained from figure14 and 15 in IEC61660. Then the transient current contribution from the capacitor has been calculated from equations (7) and (8).

The total DC short-circuit current

For the fault F1 at the terminals of the converter, the total DC short-circuit current is calculated directly by adding both currents supplied by the converter and the capacitor. Figure 11 shows the total DC short-circuit current for the fault at location F1. As for remote faults at locations F2, F3, and F4 in Figure 10, the total short-circuit currents should be calculated by adding the corrected fault currents supplied by the converter and the capacitor [36]. The peak of the fault current and the steady state value for every source should be multiplied by correction factor σ_j as given in IEC61660 as in equations (17) and (18) [36].

$$i_{pj\_c} = \sigma_j i_{pj} \tag{17}$$

$$i_{kj\_c} = \sigma_j i_{kj} \tag{18}$$

$$\sigma_j = \frac{R_{resj}(R_{ij}+R_f)}{R_{resj}R_{ij}+R_{ij}R_f+R_{resj}R_f} \tag{19}$$

Where R_f is the resistance of the feeder up to fault point, R_{ij} is the resistance of a DC source up to common feeder as shown in Figure 8, $i_{pj_c}$and i_{kj_c} are the corrected peak and steady-state fault currents, and the subscript j represents the type of the DC source. In case of the test network R_{ij} is equivalent to the internal resistances of the converter and the capacitor. R_{resj} is the equivalent resistance of the parallel resistances up to the common feeder of the other sources that contribute to the steady state short-circuit current through the common feeder. For auxiliary systems as given in IEC61660, the R_{resj} represents the equivalent parallel resistances of all the DC sources including the battery and the DC motor as shown in Figure 8.

But, in case of the LVDC test network as given in Figure 10, there are only two DC sources supply the fault, the converter and the capacitor, and the capacitor does not supply steady-state DC short-circuit current. Therefore, the $R_{res\_con} \approx \infty$, and hence from (19) $\sigma_{con} = 1$. If the resistance between the smoothing capacitor and the common feeder is neglected ($R_{i\_cap} = 0$), the correction factor related to the capacitor σ_{cap} will be also equal to one. In this case the calculated short-circuit currents for both the converter and the smoothing capacitor are the accurate values from same. The total short-circuit currents for all the applied remote fault locations are shown in Figure 13.

<u>*Simulation studies:*</u>

PSCAD/EMTDC was used to model the same test network. The main converter has been modelled as a six pulse rectifier with smoothing capacitor on the DC side, since the IGBTs switches will be inoperative during the short circuit on the DC side. The VSC will act as a diode bridge rectifier and the fault will be supplied continuously through six anti-parallel diodes as shown in Figure 12 if external protection is not used. Such a model will also give the worst DC fault scenario where no converter control action is implemented, and the highest DC short circuit can be identified. The same fault scenarios as shown in Figure 10 are considered in the simulation studies, and the output results are included in Figure 11 and Figure 13 with those calculated by application of IEC61660.

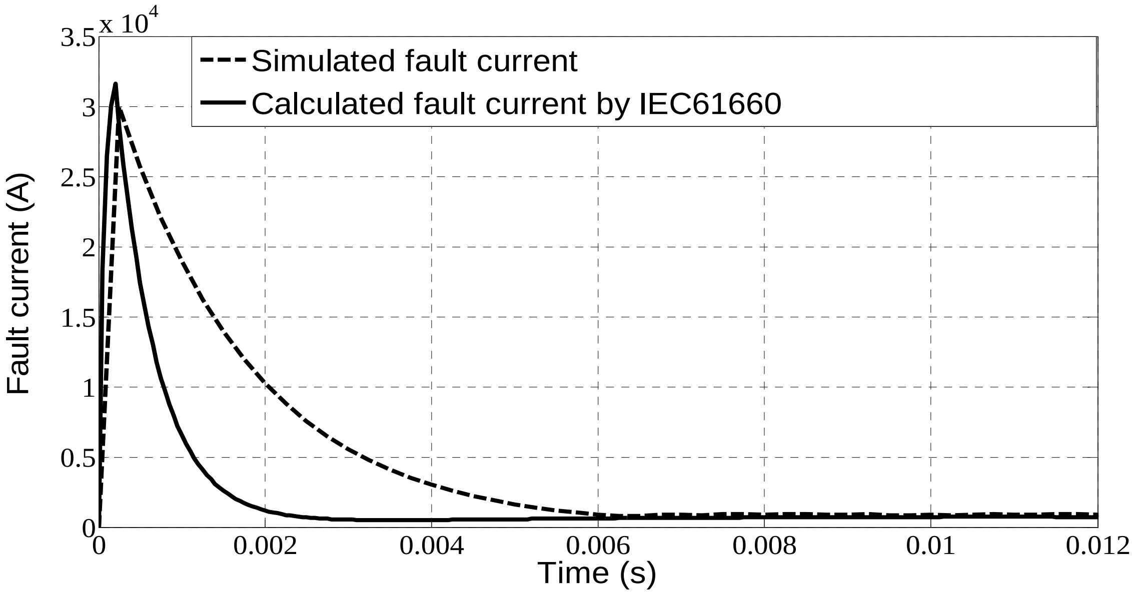


Figure 11: DC fault at the terminals of the converter

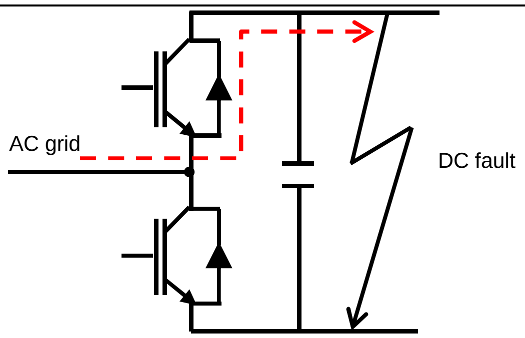


Figure 12: VSC IGBT anti-parallel diodes conduction during DC faults

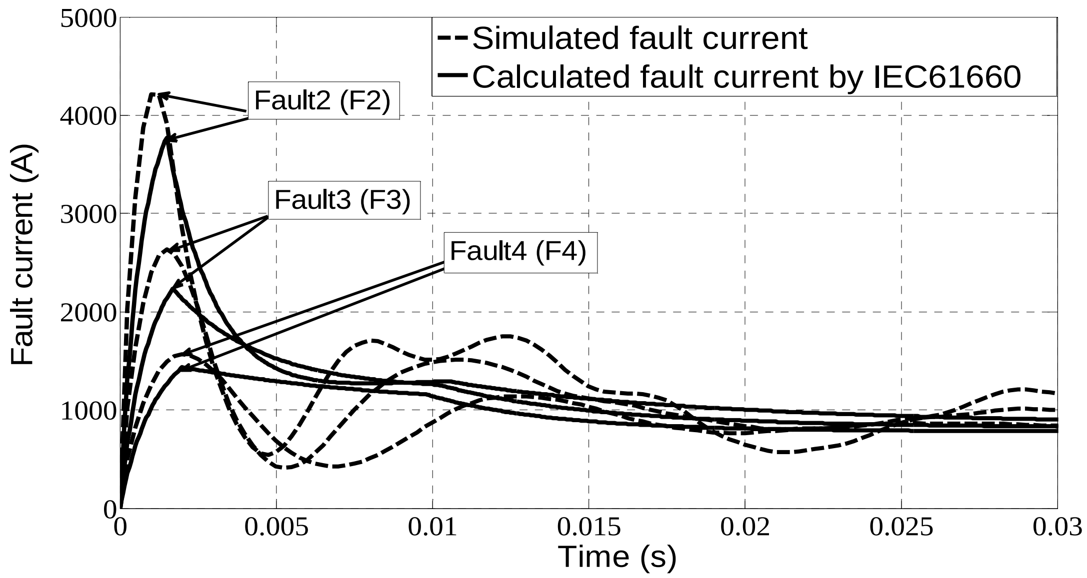


Figure 13: DC remote faults at different locations

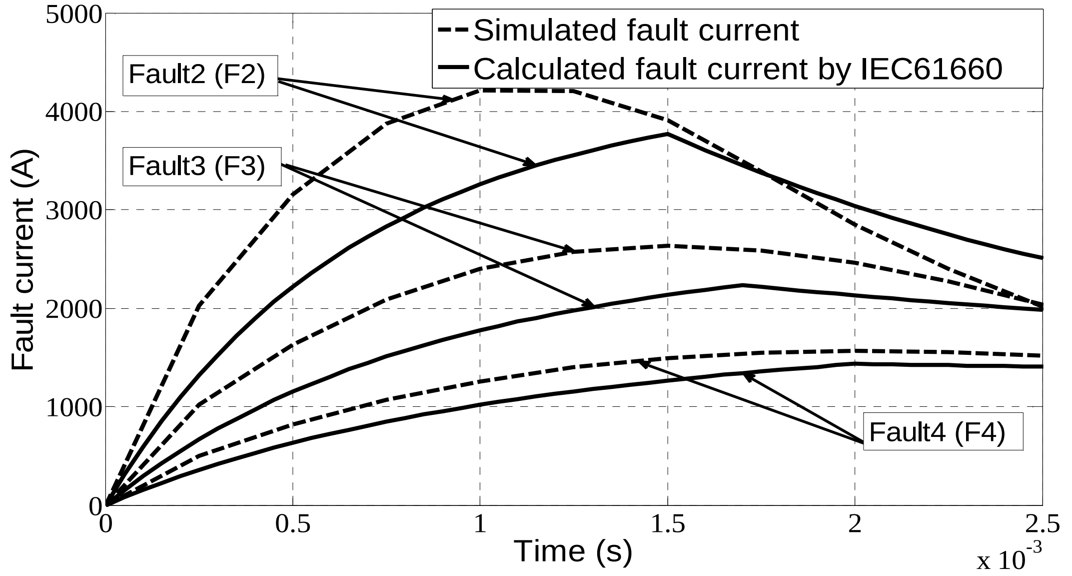


Figure 14: The rise times of DC remote faults

When the fault was applied at the converter terminals which is equivalent to the main DC bus of an auxillary system in IEC61660, the fault path impedance is zero ($R_{dc}/R_g = 0$), and the corrective factor $\lambda_D = 1$. In this case the results have shown that the calculated peak of the capacitor discharge current is very close to the simulated value as shown above in Figure 11. However, the decay time following the peak of the calculated discharge current is noticeably faster than the simulated value. The decay currents supplied by the capacitor and the converter as in accordance with IEC61660 approach do not consider the impact of the cable inductances and only consider the resistance within the fault path. This can be cleary noticed from equations (8), (13), and (16). Since, the fault path resistance $R_{dc} = 0$ during converter terminal faults, the decay time will be very small.

For remote faults F2, F3, and F4 $R_{dc}/R_g > 0$ and $\lambda_D < 1$, the discharging peak currents as given in Figure 13 are lower than the simulated values by almost 10%. Also, the simulations results for remote faults have shown that the DC fault currents have sinusoidal forms decaying exponentially in accordance with approach (4) due to the nonlinear RLC circuit with decay time larger than the calculated values. The source of these errors is the negligence of inductances impact by the standard. Referring to the equivalent LVDC circuit as given in Figure 7, the IEC61660 approach does not consider the impact of the line inductance L_{L2} and the microgenerators inductances $L_{\mu gen}$. This will lead to not capturing the current oscillations and the significant impact of the system inductances on the transient discharge fault currents. The generic IEC61660 approach has simplified the capacitive fault response by assuming the contribution from smoothing capacitors to pass very fast and to be less significant compared to steady-state contribution. Also, system inductances impact on the transient current could be neglected due to the short cable lengths of DC auxiliary systems.

The margins of error between the calculated and simulated DC short-circuit currents are expected to increase if the standard is used for characterising a faulted LVDC network with high penetration of capacitive microgenerators. This is simply, because microgenerators will be distributed across the network at different locations, and more inductances between microgenerators and fault points will be included. Omitting the impact of these inductances during transient discharge current periods as simplified by IEC61660 will lead to inaccurate modelling of the network response. The decay time and the correction factor σ_j do not include the system inductances that can have significant influences on the transient system response, and it is assumed that discharge current will decay very fast to steady state. Therefore, if an LVDC network is designed in accordance with IEC61660 calculations, the network in reality will experience a higher current with longer decay time. This can be an issue in terms of power electronics and equipment ratings, and protection performance. Also, the rise time constants of the simulated results as shown in Figure 14 are smaller than the calculated values. This can lead to fault detection issue if the detection of rate of current change threshold values is based on the IEC61660 calculations.

Therefore, one recommendation for increasing the accuracy of the standard and the potential of using it for LVDC applications is the consideration of the impact of system inductances in the calculation approaches. In this case formula (4) for modelling the transient discharging courses would be more suitable instead of the approximated equation (8). The consideration should also be included in the correction factor σ_j. Within existing IEC61660, σ_j considers only the resistances of the parallel connections of the DC sources.

5. An LVDC last mile protection issues

Traditional distribution power systems are generally considered to be of lower importance from the protection complexity perspective [38]. This is because of the cost and the radial characteristic nature of distribution networks where the direction of fault current is always known. Also, clearing faults on LV networks will lead to the disconnection of a limited number of loads compared to faults on HV networks. The devices that are most widely used for protecting distribution networks are; overcurrent relays, reclosers, sectionalisers, and fuses, and their operating principles are based on non-unit overcurrent protection schemes [39]. In non-unit protection the protection operating time decreases as the fault current increases. The operating times of several protection devices protecting the same feeder need to be coordinated by which downstream elements in the fault path will respond to faults faster than the upstream devices. LV distribution network protection does not involve extensive hardware, and fuses are typically used for protecting LV feeders against overcurrent. LV fuses are coordinated with MV feeders and transformer protection schemes to provide selectivity [22]. Fuses are normally simple to use, fail safe, their operating characteristics can be graded, and they are relatively cheap compared to other protective devices. Thereby, fuses are extensively used particularly in LV systems (415 and 660V) with rating from 2 to 1600A [39]. Moulded-case circuit breakers (MCCBs) that are rated 10 to 2500A, 600V or lower can also be used for protecting LV feeders [40].

The use of non-unit overcurrent protection has demonstrated an effective performance in terms of protecting traditional LV networks against faults, and reducing faults consequences. However, such traditional types of protection may not be suitable for protecting future LVDC distribution networks with a high penetration of microgeneration. The power electronic devices that are used in LVDC networks will introduce new challenges compared to traditional AC networks. New forms of faults such as converter switch faults can be experienced. LVDC will also have different configurations and connection arrangements, and the nature of DC short-circuit faults as discussed previously in section 4 is significantly different from the nature of AC faults. In addition, different earthing systems (important for protection design) from the traditional may be required for future LVDC in order to improve its performance. All these factors will have an impact on DC prospective fault currents that will flow through DC faulted circuits, hence impacting the protection performance. Therefore, this section of the report discusses the protection issues that are related to LVDC distribution networks. The following four main areas are considered: (i) the short-circuit current capability of power electronic devices within an LVDC network, (ii) issues related to earthing systems, (iii) interrupting DC fault current issues, and (iv) LVDC system response to the high transient of DC faults. The discussion within each area also includes some of remedial measures to improve protection performance of DC networks. This will help to answer the question whether existing LV protection schemes and components can provide reliable, secure, and stable operation for future LVDC networks, or new schemes and devices are required.

i. <u>Short-circuit current capability of power electronics devices within an LVDC</u>

The operation of power electronics converters under short-circuit overcurrent conditions is an issue due to switches poor short circuit capability [41]. Device maximum operating conditions must not be exceeded. To protect switches from being damaged by short circuits, an additional current limiting circuit is normally integrated within the converters. In order to reduce the cost of designing a system with a high short circuit tolerance, grid-connected converters utilising current limiting capability can supply a DC fault equal to only about 120%-200% of its nominal current [42]. Such an operating condition will limit the LVDC system to only experience low level short circuit currents. Low fault levels can significantly delay the protection operating time, resulting in longer stress on the protected network. Limited short circuit capability can also lead to fault detection issue for faults with high impedances. It will be difficult to use MCCBs and fuses to clear DC faults if the converter is unable to supply short circuit current as long as these devices need to react [12]. This depends on how long the fault current will flow without having internal damage to converter switches, and whether the supplied current will meet the minimum required fault current to operate the protection in the required time or not.

The following example as given in [41] can be used to explain the impact of reduced fault current on the protection performance. If an inverter rated 10kVA supplies a 230V single customer with 230V, the nominal current would be 43.5A rms. The CBs that are suitable for such an application require 3-5 times of the nominal current for B-type, and 5-10 for C-type to trip in 0.4s. If fuses are used the required current could be even higher. If 16A C-type CB is used, the inverter must provide 160A to operate the CB. The required current is more than 3 times that of the inverter rating. In case of short-circuit the inverter normally allows only 1.2 to 2 of its nominal current to pass through it, and hence the C-type breaker will not operate.

Increasing the protection operating time due to reduced fault current level will also increase the spread of post-fault consequences. For example, studies conducted in [18] have shown that when a DC fault on LV side was cleared after 1ms, the converter current starts oscillating during the fault with a peak almost equals to 2 p.u. When the fault clearance time was increased to 5ms, a large transient DC-link voltage enough to impact the loads connected to the unfaulted feeders has been experienced. So, slow protection performance due to limited fault current is a significant issue. One solution to avoid this problem is by using high converter ratings, and this will lead to increased cost. There are other alternative solutions that can be implemented. These solutions are discussed as following.

Solution1:

For detecting and isolating DC faults with relatively limited magnitude, protection systems using relays embedded into the converters have been proposed in [43]. The approach is based on the measurement of steady-stat overcurrent and undervoltage conditions for sensing faults. For example, the embedded relay monitors the converter DC output current, and uses overcurrent protection scheme to clear faults. If the measured current passes the threshold value and remains above it for a certain time, fault on DC side is assumed. To increase the level of reliability the relay measures the DC voltage likewise. If the voltage drops to less than the allowed limits, and overcurrent and undervoltage conditions are met, a trip signal to associated CBs is sent to isolate the fault. The embedded relay can also monitor the input AC line currents to decide whether the fault is on the AC or DC side. If the fault is on the AC side then the DC current will not rise, and the AC fault current can be cleared by AC protection. The disadvantage of this approach is that the embedded relay will lead to a complete blackout of the network if it is not well coordinated with downstream devices. This method also depends only on steady-state local measurements, and transient DC fault currents are not considered. This will allow the flow of a high transient fault current through the system before any protection action is taken, and this may cause physical damage to the protected converter itself or to other sensitive components.

Solution2:

A protection scheme which is based on an Active Impedance Estimation (AIE) to detect and localise faults with limited magnitudes for an LV zonal distribution system of a ship is proposed in [44]. The technique imposes small transient disturbances into the system at a point of measurement to excite the system in real time and estimate the system impedance at that point. When a fault is detected from a dip in the bus voltage, a short current pulse is injected into the protected LV distribution system in order to estimate the system harmonic impedance from the transient injection point.

Steady-state compensation method is used for transient measurements of voltage and currents [44]. The voltage and current can be measured before and after the injection and then the steady state can be removed by subtracting the data captured before the injection from the data captured after the injection. The time domain transient is then transformed into the frequency domain and the harmonic impedance can be determined. If the measured harmonic impedance values are compared for different system conditions then it can be possible to determine if a fault has occurred and where has been located. This technique may be useful for detecting a DC fault with high impedance in LVDC power networks, however additional injection units will be required to perform AIE to localise faults.

ii. Issues related to LVDC earthing systems

The grounding techniques are normally used for ground fault detection and for safety of personal and equipment [18]. The grounding options of LVDC distribution systems have been previously discussed in section 3 of the report. Without a deliberate DC path to ground (useful for earth fault decoupling), there will not be a DC reference point for the LVDC to keep the balance in bipolar system. In case of an earth fault with high impedance or a fault between a live conductor and metal bodies, it will be hard to detect the fault, and metal close to loads can be energised and risky. Some of the solutions related to this issue are discussed as follows.

Solution1:

For unearthed LVDC distribution systems, the short circuit protection cannot be used to detect and clear earth faults. Additional protection devices such as Insulation Monitoring (IM) devices are required for detecting earth faults. For example, the Low voltage electrical installations and safety at electrical work standard which is used in Finland [25] has outlined that unearthed distribution systems must be protected by IM devices against earth faults. The principles of IM devices for protecting unearthed LVDC networks against earth faults are discussed later in section 6. In unearthed LVDC systems, the protective earth connections of the consumers are provided locally, and are independent from the main grid earth. In this case all the feeders at the consumers' side must be protected by residual current devices (RCD) protection against earth faults [32]. The issue here is the additional protection equipment that will lead to increased design cost. From technical perspective, it has explained in [9] that the earth fault on DC parts could affect insulation monitors on AC sides of the network. In this case AC insulation monitors may operate and unnecessary trip can be experienced.

Solution2:

Another method to detect a high impedance earth fault within an earthed LVDC network is to measure the earth (neutral) current of the connected sources and the DC system earth currents, and if they are out of limits, pole-to-earth fault has occurred and trip signals must be sent [18]. However, accuracy of this method can still be an issue where leakage currents in bipolar systems for example must be considered when the limits are set.

iii. Issues related to interrupting DC fault currents

Interrupting a DC fault current is more difficult than an AC fault current [45]. DC fault current and voltage waveforms do not have natural zero crossing points. Therefore, standard fuses and circuit breakers are difficult to be used within DC systems. The risk of fire and burns is expected in DC systems more than ac systems due to problems associated with interrupting DC currents and arcs [46]. If electro-mechanical circuit breakers (EMCBs) intend to be used for DC system, a higher size and weight and even slower performance can be expected [34]. The following discussion includes some of techniques that have been used for interrupting DC short–circuit currents.

Solution1:

Interrupting a DC fault current is possible if current-limiting fuses and/or current-limiting CBs are used, and their ratings are adjusted to be applicable to DC systems [40]. These devices do not require zero crossing points for extinguishing the DC fault arcs. The fault current will be interrupted before reaching the peak. However, the extinguishing of arc of DC faults is more difficult than AC. It needs to reduce the voltage across the arc by increasing the arc length (e.g. increasing the distance between the contactors), and using arc splitter to split the arc [40].

Moulded case circuit breakers (MCCBs) which are widely used for an AC overcurrent protection can still be used for DC applications [18]. However, the devices must be rated and tested for DC applications, and not based on the existing AC standards [40]. For example, when an MCCB is used for a DC protection, its time-current tripping characteristics need to be revised. Considering the most common overcurrent sensing unit of the breaker which is the thermal-magnetic, the unit is provided as an AC curve and multipliers that can be converted for the use with DC circuits. The tripping characteristic of the AC curve is normally divided into three regions; the long-time delay region, the transition region, and the instantaneous region as shown in Figure 15 [40].

The deflection resulted from the fault current flowing through the CB during the long-time delay overcurrent region which typically includes currents from the full load current to the level at which the trip occurs is proportional to the rms I^2 of the fault current. Therefore, the operating time will be the same for AC and DC applications within this region [40]. During the transition region as shown in Figure 15, the tripping times can be with the delay in accordance with the thermal curve, or magnetic with no delay for higher current, depending on the level of the fault current [40]. The AC trip curves are based on rms values while DC curves will be represented as instantaneous values. This difference will require adjusting AC curves to DC systems. For example, the AC magnetic tripping level should be slightly increased by using multiplying factor of 1.1-1.4 times the AC tripping current as explained in Figure 15 [40]. The instantaneous region does not have time delay in tripping, whether in AC or DC systems [40], and the fault clearance time depends on the available electromagnet force caused by fault currents.

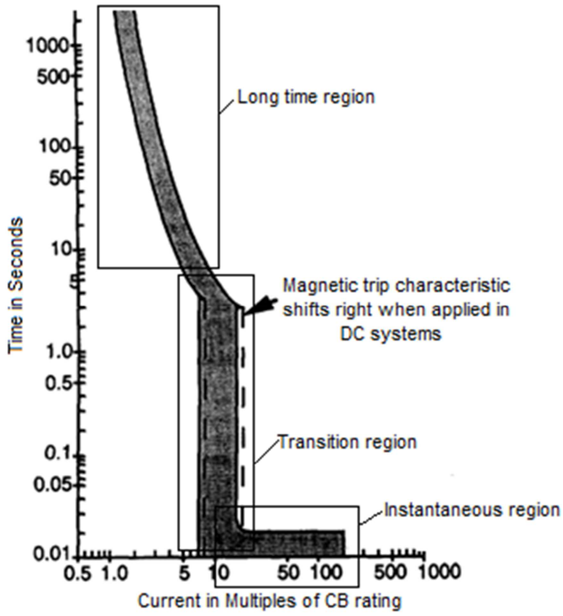


Figure 15: An example of characteristic curve for thermal-magnetic MCCB modified for DC applications [40]

The performance of a conventional overcurrent protection device for clearing DC faults at different locations has been examined on the test LVDC network that has been used in section 4 and given in Figure 10. An overcurrent protection device with extremely inverse time-current characteristic and pick up current equals to 2 of the rating current has been modelled and added at the beginning of the LV DC feeder of the test network. The speed of the protection has been tested against the same fault scenarios (pole-to-pole) as shown as F1, F2, F3, and F4 in Figure 10, and the results are added to the table below.

Fault locations	Fault at F1	Fault at F2	Fault at F3	Fault at F4
Fault clearance time (s)	0.43	0.783	0.913	1.429

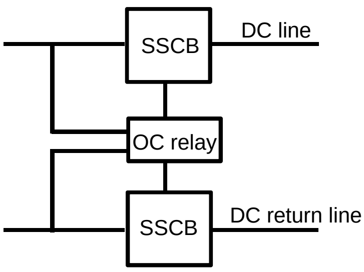
Table 7: fault clearance times of LV overcurrent protection for different DC fault locations

From the above results and discussion, the use of fuses and MCCBs devices for interrupting DC short-circuit currents is physically possible, but slower performance is expected due to the nature of the devices response. The results in Table 7 show that faults were cleared during steady-state periods, and the high peaks of the discharge currents were allowed to pass to the network. Such slow acting protection will make the system to experience longer short circuit stress, and increase the requirement for equipment with higher current ratings. Over and above, it will be significantly difficult to maintain the stability of small scale local microgenerators following transient faults with such slow acting protection devices. This is due to the sensitivity of microgenerators to undervoltage conditions during transient faults on the system.

Solution2:

As an alternative option to conventional CBs and fuses, solid state circuit breakers (SSCB) based on semiconductor turn-off devices can be used for interrupting DC short circuit currents. Unlike Electro-Mechanical Circuit Breakers (EMCBs), which require relatively longer time to clear DC faults, and fuses which require physical replacement after operation, SSCB can be immediately turned on and off within 2-20 µsec [47]. This will significantly improve the protection operation speed, and reduce the fault stress on the network and the impact of fault energy absorbed during the fault. SSCBs have also the ability to lower the fault current level, and the ability to be reset automatically after the fault is cleared to continue normal operation [48].

A gate Turn-Off (GTO) thyristor semiconductor, an Integrated Gate-Commutated Thyristor (IGCT), and an Isolated Gate Bipolar Transistor (IGBT) are common examples of SSCBs which can be used for interrupting DC currents [47]. The SSCB GTO-based has more complex gate-drive circuit and lower switching speed compared to the other types [47]. Thus IGCT and IGBT have more advantages than GTO. A Silicon Controlled Rectifier (SCR) is also another mature type of SSCBs, but it can be used only for AC applications where current zero crossing is required to turn off the device [49]. An example of using SSCBs for protecting a DC feeder is shown in Figure 16 [50]. Each DC pole is protected by one SSCB, and the two breakers are controlled by one overcurrent relay. The relay measures the currents through the two lines and if predetermined values are exceeded, a trip signal will be sent to the associated controllers to switch off the related SSCBs and disconnect both DC poles from the fault. A simplified topology of an SSCB is given in Figure 17 [51].



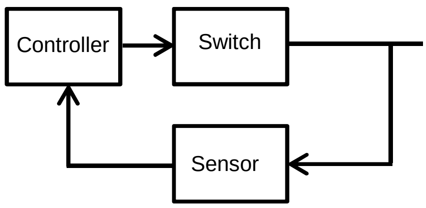


Figure 16: IGBT breaking system [50]   Figure 17: The topology of electronic CB [51]

The drawbacks of SSCB are the on-state losses and increased cost. For example, according to the comparison between different types of SSCBs as given in [46], SSCBs IGCT-based and IGBT-based have on-state voltage drop around 1.6V and 2.5V respectively. In addition to this, SSCBs have limited current and voltage capabilities compared to conventional electro-mechanical circuit breakers (EMCB). The SSCB IGBT-based has lower current capability compared to IGCT-based, but its voltage capability is higher than IGCT breaker. In general, SSCB IGCT-based is more preferred over IGBT-based if on-state losses is an issue. This is because IGCT has lower losses than IGBT, but the switching speed of IGCT is slower than IGBT [49]. In some applications a combination of SSCB IGCT-based, IGBT-based, and EMCB are used for dc network protections in order to reduce on-state losses and costs [18][48].

iv. Issues related to an LVDC network response to the transient of DC faults

A DC short-circuit current profile as discussed previously in section 4 consists of two main forms: a high transient discharge short-circuit current course and a steady-state short circuit current course. The transient discharge fault current can be relatively high in comparison to steady-state fault current, and it can cause an extreme stress to the network components and impact the protection performance [18]. Two main problems are expected to result from a high discharging DC fault current; one is increasing the risk of physical damage to sensitive equipment due the high magnitude, and the other is negatively impacting the selectivity of non-unit protection. These two main issues are discussed further as follows.

During the transient discharge current, the DC voltages close to the fault become very small or almost zero, and in some cases due to the oscillations between cable inductances and filter capacitors, the DC voltage can be negative. This will allow the antiparallel diodes to be forward biased and exposed to a high overcurrent. The studies in section 4 have shown that a high transient short-circuit up to 35 times of the steady-state fault current can flow through anti-parallel diodes within less than 4ms. For other different DC systems such as the example given in [24], the peak of transient DC fault currents was found to be up to 73 times of the steady-state fault current within 5ms. Such high discharge currents with high amplitudes and low rise times will flow through the network converters and other sensitive components with a significant thermal impact I^2t. This will result in increasing the risk of physical damage to the switches and the sensitive components. One option is to design the system with a high current rating, and this will increase the cost or by using fast acting protection to reduce the impact of high discharge currents with high amplitudes.

Form protection view, power electronics converters are very sensitive to the rapid undervoltage conditions introduced by the high spikes of transient discharge currents during DC faults. This will increase the potential to operate the converters internal protection, and resulting in poor selectivity and unnecessary outage of power for downstream faults. In this case fast acting protection which can quickly clear downstream faults before the trip of the main converters will be required. Some of other solutions to reduce the impact of high transient discharge fault current are given below.

Solution1:

One option to reduce the stress caused by the capacitor discharge current and protect sensitive components is the use of Emitter Turn-Off DC Circuit Breaker (ETO-based DCCB) to disconnect the capacitor during the transient [43]. This solution is based on the inherent current sensing capability of the ETOs which can measure the discharge current and compare it to a predetermined threshold value. If this value is exceeded, a hard turnoff is applied to limit and interrupt the discharge fault current within 3-7µs [43]. Such fast interrupting action will protect the capacitor from extreme stress, and reducing the impact of the energy absorbed during the DC fault by the other system components. In this case the system will experience only the steady-state fault current which is less severe than the transient. This can help in avoiding unnecessary converter trip, by giving downstream protection time to some level to react before the converter during remote faults.

Summary of protection issues:

Based on the above discussion, it is unlikely to have an effective performance of an LVDC distribution network with the use of traditional LV protection schemes. This is because traditional protection schemes are incapable of providing fast actions that are required for minimising DC fault consequences. Mainly there are two reasons of slow protection performance. One is the reduced fault level by the converters which will lead to slower speed of protection, and the other is due to the nature of conventional interrupting devices such as fuses and EMCB. These devices require longer time to extinguish DC arcs compared to the AC. Slow protection performance will lead to the following fault consequences:

- It will make the converters and the network to be defenceless against high transient DC faults, and this is because fuses and MCCM are difficult to operate during the transient period. This will lead to increase the requirements for a high current rating system design to avoid damages where thermal energy will be absorbed for longer time. As result more cost will be added.

- It will make the rapid depression of DC voltages to last longer which will make the converters to loss control with a big chance to trip before other downstream protection. This will result in substandard protection selectivity and unnecessary disconnection of the entire LVDC network.

- It will lead to a post-fault power quality issue by causing post-fault high transient spikes of DC voltages enough to affect sensitive devices.

- It will be difficult to maintain the stability of local microgenerators against remote transient faults. This is because microgenerators are very sensitive to undervoltage conditions with very poor inherent damping. The outage of large amount of local generators could lead to emerging shortage (deficit) of active and reactive power, and increasing the risk of local cascading events.

6. Protection solution options for an LVDC last mile network

There are numbers of protection schemes that have been developed and implemented for protecting different DC power system networks. The schemes have been introduced for protecting compact DC microgrids and HVDC links. The possibilities and the limitations of implementing these schemes for protecting LVDC distribution networks are discussed in this section, and the most suitable scheme for effectively protecting LVDC systems has been proposed. The section discusses numbers of schemes that can protect DC networks from AC side or from AC and DC sides.

i. Protecting DC systems from AC side

This type of protection arrangement is widely used for an HVDC protection, and considered as the most economical way to protect DC lines in HVDC systems [52]. It can be achieved by locating AC CBs on the AC side of the converter as shown in Figure 18. During faults on the DC side, the DC voltages will be sharply decreased and the currents in the faulted part will increase. The undervoltage and overcurrent are measured by the converter and fed back to the relay that is responsible for operating the CB on the AC side. The breaker on the AC grid then will disconnect the converter and the DC link completely from the grid.

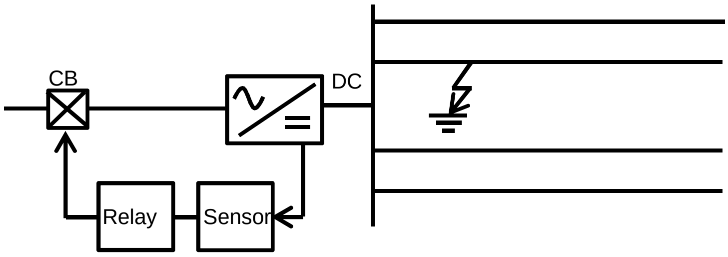


Figure 18: protecting a DC system from AC side

If this scheme is used for protecting an LVDC network, a complete unnecessary disconnection of all downstream feeders including healthy feeders will occur during faults on the DC side. Moreover, conventional AC CB will be relatively slow for clearing faults on the DC as discussed previously. Therefore, this protection solution will not provide the best performance of an LVDC network, where the entire network will be disconnected.

ii. Protecting DC systems from AC and DC sides

In this case the system is protected from the AC and DC sides as shown in Figure 19. Using protection devices on the DC side will allow the system to be more sectionalised, and more protection selectivity can be achieved. The protection on the DC side can be achieved by using normal MCCB or LV fuses that have been designed and tested for DC or by using SSCBs as discussed earlier. The protection on the DC side will operate as main protection for downstream faults and AC protection will backup DC protection. AC protection will protect the system from the AC side and the converter against faults.

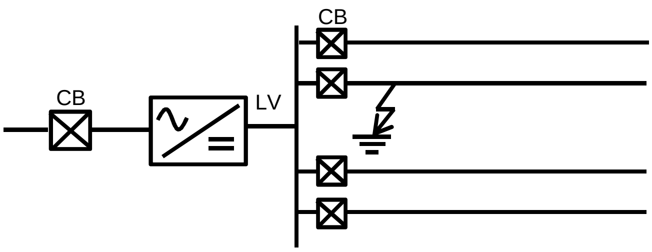


Figure 19: DC protection with AC and/or DC devices

SSCBs as discussed earlier in section 5 are faster and more controllable compared to traditional CBs and fuses, and the only issues with SSCB are the cost and the introduced losses. Therefore, cheaper and less complex in hardware DC switches can also be used for helping protection against DC short circuits instead of SSCBs on the DC side. For example, handshaking method as proposed in [53] uses AC CBs and fast acting DC switches for locating and isolating DC faults in multi-terminal DC systems. The switches are not capable of breaking any DC faults. They are mechanical devices which can be used for disconnecting and reconfiguring DC lines after the DC fault is cleared by the AC CBs. The method is based on the measurement of current magnitudes and directions received by VCSs to identify the faulted DC lines.

In case of DC faults, all the CBs related to the faulted part and located at the AC side before VSCs will trip. Then each VSC will receive current measurements from associated switches to identify the faulted lines and which switches should react. The switiches of the line with largest current and positive in direction (positive is out of the node and negative is into the node) will be selected as faulted line and opened by the converter. The swiches with negative currents will remain closed. After the faulted line is disconnected by the related switches, reclosing function is applied to restore the system.The converters will then be enrgised from the AC sides by the related AC breakers.

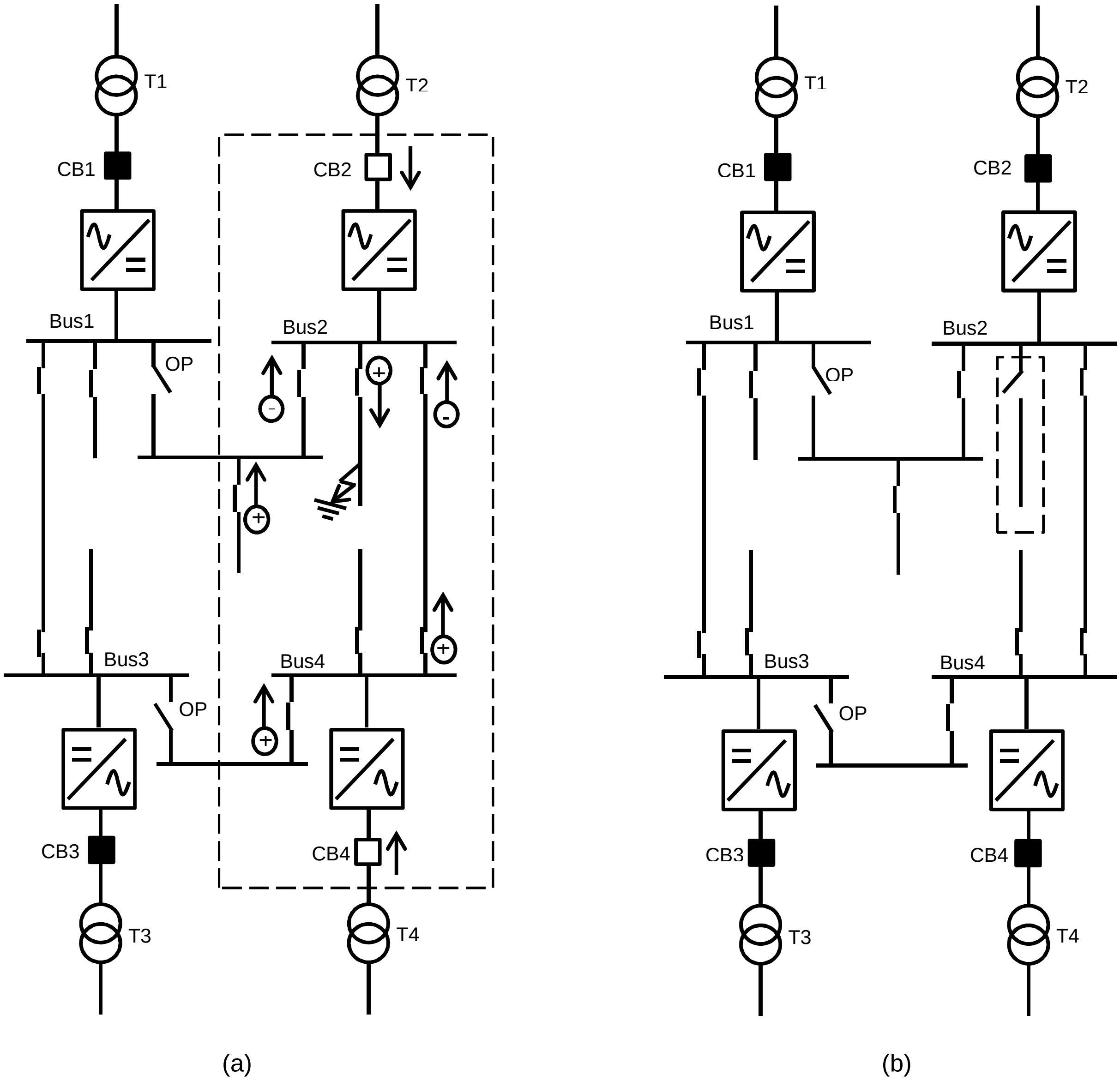


Figure 20: A ring configuration LVDC network protected by handshaking method

In order to investigate the effectiveness of handshaking method for protecting LVDC distribution networks, an example of a ring configuration LVDC as shown in Figure 20 is used. Each main converter is protected by one AC CBs on the AC side plus fast switches on the DC side. The AC CB can be used for clearing DC faults and DC switches for reconfiguring the healthy system. Before any fault is applied, it is assumed that the transformers T1 and T3 supply one part of the local LV loads, and T2 and T4 supply the other loads. When a DC fault occurs on one of the LV feeders as shown in Figure 20, the handshaking protection schemes takes the following actions:

Action 1: since the fault is on the side of the network supplied by T2 and T4, all this part of the network is shut down by the AC CB2 and AC CB4 as explained by the dashed line in Figure 20-a. The breakers CB1 and CB3 will not see the fault, and they will remain close.

Action 2: based on the directions of the currents and the magnitudes, the faulted feeder is identified. It is possible for more than one current to have the same direction, but the fault current in the faulted feeder will have positive direction with the highest magnitude.

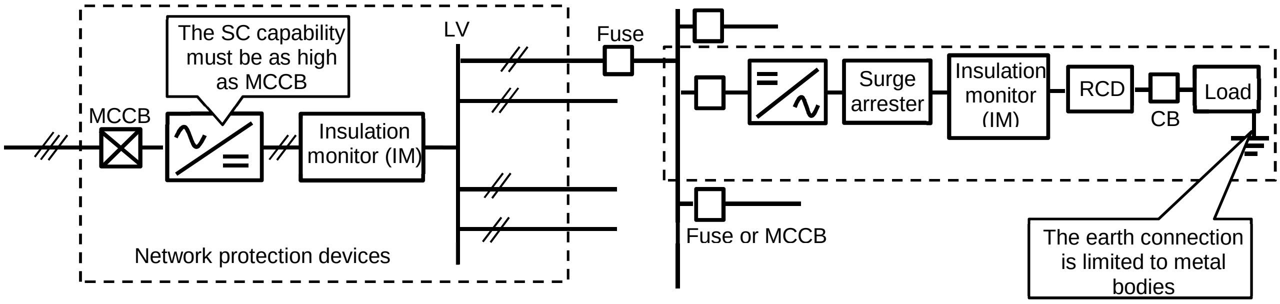
Action 3: using the fast acting DC switches to reconfigure the network by opening the switches of the faulted feeder, and remaining all the other switches close. This will happen during network dead mode.

Action 4: restoring the healthy system back to normal by closing the AC CB2 & CB4.

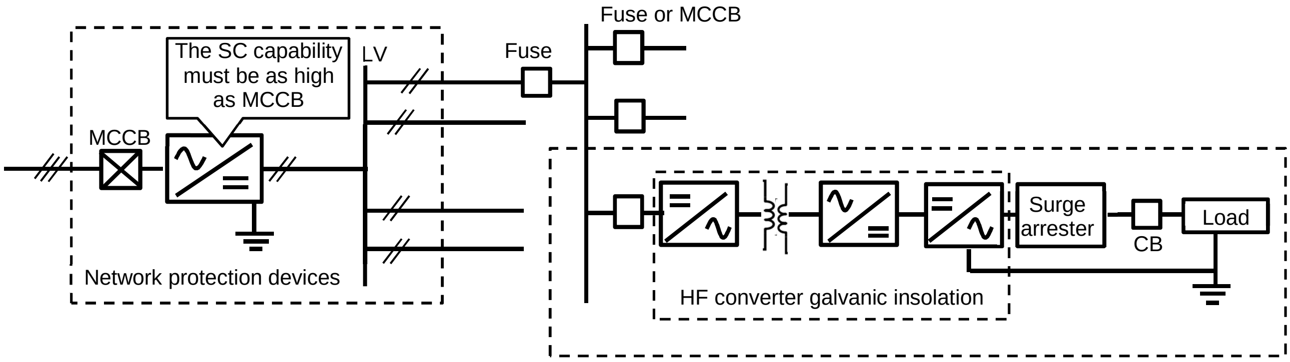
Handshaking method has the advantage of limiting the number of disconnected loads. Also the use of cheap and simple switches will not increase the losses in the DC feeders and the cost compared to the use of SCCBs on the DC side. However, disconnecting the whole downstream loads (including faulted and unfaulted) even temporarily in order to disconnect the faulted feeder is not desirable. Sensitive loads and the stability of local microgeneration will be impacted during temporary power outage, and power quality can be a real issue.

Another example of using AC and DC protection devices for protecting DC power systems is a non-unit protection scheme with AC and DC interrupting devices that has been developed in [9] and [54]. The scheme is used for protecting a simple earthed TN-system and unearthed IT-system LVDC networks. More devices compared to traditional non-unit protection are added for better performance. Overcurrent short circuit protection, earth fault protection devices, and insulation monitoring (IM) devices are used. An MCCB is used on the AC side as shown in Figure 21 for protecting the network against AC short circuits, and the converter against switch faults. The MCCB will provide backup protection for downstream DC protection.

As for DC side, the DC feeders are protected by DC fuses as shown below in Figure 21. For unearthed IT-system LVDC network as explained in Figure 21-a, Insulation Monitoring (IM) relays are used for protecting the network against earth faults. IM devices can also be equipped with an additional device for selective directional functions [9]. The IM relay will measure the insulation between the DC poles, and if the insulation resistance is decreased to < 1MΩ due to a fault on the DC side, an external trip signal will be sent to the MCCB on the AC side for clearing the fault [21]. Surge arresters devices are also used for protection against converter/inverter switch faults. For example, a double fault between switches or a fault in (DC/AC) inverter control at AC consumers' side can be protected by surge arresters and fuses or DC breaker [54].



(a) unearthed IT-system LVDC network



(b) earthed TN-system LVDC network

Figure 21: Protection schemes of earthed and unearthed LVDC distribution networks [54]

The protection of the earthed TN-system LVDC network is different from unearthed network. The main differences are the earth fault protection and converter/inverter constructions [54]. For the earthed network, there is no need for IM devices for protecting against earth faults. Short-circuit faults between the DC poles and earth faults are protected by DC fuses on the DC feeders. In order to achieve decoupling between DC system and AC system on the consumers' side, a galvanic isolation (GI) transformer is used between the DC network and the AC consumers network as shown in Figure 21-b.

The performance of such protection arrangements as explained in [9] has been tested on a simplified unearthed LVDC network by simulation and experimental studies against the following different fault conditions: short circuit and earth faults in the consumer AC network, and an earth fault in the DC network. The short-circuit fault in the consumer AC network was cleared within 0.04s by the breaker as shown in Figure 21-a as CB before the load. The earth fault in the consumer AC network was cleared by the IM device at the consumer end within 1.55s. As for the third fault condition earth fault on one of the DC feeders, the fault was cleared by the DC IM device and the breaker on the AC grid side within 5.1s. In the last case whole the LVDC network was disconnected from the grid.

The results of these investigations are useful evidences to prove that conventional protection devices such as fuses and MCCB will not provide fast fault clearance times that can help to make the most of LVDC systems. This protection arrangement and protection operating times have been developed in accordance with the Finish national standard for LVDC applications [25]. It can be clearly noticed that such type of protection schemes have two main drawbacks; one is the relatively long operating times which can be a significant issue as already discussed, and the other is the poor selectivity performance against faults on the DC feeders which will lead to disconnection of all the LVDC network. Therefore, such schemes could still be valid for protecting a simplified radial DC network, but they are not the optimised options for protecting LVDC systems with a high penetration of local generation where the stability of these units will remain a significant issue with such protection performance.

iii. Using unit protection for protecting DC distribution networks

To achieve greater levels of DC fault discrimination and better system performance, the research in [34] has proposed the potential use of unit protection instead of only relying on non-unit protection for protecting DC networks. The proposal is based on that unit protection has a greater level of selectivity and more reliable compared to non-unit protection. In addition, it is less sensitive to the impact of different fault levels and impedances compared to non-unit protection. Another advantage is that unit protection in DC applications will not require phasor measurements and comparison, and only current amplitudes are required. This saves time and increases the speed of protection. Also, the features of the transducers used for dc measurement such as hall affect devices can help to measure the dc current in form of voltages which can be more useful for integration with digital processing devices [34]. Another important factor is the deployment of advanced infrastructures such advanced sensors and communication within distribution networks which can achieve fast measurements of the currents and voltages at different points. This can be used for an accurate synchronization between inputs and outputs of unit protection [34].

Because unit protection does not provide backup protection, the research in [34] has proposed the use of a protection framework that allows the use of non-unit protection alongside unit protection to provide the required backup protection. For example, unit protection can be used for feeders with difficult coordination, and non-unit protection can be used for other downstream devices. Such framework could be used for protecting compact DC systems that can be divided into zones, and upstream unit protection will release constraints on downstream non-unit protection [34]. However, it will be impractical example for LVDC systems. This is simply because the common topology of LVDC is radial in nature and cannot be divided into protected zones as same as in MV and HV systems.

Therefore and based on the above discussion of the all available protection schemes, better protection solution that can provide continuity of supply to healthy parts where other parts of the network are faulted, and offer better selectivity and reliability are required for more effective LVDC performance. The next section discusses advanced protection structure for protecting LVDC networks which can offer much better performance compared to the previous options.

iv. Advanced protection scheme for protecting LVDC last mile distribution networks

With help of the deployment of advanced communication technologies and advanced power electronics, a smarter fast acting protection that has the ability of detecting the presence of fault conditions, initiating the operation correctly, and clearing the fault within required timeframe can be developed. A combination of AC protection on the AC side and fast acting electronic-based DC protection on the DC side will significantly improve the performance of LVDC systems with a high penetration of local generation. The AC protection can be used to protect the system against AC grid faults and providing backup protection for DC protection. The DC protection can be used to sectionalise the DC system and protecting the downstream feeders against DC faults. The converters can be equipped with internal protection for protecting the converter against internal faults and at the same time providing backup protection for downstream DC protection.

As discussed earlier in section 5, semiconductor turn-off SSCB can be used for interrupting DC short circuit currents. These devices will significantly improve the protection operation speed, where they can have immediate hard turnon and off within very few fractions of milliseconds. The devices are more controllable and they can be reset automatically after the fault is cleared to continue normal operation.

The local measurements at each converter station and at each SSCB are used for fast detection and locating DC faults, and for fast fault interruption to limit the spread of DC fault impacts. Each converter must be able to identify if one of its related feeders is faulted or not. This can take the advantage of electronic transducers such as Hall Effect devices and other advanced sensors that can be used for fast measurements across the network.

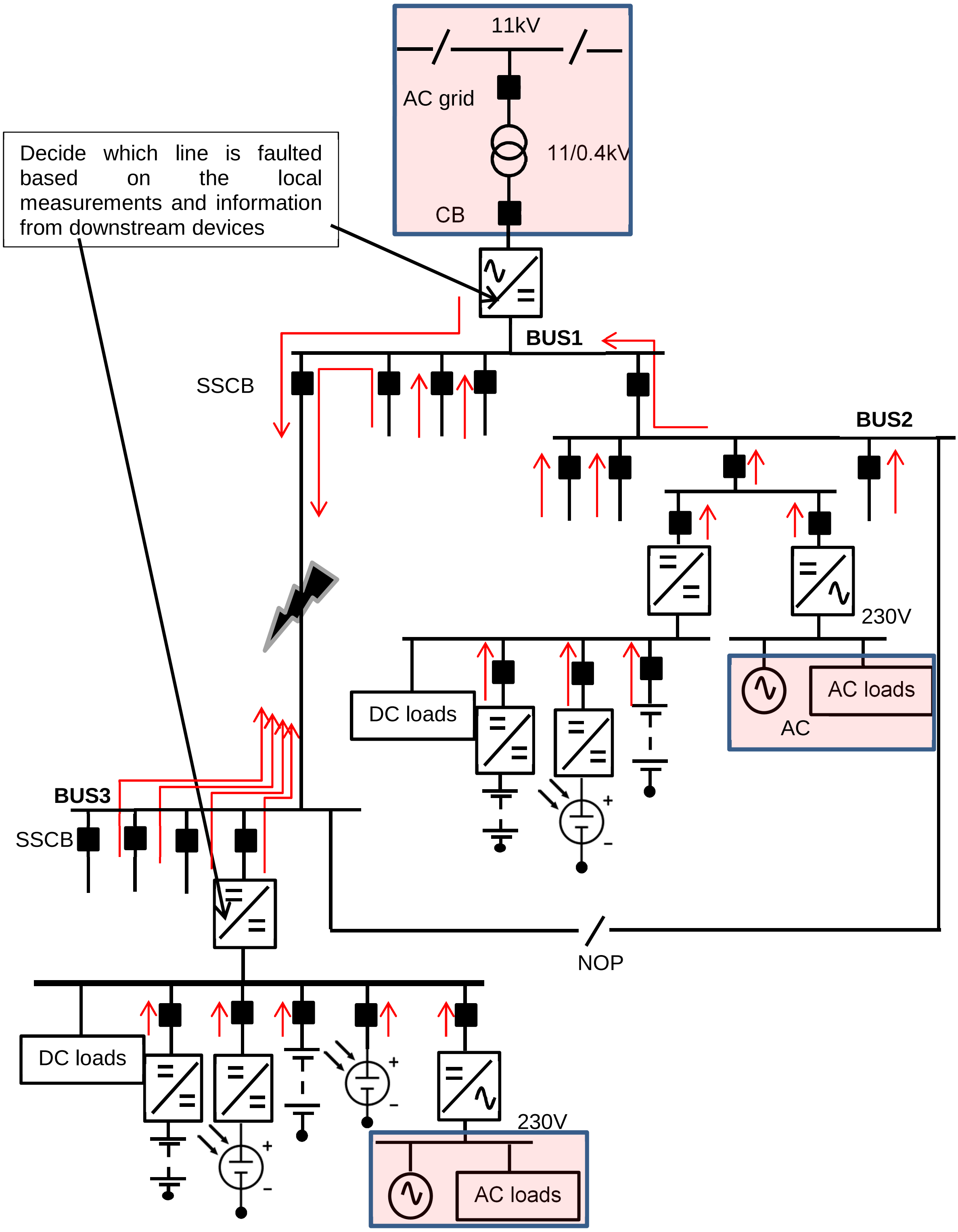


Figure 22: Fast acting protection structure for an LVDC network

Figure 22 above is used to explain the principles of the fast acting protection scheme for protecting an LVDC. During normal operation, all the DC currents in the DC feeders are steady state with $dI_{dc}/dt = 0$. When a DC fault occurs on one of the DC feeders as shown in Figure 22, all the devices on the network will notice the nuisance of the system in different ways. For example, the currents in the feeders will increase with a high rate of change and $dI_{dc}/dt \neq 0$ anymore. High currents with different magnitudes at different parts of the network will be experienced. Also some of the components will experience reverse current with different magnitudes compared to prior fault conditions due to local generation. The AC grid current will also increase and the voltage on most of the DC network will rapidly decrease. Thus all the protection devices including the AC protection, the internal converter protection, and the SSCB will notice the fault. The downstream DC protection devices will experience reverse fault current supplied by local generators, and downstream converters will experience undervoltage conditions. The challenge is how to usefully use this information for fast detecting the fault and isolating only the faulted part by the associated protection device.

The direction of the currents as used in handshaking method can be used for identifying the faulted feeder. For example, the main converter will receive the information from all downstream SSCB. All the SSCBs with positive currents in direction (outward the nodes) will be in contact with the converter to identify which one has the faulted line based on the features of the DC fault current and the local voltages. The faulted line can be identified based on the information of the following current indexes: the peak of the transient discharge current index, the rise time of the first wave front index, and the oscillation pattern index.

- The rate of change of the transient current of the faulted feeder will be the fastest (fastest rise time) compared to other feeders.
- The peak of the transient current of the faulted feeder will be the highest, and the peaks of the transient currents of other feeders will be smaller.
- The currents of the faulted feeder will have oscillation pattern with widest pulses.

In terms of measured voltages, the change in DC voltages can be used simultaneously with the features of DC fault currents for fast detection and interruption of DC faults. If the DC voltage decreases under predetermined values, and the growing DC current passing through the SSCB with positive direction exceeds the threshold values for pre-determined time duration, the SSCB will be turned off and disconnect the fault. Another advantage of measuring the voltage is to distinguish between DC faults and AC fault at consumers' side, where currents and voltages are oscillatory during AC faults.

This proposed protection scheme as structured in Figure 22 will overcome most of the outlined issues in section 5 of the report. The scheme is more selective and reduces the need for interrupting large part of the system in comparison to the pervious solutions as mentioned earlier. Moreover, minimum protection operating time is more feasible with such type of protection. This is important in order to control the post-fault issues and support the capability of microgeneration to ride through different system disturbances. In spite of all these advantages of fast acting protection scheme, the scheme is not the most economical solution. Extra cost and losses introduced by SSCB are expected. However, advanced local measurements and communications between the converters and SSCBs and the flexible controllability of SSCB and converters can be more usefully used for fault management in order to increase the efficiency of the scheme. For example, in addition to fast detection and interruption actions, other added functions such as blocking reverse currents to reduce the fault stress on the network, limiting fault levels, and reclosing for temporary faults can be also achieved. The design and the types of SSCBs at device level which are the key elements of effective fast acting protection scheme is out of the scope of this report, but it has been considered by the authors as further area of research.

7. Conclusions

The report has quantified the potential benefits of LVDC last mile distribution networks, and potential architectures that best utilise existing plant have been also identified. Faulted LVDC networks have also been characterised, and recommendations for improving IEC61660 for better characterising short-circuits on an LVDC have been discussed. In addition, the protection challenges for an LVDC last mile network with a high penetration of microgeneration have been investigated and numbers of alternative protection schemes for protecting LVDC networks have been evaluated. The main key findings are listed as follows:

Finding1: LVDC distribution systems have the potential to bring technical and economic benefits for future power systems, and to be considered as a good enabler of increased penetration of distributed renewables. Better controllability of generation and use of energy can be offered, resulting in overall cost and losses to be reduced, and system efficiencies improved. In addition, better utilisation of existing AC components such as MV/LV transformers and LV cables (through their conversion to DC) for delivering higher power than the corresponding LV AC systems with reduced losses is anticipated as a result of DC voltage and LVDC connection type. However, the disadvantage is that the lifetime of the electronic converter devices will be shorter than traditional network components.

Finding 2: IEC61660 will require further improvement in order to be usefully used for characterising faulted LVDC last mile networks. If an LVDC network is designed in accordance with existing IEC61660 calculations, the network in reality will experience a higher current with longer decay time. This can be an issue in terms of power electronics and equipment ratings, and protection performance. One recommendation for increasing the accuracy of the standard for capturing the transient of DC fault currents is the consideration of the impact of system inductances between DC sources and fault points in the calculation approaches.

Finding 3: traditional non-unit LV protection schemes using LV fuses and conventional breakers are not suitable for providing fast acting protection that can reduce the impact of DC faults. This has been found to be due to the nature of fuses and conventional circuit breakers which take longer time for interrupting DC faults, and due to the reduced fault level caused by the converters for self-protection against high short circuits. Traditional LV protection cannot protect LVDC components during high transient discharge DC currents, and it allows the pass of these currents to sensitive devices. During this transient, rapid depression of DC voltages are resulted, and because of converter sensitivity to undervoltage conditions, substandard coordination between the main converter and downstream protection devices can be experienced. Furthermore, it is also hard to maintain the stability of local microgenerators against remote transient faults, where microgenerators are very sensitive to undervoltage conditions, and have very poor inherent damping. Slow DC protection can also lead to a post-fault power quality issue by causing post-fault high transient spikes of DC voltages enough to affect sensitive devices.

Finding 4: the report has evaluated numbers of protection schemes which have been proposed for protecting different DC power systems. Based on the possibilities and limitations of using these schemes for protecting LVDC last mile networks, a concept of an advanced LV protection scheme has been introduced. The scheme is a communication-based protection with combination of AC and DC protection devices. Better protection selectivity and effective fast acting protection will be offered. It may not be the most economical LV protection solution, but a good performing system is expected. Further research on evaluating and validating the proposed advanced protection is being conducted by the authors.

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