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# Experience from Research into Low Voltage DC Distribution System Protection: Recommendations for Protecting Hybrid HV DC-AC Grids

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This paper presents experience and outcomes of a research project concerned with protecting an LVDC "last mile" distribution network. The paper introduces the following contributions that reduces the risks associated with shifting from AC to DC for LV distribution purposes: understanding of how an LVDC system behaves during fault conditions through presentation and analysis of simulation results; outlining the issues associated with using traditional LV overcurrent protection for protecting future LVDC networks; and simulation of a new DC protection scheme that provides fast dc fault detection and location with a good level of selectivity. In addition, the paper presents a discussion of the lessons learned from the LVDC protection research project and how they can be utilised to understand and address the protection challenges in a higher voltage hybrid DC-AC grid.

## 1. Introduction

The electricity demands and generation are constantly growing, and power systems at transmission and distribution levels have to expand to cope with such growth and at the same time contributing to carbon emissions reduction. DC technologies supported by advanced power electronics and smart controls, and intelligent information communication technologies (ICT) have a key role to play for meeting such changes.

*DC at transmission level:* point-to-point voltage source converter-based high voltage DC (VSC-HVDC) systems have already proven their effectiveness for transferring electricity over long distances in more controllable and efficient manners. Point-to-point HVDC have also enabled the access to many remote energy sources such as offshore wind, and facilitated the connection of different regions such as UK-France and UK-Netherland connections by which and the diversity of loads and sources can be shared in the regions. This is in addition to the capability of HVDC systems to provide a higher power transfer capacity which is important to exploit the connection of rich renewable sources, and reduce congestions in existing AC systems. In order to maximise the benefits of HVDC systems and reduce their associated operating costs, Multi-Terminals VSC-HVDC (MTDC) systems as a next step of HVDC have been recently introduced [1]. Instead of using many point-to-point HVDC links, MTDC can offer more power flow paths with a reduced number of converter stations. Another more advanced concept of HVDC systems is the introduction of a meshed HV "DC grid". It is strongly believed that HVDC grid is more economical and environmentally friendly solutions that can help in realising the "Supergrid" vision to connect the whole Europe and North Africa, and enable the share of different renewable energy resources across these regions [2].

*DC at distribution level:* DC distribution systems have the potential to be used as an alternative to present AC system architectures to facilitate the connection of more renewable and low carbon energy sources, while improving the energy efficiency and power capacities of existing distribution networks. The motivation is driven by the fact that most decentralised renewables, such as photovoltaic, fuel cells, batteries, and variable frequency generation sources either produce DC natively or require DC at intermediate stages prior to interfacing to the AC grid. Such units can often be connected directly to LVDC systems and energy losses and capital costs of interfacing equipment may be reduced. Furthermore, the "digitising" of our world is growing rapidly, and the vast majority of electronic devices operate on low power DC. Powering such devices using existing AC requires many DC-AC conversion stages resulting in increased energy losses and costs. LVDC systems are inherently more suitable to directly power such consumer electronic loads, and advances in power electronics for LVDC applications will also offer better controllability of energy sources and demand. More details on the potential economic and technical benefits of LVDC systems for different applications are given in [3]-[7].

However, integrating DC technologies within existing AC infrastructures is very challenging. A new complex arrangement of mixed AC and DC will be introduced, resulting in significant challenges for operating and protecting the emerged hybrid AC-DC network. To date there are no comprehensive standards for how to configure, operate, and protect such complex systems, and one of the main barriers is an effective and reliable DC protection. This is because new forms and types of faults that make DC protection is more difficult than AC protection will be introduced. Therefore, this paper investigates this issue, and providing the following contributions that reduce the risks associated with shifting from AC to DC:

- insight and understanding of how an LVDC distribution network behaves during fault conditions;
- outlining the effectiveness of using traditional LV overcurrent protection for protecting future LVDC networks; and
- presenting simulation of a new developed DC protection scheme that provides fast dc fault detection and discrimination for a public LVDC distribution network.

Finally, a discussion of the lessons learned from the LVDC protection research project and how they can be utilised to understand the protection challenges in a higher voltage hybrid DC-AC grid will be presented.

## 2. Protection challenges

In general DC faults are very different form AC faults. DC faults are more difficult to be located and interrupted because of the following reasons:

- The polarities of DC current and voltage waveforms do not change overtime (no natural zero crossing points), and this makes DC arcs very aggressive and take longer time to be cleared, resulting in the requirement for higher rating and larger size equipment.
- The resistance of DC lines are very small compared to AC lines, and the line reactance is almost negligible. Thus the impact of these parameters on DC fault will be very limited, leading to rapid propagation of faults across wider areas. This may increase the complexity of detecting and locating DC faults, and lead to substandard selectivity issue.

These DC natural phenomena will have a significant impact on the behaviour of hybrid AC-DC systems. Hybrid AC-DC systems are very complex and consist of a large number of different equipment with different response and capabilities to DC faults. More sensitive devices based on power electronics are introduced. These devices have their own direct impact on the characteristics of DC faults profile. For example, the smoothing capacitors of VSC-based DC systems will generate a high transient current with very high rate of change during the fault. VSCs cannot control such high transient current amplitudes which may flow through the network sensitive components with a significant thermal energy. Another issue is that semiconductor switches have poor short circuit capability, and to protect them from being damaged by short circuits, an additional current limiting circuit is normally integrated within the converters to supply only 120%-200% of its nominal current [8]. Such an operating condition will limit the fault current to the level that may delay the protection operating time, resulting in longer stress on the protected network.

## 3. Fault characterisations of an LVDC distribution network

To date there is no inclusive DC protection standard for a utility DC distribution network at low voltages. The most known models are the static model, the models implemented in ANSI/IEEE guidelines, and the dynamic model represented by IEC61660 [9]. IEC61660 which has been originally developed for DC auxiliary systems of power plants and substations considers the fault response of smoothing capacitors and batteries which can be found in public LVDC networks. However, IEC61660 can be more accurate for calculating the steady-state of the DC short-circuit faults in LVDC networks, and less effective for characterising the capacitor discharging currents in an LVDC network with long feeders [4]. This section characterised the behaviour of an LVDC network under fault conditions using a detailed model of a unipolar LVDC network.

*Test network:* a typical UK LV distribution network shown as single line diagram in Figure1 has been modelled in PSCAD/EMTDC and used for studying the natural response of a number of DC faults at different locations. The LVDC network is assumed to be interfaced to the AC system by a VSC. The VSC has been modelled as a six pulse rectifier with smoothing capacitor on the DC side. This simplification is based on the elimination of the IGBTs switches since the VSC will act as a diode bridge rectifier during short circuits on the DC side, and the IGBTs switches are normally blocked. 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 LVDC test network supplies 612V DC between the two poles, and the parameters of the used LV cables are Rdc=0.164Ω/km, and L=0.24mH/km, and the smoothing capacitor C=6750µF. The AC medium voltage (MV) 11kV network has been modelled using an ideal voltage source and impedance with X/R=5 to provide a fault level of 156MVA at the ring main unit (RMU) supplying the secondary substation. An impedance of 4.5% and rating of 0.5MVA has been used for the secondary substation transformer (11/0.433kV).

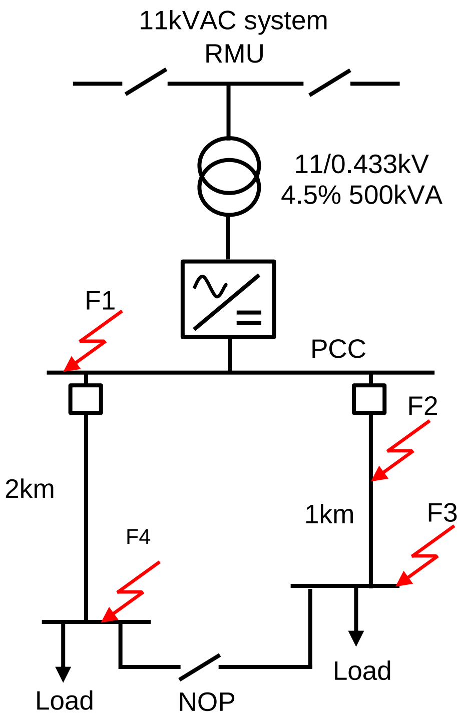


Figure1: LVDC test network model

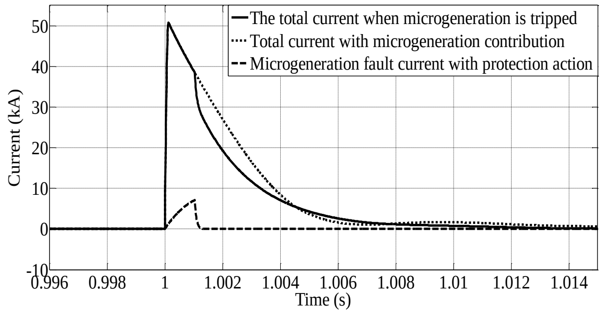


Figure 2: The transient discharge pole-pole DC fault at the PCC with and without microgeneration contribution for the fault F1

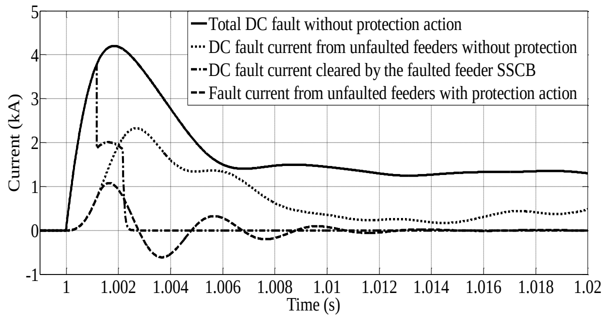


Figure3: Comparison between uninterrupted DC discharge fault current and interrupted fault current by SSCB for the fault F2

A short-circuit fault between the two DC poles is applied at four different locations on the DC side. Fault1shown as F1 in Figure 1, 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. The simulation results for the fault F1 on the terminals of the converter and the fault F2 on the feeder when no protection actions are taken are given in Figure 2 and Figure 3. Very high transient currents are supplied after the faults are initiated, and for the fault at the terminals of the rectifier the peak transient current has reached almost 50kA within less than 4m. The transient currents then decay exponentially followed by steady state fault currents from the grid through the antiparallel diodes. Such DC fault profile with high transient currents up to tens of kAmps may flow through the network components with large thermal energy, resulting in the requirement for very fast speed.

## 4. The effectiveness of using traditional LV protection for protecting an LVDC network

This section investigates the effectiveness of using traditional LV protection for protecting the LVDC network against the DC faults presented in Figure1. The capability of non-unit overcurrent protection based on time-current inverse characteristics (widely used in existing LVAC networks) to detect such DC faults at different locations is evaluated. Each DC feeder is assumed to be protected by an overcurrent (OC) breaker, and the OC been modelled as an extremely inverse time-current characteristic using the component that is available in PSCAD library. The IEEE Std. C37. 112 standard has been chosen for calculating the protection operating times, and the simulation results are given Figure 4.

The results of the protection operating times presented in Figure 4 show that non-unit OC protection based on time-current inverse characteristics can operate only during steady-state periods, and the high peaks of the transient discharge currents with large peaks have passed to the network. Such slow acting protection with longer short circuit stress may increase the requirement for equipment with higher current ratings. Over and above, it will be significantly difficult to maintain the stability of small scale DC microgenerators with such slow acting protection. This is due to the sensitivity of these devices to undervoltage conditions during transient periods. In order to avoid such issues, fast protection that can detect, locate, and interrupt DC faults within time scale less than 5ms will be required. Next section presents an advanced protection scheme that can detect DC faults within time scale less than 5ms, and provide a good level of protection selectivity for LVDC systems.

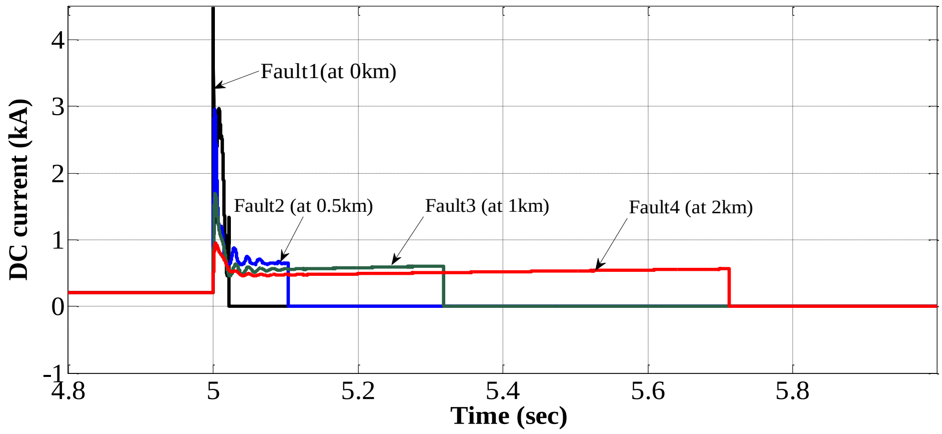


Figure 4: DC fault profiles for faults at different locations and protected by an LV overcurrent protection

## 5. DC protection scheme for fast dc fault detection and discrimination

This section presents an advanced protection scheme that addresses the outstanding challenges in detecting and locating, and fast interrupting DC faults. The initial concept of the scheme was introduced by the authors in [3]. The scheme is communication-assisted and mainly based on the measurement of DC fault currents and voltages magnitudes, and current directions during the fault transient period using multiple Intelligent Electronic Devices (IEDs). Solid state circuit breakers (SSCBs) with an excellent control capability have been used for interrupting the faults. Figure 5 is used for describing the principles of the schemes.

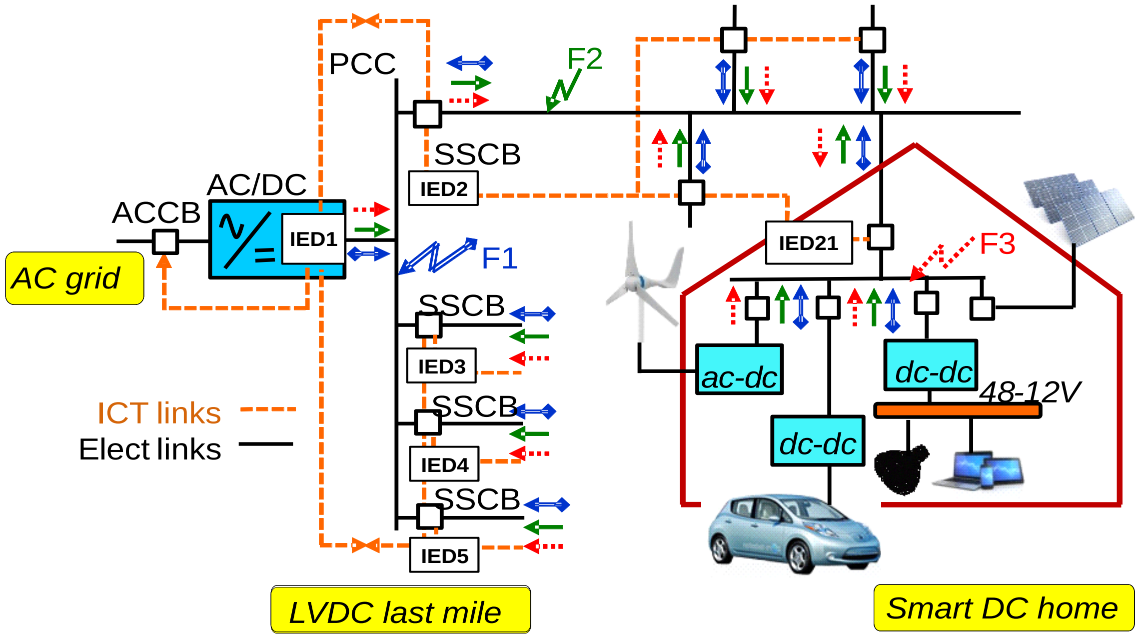


Figure 5: An LVDC network protected by fast acting protection scheme

The fault detection is based on sensing of the rapid increase in the DC currents and the rapid drop in the voltages when a DC fault occurs on the DC side. The IEDs also measure the directions of the currents at multiple locations, and when a fault is detected the directions will be converted to digital signals that can be used for locating the faulted part. It is assumed that the current direction flow towards the downstream is positive and it can be converted to signal “1”, and the opposite current direction is negative and represented by “0”. The faulted part will be located between the IEDs with current direction signal “1” and the IEDs with current direction signal “0”, and experience the highest current magnitude and lowest voltage drop. The protection actions are based on selective tripping signals that can be provided by the associated IEDs and SSCBs, and these signals are controlled by the fault location. For example, during the fault F1 at the main DC bus as shown in Figure 5, the main converter IED1 as shown in Figure 5 will notice the fault with direction signal “1” and the IEDs of the feeders will experience fault currents with direction signals "0". Two min protection actions will be performed. The converter IED1 will send a trip signal to the AC CB on the AC side for interrupting the current from the grid, and the IEDs of the main feeders will remotely trip the all downstream generators for blocking the fault current contribution from these generators. Table 1 and Table 2 give the protection functions that are required from the different relays for the fault F1 and F2 that are shown on the network layout in Figure 5.

| Protection functions | Relays | IED1 | IED2 | IED3 | IED4 | IED5 |
|---|---|---|---|---|---|---|
| | Current directions | 1 | 0 | 0 | 0 | 0 |
| Trip function | | ✓ | - | - | - | - |
| Blocking reverse current | | - | ✓ | ✓ | ✓ | ✓ |
| Reclosing function | | - | - | - | - | - |

Table 1: Converter and main feeder relays performance during fault F1

| Protection functions | Relays | IED1 | IED2 | IED3 | IED4 | IED5 |
|---|---|---|---|---|---|---|
| | Current directions | 1 | 1 | 0 | 0 | 0 |
| Trip function | | - | ✓ | - | - | - |
| Blocking reverse current | | - | ✓ | ✓ | ✓ | ✓ |
| Reclosing function | | - | ✓ | - | - | - |

Table 2: Converter and main feeder relays performance during fault F2

This developed protection approach has been tested through simulation studies using the same model that has been described in section 3. 100% penetration of microgeneration (i.e. meeting all local loads) has been considered for representing the local generation, and they have been modelled as DC current sources connected in parallel with capacitors with C=470µF. While the protection model has used IGBT switch model connected in parallel with a snubber RC circuit, and has a minimum extinction time=30µs. The pickup current and undervoltage of each IED relay have been set to twice of the full load current and to be 85% of the nominal Vdc respectively. A fixed communication delay equals to 1ms has been applied for considering the anticipated communication delay.

The simulation results of fault F1 and F2 as presented in Figure 2 and Figure 3 have demonstrated quick detection and interruption of the DC faults during the transient periods, and at low current levels, resulting in reduced fault levels. The performance of the developed scheme has also been tested on an enhanced low power laboratory rig, and the results will be considered in future publications.

## 6. Protecting hybrid AC/DC grid

Existing AC grids are normally protracted by different protection relays such as directional, ratio, magnitude, and differential relays. Because of the nature of a DC system as discussed earlier, some of these relays may not provide DC protection standards as same as for AC systems. For example, distance protection which is widely used for detecting and locating faults on AC transmission lines may not be viable for DC. Distance protection estimates the line impedance based on the measurement of current and voltage values, and identifies whether the fault is located within its protected zone or not. In DC systems, the line impedances are relatively small, and this makes using impedance relays for locating DC faults is less effective [10]. This can be more complicated in the case of resistive faults where the fault resistance could control the total fault path resistance, resulting in increased errors in the line impedance estimation and protection discrimination.

Alternative methods such as the use of differential protection and signal processing techniques-based such as travelling wave and wavelet have been proposed as suitable approaches for protecting HVDC girds [11]. The issue with differential protection is the communication time synchronisation between the two relays where two remote current values have to be accurately measured and added at the same synchronised time for delivering an accurate protection decision. Long HVDC lines may also increase the significance of this issue, as the communication delay will be larger.

The use of current direction signals for identifying the location of a DC fault as discussed in section 5 for protecting an MTDC grid may potentially address the accuracy issue relating to the communication time synchronisation. In this case no current magnitudes need to be compared, and only digital signals

“0” and “1” representing current directions can be compared. The communication delay can still be an issue, however the accuracy of fault locations will be improved in comparison to differential protection. Figure 6 which present an MTDC network example is used for discussing the effectiveness of using the DC protection method discussed in section 5 for protecting such type of network.

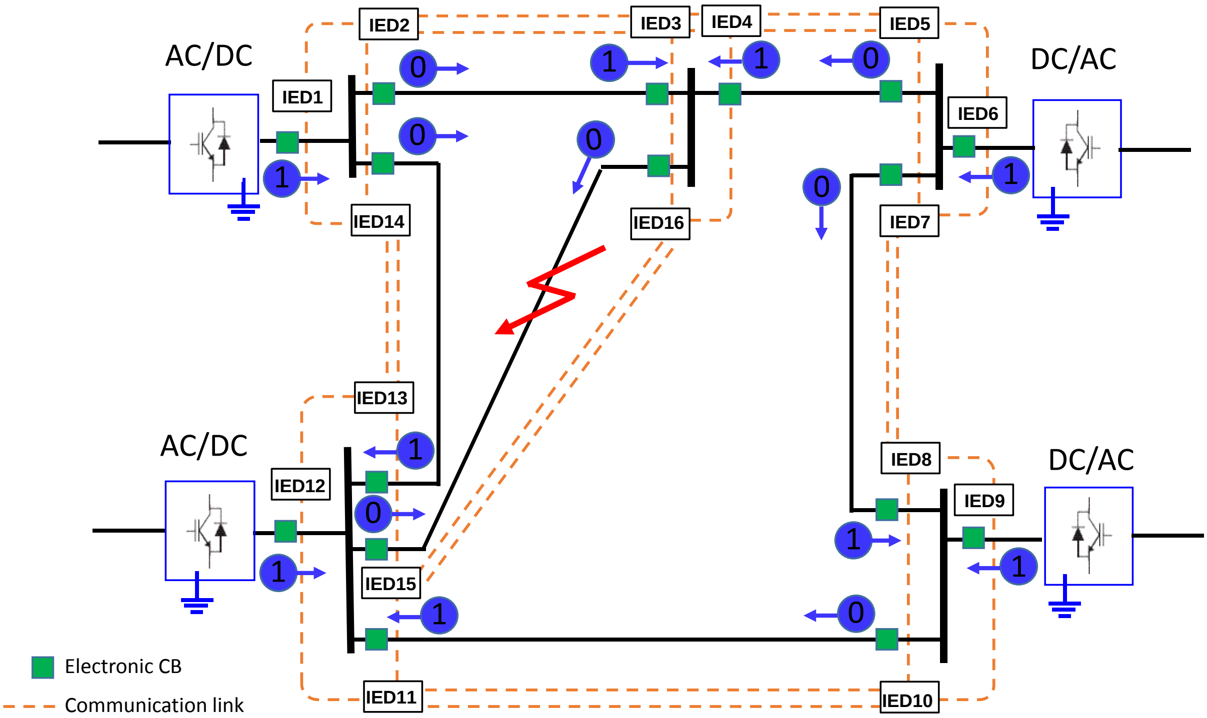


Figure 6: An MTDC network protected by fast acting protection scheme

As discussed in 5, the developed DC protection scheme is based on the use of SSCBs, IEDs, and communication. At HVDC level, the commercialisation of an electronic breaker that can operate within less than 5ms is expected to be seen very soon. The new ABB hybrid breaker has been already prototyped for 320kVdc and with current breaking capability of 9kA, and can operate within <5ms [12]. The philosophy of detecting DC faults in MTDC systems based on the current directions method have to be different from the LVDC last mile applications due to the difference in the configurations between the two systems. In the case of the MTDC shown in Figure 6, the buses will be used as references for identifying the current directions as used in the “handshaking” method which has been introduced in [13]. So, the currents flowing into the bus will be positive and represented by a signal “1”, and the currents leaving the bus will be negative and represented by a signal “0”. In this case, the directions of the currents measured by multiple IEDs and the communication between these devices will accurately enable the identification of the fault locations and also the faulted component type if it is a line or a busbar. Only a faulted bus can be located between IEDs with signals “1”, and only a faulted line can be located between two IEDs with signals “0”. The healthy feeders and buses will be always between IEDs with different current directions “1” and “0”. These are different from the application of the developed scheme of the paper when it was used for the LVDC where the faulted component has to be between the IEDs with different direction signals.

Unlike the “handshaking” method [13], the interrupting of the DC fault has to be on the DC side and not from the AC side, and only with electronic-based CBs, fast interruption and protection <5ms can be realised. In this case, a master IED for each bus and each line is required to compare the digital direction signals for locating the fault and controlling the tripping signals for disconnecting only the faulted part. For example, for the fault shown on Figure 6, only the line between the IED15 and IED16 has two similar current direction signals “0”. The IED15 or IED16 has to be set as a master relay for comparing the direction signals between these two IEDs, and provide the trip signal for the two breakers at the two ends, and perform other protection functions such as reclosing if required. This concept will be investigated and developed by the authors in future work.

## 7. Conclusions

The paper has presented how integrating LVDC systems within existing AC grids will present significant protection challenges, and characterised the response of a faulted LVDC network system with a high penetration of microgenerators. Very high DC transient fault with peaks up to tens of kAmps and with very high rate of change will be passed through the network during DC pole-to-pole faults. The paper has also concluded that using DC overcurrent-time protection schemes based on fuses and mechanical breakers will not provide fast protection that is required to interrupt the DC fault during the transient period. Such slow protection acting will make the system to experience longer short circuit stress and the converters to be defenceless against high transient DC faults. This will increase the requirement for more expensive equipment with higher current ratings, and create power quality issues by generating high post-fault transient voltages on the healthy feeders. In addition, the paper has presented a new protection solution which provides the fast and selective tripping required of enabling future LVDC last mile distribution networks. The concept of utilising this developed LVDC protection solution for protecting a higher voltage MTDC grid has been discussed, and the required improvement for the proposed scheme to be used for larger DC grids has been outlined.

## 8. Acknowledgement

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