Power-System Level Classification of Voltage-Source HVDC Converter Stations Based Upon DC Fault Handling Capabilities

Citation for published version:
Judge, P, Chaffey, G, Wang, M, Zerihun-Dejene, F, Beerten, J, Green, TC, Van Hertem, D & Leterme, W 2019, 'Power-System Level Classification of Voltage-Source HVDC Converter Stations Based Upon DC Fault Handling Capabilities', *IET Renewable Power Generation*, vol. 13, no. 15, pp. 2899-2912. https://doi.org/10.1049/iet-rpg.2019.0462

Digital Object Identifier (DOI):
10.1049/iet-rpg.2019.0462

IET Research Journals

Journals
The Institution of Engineering and Technology

Power-System Level Classification of Voltage-Source HVDC Converter Stations Based Upon DC Fault Handling Capabilities

ISSN 1751-8644
doi: 0000000000
www.ietdl.org

P. D. Judge[1]* *G. Chaffey*[2] *M. Wang*[2] *F. Z. Dejene*[2] *J. Beerten*[2] *T. C. Green*[3] *D. Van Hertem*[2] *W. Leterme*[2]
[1] *Institute of Energy Systems, School of Engineering, University of Edinburgh, EH9 3DW, U.K.*
[2] *EnergyVille/Electa Research Group, Electrical Engineering Department ESAT, KU Leuven, Heverlee 3001, Belgium*
[3] *Department of Electrical and Electronic Engineering, Imperial College, London SW7 2AZ, U.K.*
* *E-mail: pljudge321@gmail.com*

Abstract: To date, numerous concepts for converter station designs for use in Voltage Source Converter (VSC) based high-voltage direct current (HVDC) systems have been proposed. These differ not only in converter circuit topology, sub-module design and control scheme, but also in AC-or-DC switchgear and other auxiliary equipment. In the main, the existing literature categorises these converter stations according to just the converter circuit technologies and controls. However, for the development of network codes and to enable systematic network studies, a system-focused and technology-independent classification is needed. As such a classification does not yet exist, this paper proposes a new framework which categorises VSC station designs according to their capabilities during a DC-side fault and the method by which post-fault restoration may be achieved, given that these are the main differentiating factors from a system perspective. The classification comprises six converter station types and three time-intervals through which to fully characterise a design. Many well-known forms of converters are used as case studies, and simulation results are used to exemplify the classification framework. The outcome is a generic and technology-independent way of characterising converter station designs that is useful in wider power-system analysis but also for putting proposed converter stations into context.

1 Introduction

Voltage Source Converter (VSC) based HVDC systems are increasingly used in modern power systems and are a key-technology for directly integrating renewable technologies into modern power systems [1, 2], as well as unlocking the system flexibility required to facilitate wide-scale system integration of renewable resources [3]. They are used as point-to-point links between asynchronous AC networks, connections of offshore renewable energy sources, embedded links for transmission infrastructure enhancement, and in the form of multi-terminal HVDC networks which combine several or all of these applications [4, 5].

For these VSC HVDC systems, the Modular Multilevel Converter (MMC) [6, 7] has emerged as the dominant converter topology, supplanting previous generations of two- and three-level converters due to its high efficiency, controllability and modular design. This topology has been explored in detail in the literature, with focus on sub-module (SM) design [8–14], control design [15–18] and capacitor sizing [19–21]. Numerous other converter topologies derived from the MMC have also been proposed, either with different SM types [22, 23] or hybrid topologies [24–28].

As MMC-based VSC systems increase in maturity, efficiency, voltage level and fault handling, the extension to multi-terminal and meshed HVDC networks is increasingly considered [5]. At present, two multi-terminal HVDC networks have already been implemented, albeit at relatively low overall power [29, 30]. The Zhangbei HVDC grid project is expected to be the world's first multi-gigawatt multi-terminal VSC HVDC network, with a combined overall power processing capability of 7.5 GW [31]. One of the key remaining challenges in implementing multi-terminal and meshed HVDC networks is the requirement for the system to react to DC-side faults in ways that preserve as much of the original functionality of the network as possible.

The converter station - formed of the VSC plus any AC or DC switchgear and additional auxiliary circuits - can give rise to widely different responses to, and capabilities during and after, a DC-side fault. Currently, many different technologies for clearing DC-side faults have been proposed by both industry and academia. These make use of various converter design options [24, 32, 33], fault clearing equipment such as AC or DC circuit breakers [34–39], or other auxiliary equipment [40]. Furthermore, numerous options for converter control exist, increasing the number of possible converter responses during and after a DC-side fault [41, 42].

The responses and capabilities of the converter station impact several network performance criteria, including the duration for which fault current is fed from the AC-side of the converter station, the reactive power support that the converter station is capable of providing to the AC system during a DC-side fault, the required response of the HVDC network protection, and the speed and method by which post-fault DC voltage and thence power-flow recovery may be achieved. All of these could have significant impact on the stability of future power systems that incorporate multi-terminal HVDC networks [43]. To facilitate a multi-vendor market with several suppliers of converter stations it will be necessary to establish network codes that define converter station responses to key events and can be used to specify functional requirements. These would also establish a context in which new converter station designs could be compared to existing designs. Further, generic models are required that capture the key features of converter stations for use in systematic network studies similar to existing generic models for wind turbines used in dynamic studies [44]. In [44], wind turbine generators have been categorized into four basic types based on the technology used for the wind turbine generator, its control and the resulting grid interface. Due to the vast range of potential converter station topologies that exist, it is considered imperative that the classification of HVDC converter stations be technology- and vendor-independent, and so, unlike the wind-turbine classification system, a capabilities focused classification for HVDC converter stations is proposed. For such a specification or standard to be developed, the variety of converter station responses to events such as faults needs to be acknowledged and categories of converter must be defined in which the key differentiator is their capability during and following DC-side faults. Indeed, after fixing certain design choices such as the converter topology, the response to DC-side faults is largely defined and cannot be substantially changed by modification of equipment ratings or control as would be the case for adjusting operation in normal conditions or in response to AC-side faults. However, to date, none of the existing literature which compares VSC topologies, e.g., [22, 24, 32, 33, 45–49], take into account all capabilities during and after DC-side fault clearing in a comprehensive and general manner, but instead tend to categorise converter topologies or stations according to circuit technology, internal control, number of semiconductors and losses incurred. Some specific work has been done comparing converter/sub-module designs that are capable of achieving DC fault blocking [24, 41, 50–52], as well as STATCOM capability during DC pole-to-pole faults [48], however these works focus purely on these specific capabilities and consider only the converter design itself. Crucially, this paper takes into consideration the power-system level capabilities of the whole converter station, which are determined by a combination of the physical characteristics of the converter itself, any DC switchgear included, any AC switchgear included (if used in the event of a DC-side fault), other auxiliary equipment, and the overall control scheme adopted.

This paper proposes a classification of VSC stations based upon their capability during and after a DC-side fault. The aims of the classification are threefold:

- To enable generic technology-independent modelling of VSC stations in AC and DC power system studies while recognising the potential large variety of designs.
- To support the development of converter station specifications in future AC and VSC HVDC system grid codes.
- To create a framework for the comparison of new converter station topologies against existing types.

To categorise VSC converter stations in a generic and technology-independent way, this paper proposes six generic converter station types based upon their capability during a DC-side fault to (i) operate as a STATCOM (i.e. generate reactive power), (ii) control rectifying DC current and (iii) control inverting DC current. Furthermore, this paper defines three time intervals that also play a role in comprehensively classifying the capabilities of a converter station given a particular network within which it should operate. These intervals are based upon the (i) time taken for the converter station to drive its DC-side current to zero during a DC-side fault, (ii) the time taken to achieve STATCOM mode operation during a DC-side fault, and (iii) the overall time to restore the DC voltage post fault-clearance. This classification is intended to enable generic modelling of VSC stations in AC and DC power system studies, to support the development of converter station specifications in future VSC HVDC system grid codes and also provides a generic framework for the comparison of new converter station topologies against existing solutions.

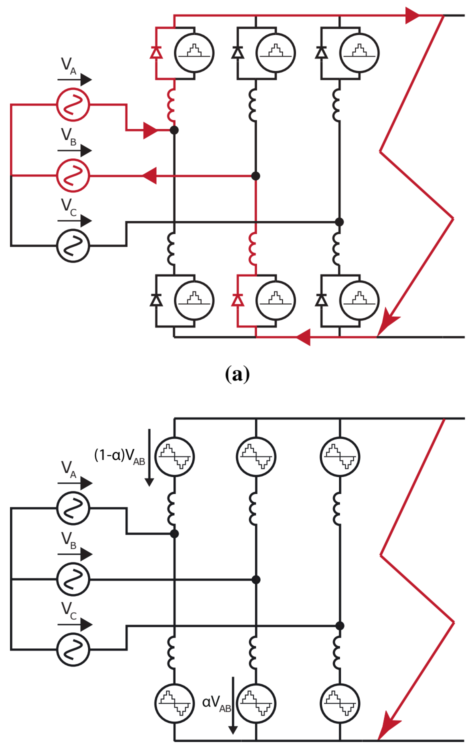
The paper first provides a review of existing technologies and discusses how these impact the capabilities of the converter station. Thereafter, the paper proposes six generic converter station types and explains the classification framework used to derive these. Next, the paper provides examples of the six types using the converter station technologies drawn from those in use today or proposed in the literature. Finally, a case study is performed to demonstrate the application of the proposed classification framework in an example HVDC grid to specify required converter types in a technology-independent way.

2 Technology Review

Before discussing the classification of converter stations according to their DC-side fault handling capabilities, this section first discusses the physical and operational characteristics identified as relevant for each converter station component.

2.1 Converter and Sub-Module Topology

The capability of the converter to generate a counter-voltage to oppose the AC line voltages while the voltage at its DC terminals is zero (or depressed to a value close to zero) determines the AC-side fault current contribution of the converter to a DC-side fault [53]. If the converter is not capable of opposing the AC line voltages (e.g., in the case of the half-bridge MMC [6]), uncontrolled rectified AC current is fed into the DC-side fault (Fig. 1a). Converters which are incapable of generating sufficient negative voltage in this condition are referred to within this paper as fault-feeding converters (FFC). Converters with sufficient negative voltage capability for faults at their DC terminals are able to prevent AC-side fault contributions to all DC-side faults (Fig. 1b). DC fault blocking can be achieved in two ways, namely uncontrolled or controlled. Uncontrolled DC fault blocking relies upon the passive insertion of the sub-module (SM) capacitor voltages into the fault current path to drive the currents flowing through the converter to zero, e.g., by de-gating all semiconductor switches during a DC-fault. Controlled DC fault blocking implies remaining in an actively switched state whilst preventing the AC network from contributing to the DC fault current. In controlled DC fault blocking, the converter thus retains control of its currents.



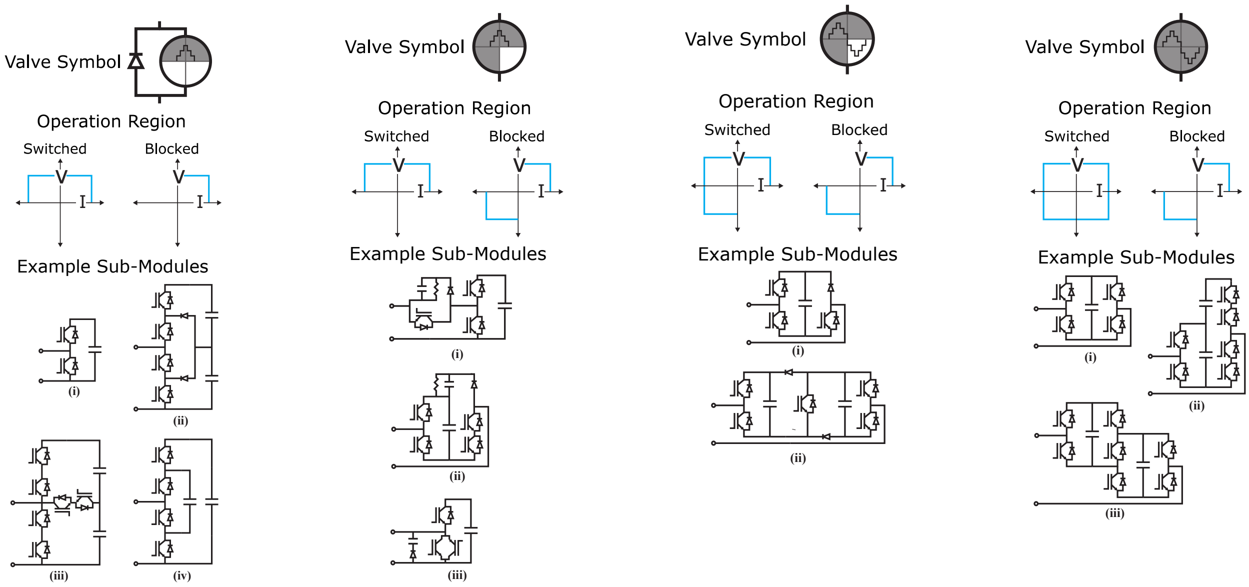
(a)

(b)

Fig. 1 *Voltage capability requirements of modular converter topologies to prevent uncontrolled rectified current contribution to a DC-side fault. Example fault current path shown in red. a) Example of topology without negative voltage capability resulting in a fault current feeding converter. b) Example of topology with negative voltage capability resulting in a converter that can control or block the DC-side fault current.*

The voltage capabilities of modular multilevel style converters are determined by the types of SMs that form the valves within the converter. Numerous SM types have been proposed in the literature and have been extensively described [24, 33, 42]. In addition, SM topologies have been proposed that have multiple capacitors and, consequently, multiple voltage output levels [42, 54]. For the purpose of this paper, which focuses on the overall system-level converter station capabilities, four different multilevel valve types have been identified (Fig. 2). To the best of the authors' knowledge, these four valve types are representative of every known SM type at the valve level.

The first valve type identified is the two-quadrant valve, Fig. 2a, and is capable of generating voltages in the first two quadrants in the V-I-plane when its SM are being actively switched. It can generate voltages in only the first quadrant when its SMs are blocked. The most common SM of this type is the half-bridge SM (Fig. 2a(i)). Other examples of SMs of this valve type are multilevel SMs



(a) *Two-quadrant* **(b)** *Two-quadrant with reverse blocking capacitor sub-modules* **(c)** *Three-quadrant* **(d)** *Four-quadrant*

Fig. 2 *Generalised multilevel valve symbols, associated operation region diagrams in passive sign convention, and example sub-modules that could be used to form each valve type. Note that depending on the sub-modules, or combination of different sub-modules, which are used to form the overall valve, the valve may have asymmetric voltage capabilities.*

based upon flying capacitor or neutral point clamped arrangements (Fig. 2a(ii)-(iv)) [32, 55–57]. In the event of a DC-side fault a converter with this type of valve will feed rectified AC current into the fault, and so must rely on either AC or DC switchgear, or auxiliary circuits to interrupt this fault current.

The second identified valve type is the two-quadrant valve with reverse blocking capacitors, Fig. 2b. Under active switched operation this valve has the same capabilities as the two-quadrant valve. When it is blocked, however, it is capable of generating a negative voltage in the third quadrant due to the addition of a reverse blocking capacitor inserted into the current path. The reverse blocking capacitor is typically an order of magnitude smaller in capacitance than the primary SM capacitor. A defining feature of this valve type is that it is only capable of generating a negative voltage in its blocked state, and so its negative voltage capability cannot be used to actively control current. Examples of SMs which could be used to form this valve type are shown in Fig. 2b(i)-(iii) [58–60]. A converter with this type of valve is capable of interrupting DC fault currents flowing through it while its DC bus voltage is below the natural rectification voltage, but is not capable of controlling any of its internal currents while it does so.

The third valve type identified is the three-quadrant valve, which is capable of generating voltages in the first three quadrants during switched operation, and in the first and third quadrant when blocked. Generating voltages in the third quadrant during switched operation relies upon semi-blocked SM states, where a portion of the IGBTs within each SM are blocked, while the remaining IGBTs remain actively gated [61, 62]. Examples of SMs which can be used to wholly or partially form this valve type are the sparse full-bridge (Fig. 2c(i)) [53] and the clamped double SM (Fig. 2c(ii)) [50]. Converters with this type of valve are capable of controlling their DC-side currents during a DC-side fault. They can at the same time also partially control their AC-side currents, but this inherently results in rectified DC current [61, 62].

The last valve type identified is the four-quadrant valve, which can generate voltages in all four quadrants during switched operation, and voltages in the first and third quadrant during blocked operation. The most common example of this valve type is the full-bridge SM (Fig. 2c(i)). Other examples of SMs of this type typically have asymmetric voltage capabilities (Fig. 2c(ii)-(iii)) [32, 63]. Converters with this type of valve are capable of controlling both their DC and AC side currents in the event of a DC-side fault.

Hybrid multilevel valves, which combine two or more different SM types, have become one of the most prominent proposed solutions for achieving DC-fault tolerance without significantly compromising the overall efficiency of modular converters [24, 26, 64–66]. These valves are able to block or control a DC fault current by combining a two-quadrant SM (or series IGBT switches in the case of the alternate arm converter) with a sufficient number of SMs capable of generating a negative voltage. Assuming a sufficient number of SMs with negative voltage capability to oppose the AC line voltage, the overall capability of a hybrid valve can be described based upon the SM type used to generate the negative voltage. Similarly, the overall capability of valves formed of multi-SM structures, e.g. [28, 67], can be described based upon the SM types included within the multi-SM structure.

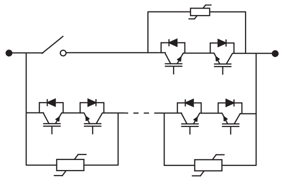
2.2 *Circuit Breakers and Switchgear*

Switchgear, as part of the converter station, can be broadly classified into circuit breakers, load switches and disconnect switches. The former two have the capability of interrupting a short-circuit or load current, respectively, whereas the latter has no current interruption capability.

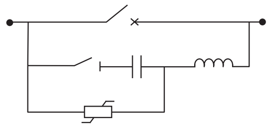
AC circuit breakers (ACCB) are the only AC switchgear considered in this paper, as they are the standard equipment used for DC-side fault interruption in existing point-to-point or multi-terminal HVDC networks [68, 69]. Upon opening they completely isolate the converter station from the AC system, and, consequently, must be re-closed before the converter station can exchange reactive or active power with the AC system [70].

DC switchgear includes DC circuit breakers (DCCB), DC load switches and DC disconnecting switches. DC load switches and DC disconnecting switches have been installed in existing Line Commutated Converter (LCC) and VSC HVDC systems to provide load current transfer and isolation functions, an overview of which is given in [71].

Because the fault current of DC-side faults exhibits no natural recurring zero crossings, DCCBs must be capable of absorbing



(a) *Example topology with fault current limiting*



(b) *Example topology without fault current limiting*

Fig. 3 *Example DC circuit breaker topologies.*

the stored energy within the circuit that is being isolated. Therefore, in practical realisations, the basic DCCB structure includes at minimum two parallel branches: a branch for load current and commutation, and a branch for energy absorption [34]. The load current and commutation elements are responsible for carrying and interrupting load and fault currents, respectively. The energy absorption branch absorbs the energy stored in the circuit during interruption of the fault current.

Numerous DCCB topologies have been proposed to fulfil the need of individually protecting transmission lines in future meshed HVDC grids, e.g. [34, 39, 72–74]. DCCBs can be distinguished based upon their ability (or inability) to operate in fault current limiting (FCL) mode. The FCL mode is achieved by active regulation of the impedance which the DCCB presents to the network. Within known topologies, active regulation can be achieved by DCCBs which use modules of self-commutating switches in the commutation branch, e.g. [36, 39, 75], Fig. 3a. Other known types of DCCBs do not have FCL capability, e.g. [73, 76–78], Fig. 3b.

2.3 Auxiliary Circuits

Some converter topologies proposed in the literature include additional auxiliary circuits which influence the response of the converter station to a DC-side fault. Notable examples of such are the solutions proposed in [40, 79], which use thyristor-based circuits to create a low impedance symmetrical fault on the AC side of the converter during a DC-side fault, and the thyristor-based bypass circuit presented in [80], which is used in conjunction with a fast DC-side disconnect switch during DC-side faults.

3 Converter Station Classification Framework

The power-system level capabilities of a converter station can be divided into AC-side and DC-side capabilities. The requirements for AC-side capabilities have been well defined in various network codes, e.g. as done in the ENTSO-E Network Code on high-voltage direct current connections [81]. The categories in [81] are (i) Active Power Control and Frequency Support, (ii) Reactive Power Control and Voltage Support, (iii) Fault Ride Through, mainly for AC-side faults, (iv) Control requirements e.g., converter energization, system interactions, power oscillation damping, (v) Power System Restoration, mainly related to black-start of connected AC systems. Given the relatively recent appearance of the first multi-terminal DC networks, required power system-level capabilities at the DC-side are less documented. The capabilities at the DC-side could be categorized into active power control, DC voltage control, control for DC-side ancillary services and DC-side fault ride through and restoration.

This paper proposes six types to categorise converter stations according to their system-level characteristics, i.e. at both the AC- and DC-sides, during DC-side faults. The capabilities during and following DC-side faults are the key aspect differentiating converter stations, and are therefore taken as the basis for the proposed classification. Whilst there are numerous differences between converter station designs (e.g. converter topology, transformer winding configuration, grounding system, switch-gear present, control schemes), these design aspects do not result in fundamental differences from the system perspective during normal operation or following AC-side disturbances.

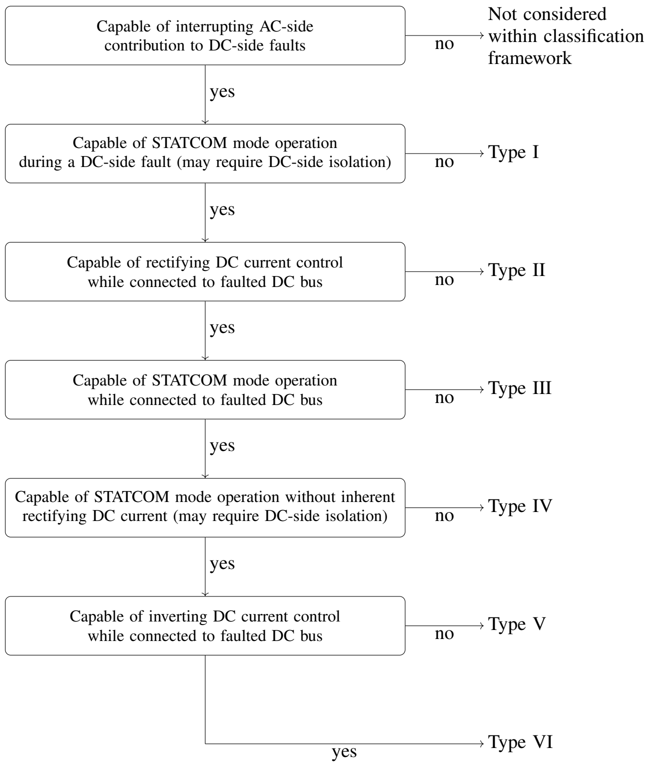


Fig. 4 *Converter station classification framework.*

The converter station types are derived using the classification framework of Fig. 4. Converter stations which are incapable of interrupting or preventing AC contribution to DC-side faults are considered infeasible given that all HVDC converter stations will have some means of self-protection. The classification alone, although distinguishing the functional features of the converter station, is not enough to fully describe a converter station given that the timings related to each characteristic could result in critical differences in system impact. Specification of time intervals are therefore also included with the classification to further distinguish converter station designs or requirements.

3.1 Converter Station Capabilities during and following DC-side Faults

Depending on topology and/or configuration (e.g., converter and SM topology, current controller, circuit breakers or switchgear and auxiliary circuits), the station can present various capabilities to the AC and DC systems to which it is connected during and following a DC-side fault. In the following subsections, the capabilities essential for the classification framework are discussed, together with the potential benefits of these capabilities for the connected systems. No judgement is made on whether all of these benefits apply, or indeed whether all of these capabilities are required, for a specific interconnection of AC and DC power systems.

3.1.1 Interruption of AC-Side Contribution to DC-Side Faults: The first capability identified is the ability to interrupt or prevent contribution of AC-side current to DC-side faults. This capability is the minimum requirement for inclusion in the proposed classification system. The speed at which this prevention or interruption can be achieved influences the peak current contribution from the converter station to the DC-side fault, and, in case the converter behaves as an uncontrolled rectifier during the fault, the duration for which a DC-side fault appears as a three-phase fault to the AC systems.

3.1.2 STATCOM Mode Operation: The second identified capability is the ability of a converter station to operate as a STATCOM (i.e provide reactive power support) while the HVDC network is faulted. This capability may have advantages in terms of increased AC system voltage stability and control during the fault ride-through process [82, 83], as well as allowing the converter stations to provide other ancillary services while there is a fault on the HVDC network, such as power system oscillation damping using reactive power modulation [84, 85]. The precise form of converter topology will dictate whether the ability to act as a STATCOM is temporarily interrupted during the initial fault transient and whether STATCOM mode operation may also have to be interrupted during post-fault recovery, if the converter station is used post-fault to re-charge the HVDC network.

3.1.3 Rectifying DC Current Control Capability: The third identified capability is the control of the DC-side current in the rectifying direction during a DC-side fault. Two potential applications of the capability are identified here. First, the ability allows a converter station to maintain a desired DC-side fault current level or to inject a pulse of current into the DC-side, which may be useful for fault location purposes, e.g., similar to the technique proposed in [86] for medium-voltage DC shipboard systems. Second, this capability is also associated with the ability to actively recharge the HVDC network as part of the post-fault recovery [87], which otherwise might require current limiting resistors or other auxiliary circuits and switchgear. This capability can therefore be expected to significantly influence the manner and speed in which post-fault restoration of the HVDC network can take place. Further discussions of this will be given in Section 3.5.

3.1.4 Inverting DC Current Control Capability: The fourth identified capability is the control of DC current in the inverting direction during a DC-side fault. A potential application of this capability is the active quenching of arcing faults, achieved by driving the polarity of the DC system slightly negative when a DC-side fault is detected [88–90].

3.2 Example Converter Station Topologies and Simulation Results

This section provides a detailed description of selected examples in each of the proposed converter types, and simulation results for a subset of these to highlight their capabilities. The system and converter circuit parameters for the simulations are shown in Table 1, and a converter control scheme similar to the one presented in [91] is used. When converters with hybrid multilevel valves containing more than one SM type are simulated, a 50:50 split of half-bridge to other SMs is used. Typical interruption times for the switchgear associated with a converter station are shown in Table 2, along with the ones chosen for the simulation.

An AC system with a high short circuit ratio is used to show indicative peak DC-side fault current levels. For each result a low impedance pole-to-pole fault at the converter station terminals was used. Pole-to-ground faults are not considered here, as, in asymmetric monopolar or bipolar configurations, similar results would be obtained and in symmetric configurations, pole rebalancing following the fault are not expected to require additional types in the classification framework. A pole-to-ground fault results in a voltage imbalance on the HVDC network, following which rebalancing would be required before resuming normal operation. Pole rebalancing involves either external equipment in form of a dynamic breaking system or can be added to the converter station design in the form of a path for zero sequence currents and an associated controller [92]. In the case of converters with fault blocking capability, the approach to deal with pole-to-ground faults does not result in the need for an additional type to differentiate its capabilities compared to those available with pole-to-pole faults [93].

3.2.1 Type I: Examples of converter station topologies that fit within this type are FFCs, such as a half-bridge MMC (or MMC using other two-quadrant valves) [6] or a two- or three-level converter [100], used in conjunction with ACCBs (Fig. 5a) [101]. Another converter station topology which fits within type I is an

Table 1 Parameters of AC/DC system and converter station used in simulation results

Parameter	Value
Converter Rated Power	960 MW
DC Voltage	$\pm$320 kV
AC Primary Side Voltage (L-L RMS)	400 kV
AC Converter Side Voltage (L-L RMS)	380 kV
AC X/R Ratio	7
AC Short Circuit Ratio	10
Transformer Leakage Reactance	0.14 pu
Arm Inductors	0.15 pu
Nominal SM Voltage	7.28 kV
Number of SMs per Arm	93
Equivalent Stored Energy	30.8 kJ/MVA
Overcurrent Limit	2.25 kA

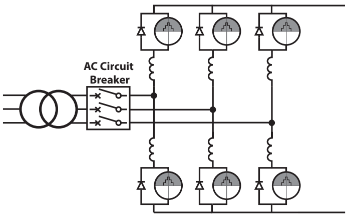
Table 2 Switchgear parameters used in simulation results

Technology	Parameter	Selected simulation value
AC circuit breaker	**Rated break time**	
SF_6, air blast, oil	40 $\sim$ 60 ms	40 ms
DC circuit breaker	**Breaker opening time**	3 ms
Passive resonant	$\geq$ 20 ms [94, 95]	
Active resonant	5 $\sim$ 10 ms [76, 96]	
Hybrid	2 $\sim$ 3 ms [39, 72, 73]	
Power electronic	$\sim$ few μs [97]	
DC disconnect switch	**Opening time**	2 ms
Ultra fast mechanical disconnect switch	2 ms [39, 98]	
High-speed switch (as disconnect switch)	2 $\sim$ 30 ms [99]	

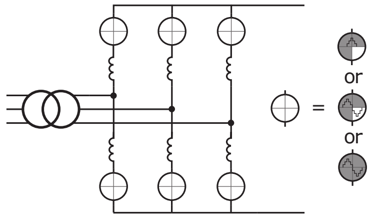
MMC that contains multilevel valves capable of generating voltage in the third quadrant (either of two-quadrant with reverse blocking capacitors, or three- or four-quadrant) - Fig. 5b - in which the interruption of the AC contribution to the DC-side fault is achieved by blocking the converter rather than using active current control. From a functionality perspective, the main distinction between these two options is the time taken to interrupt the DC fault current. For the converter topologies that use three- or four-quadrant valves, the defining feature that distinguishes the capabilities of the converter is the control scheme applied, with additional capabilities achievable if the converter is kept actively switching during the DC-side fault. Two-quadrant valves with reverse blocking capacitors are not capable of generating a negative voltage under actively switched operation, and so additional capabilities cannot be achieved.

Simulation results for both examples within this type are given in Fig. 6a-b. For the example of an FFC with an ACCB the depressed voltage at the converters' DC-side results in the lower anti-parallel diode in each SM conducting an uncontrolled fault current. The converter is unable to control its arm currents due to an inability to insert a negative arm voltage to oppose the AC line voltage. Before the ACCB operates, the large current that flows from the AC-side into the fault depresses the AC-side voltage and appears to the AC system as similar to a three-phase AC fault. Following the operation of the ACCB, the inductors within the fault current path (arm, DC-side and line inductances) remain energised and cannot discharge instantaneously, resulting in a sustained DC fault current. The discharge time constant is inversely proportional to the resistance in the current path, and therefore the longest discharge is experienced during a terminal fault, i.e., with the lowest resistance. The inductors must discharge before the fault is cleared, and in some cases the discharge could take in the order of hundreds of milliseconds [102]. Methods have been proposed to insert resistance into the arm to reduce the discharge time [103], however a significantly quicker discharge is not expected to be achievable without a large penalty in steady-state losses and additional equipment.

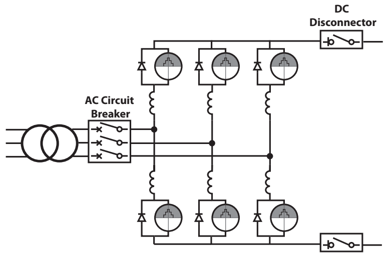
Although the blocking converter example loses current control immediately after the inception of the DC-side fault, the DC fault current is quickly limited due to the fast blocking action. In blocked mode, the three- or four-quadrant SMs output their nominal voltage, whereas the two-quadrant valve with reverse blocking capacitors inserts its capacitors into the current path, each of which charges until their total voltage supports the negative AC line voltage. The



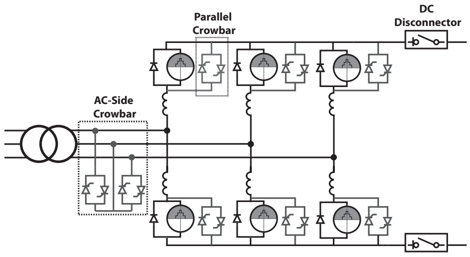
(a) ***Type I Example 1*** *- FFC with two-quadrant valves and AC-side CB*



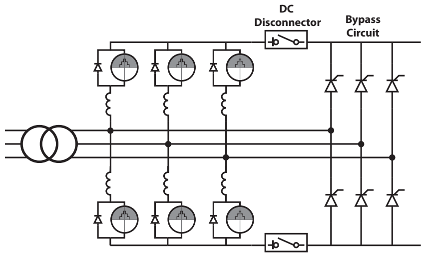
(b) ***Type I Example 2*** *- MMC with valves capable of generating voltage in third quadrant and blocked operation during DC fault*



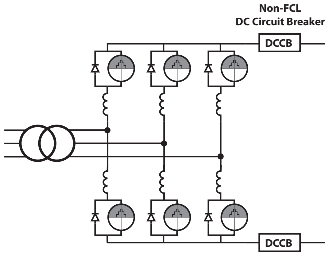
(c) ***Type II Example 1*** *- FFC plus AC-side CB and DC disconnector*



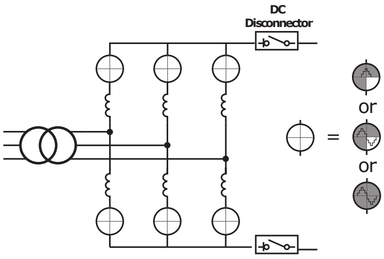
(d) ***Type II Example 2*** *- FFC plus thyristor-based crowbar circuit and DC disconnector*



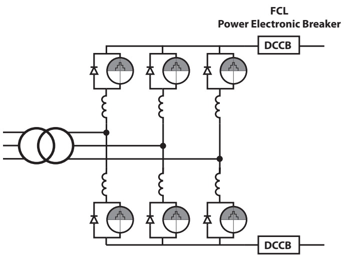
(e) ***Type II Example 3*** *- FFC plus hybrid bypass circuit and fast DC disconnector*



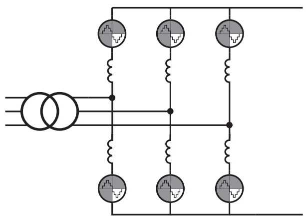
(f) ***Type II Example 4*** *- FFC plus non-fault-current-limiting DCCB*



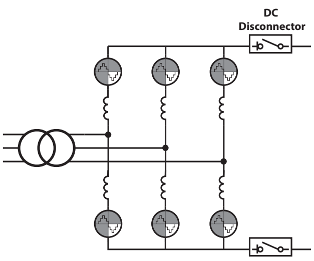
(g) ***Type II Example 5*** *- Blocking converter and DC disconnector*



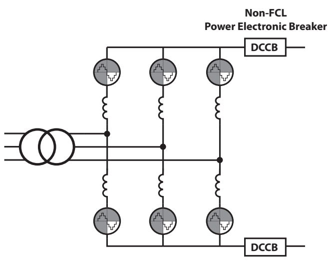
(h) ***Type III Example 1*** *- FFC with FCL DCCB*



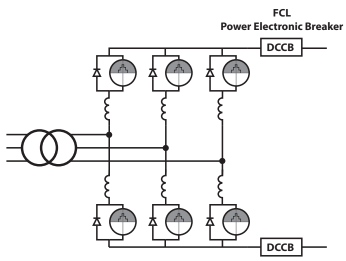
(i) ***Type IV Example 1*** *- MMC with three-quadrant valves*



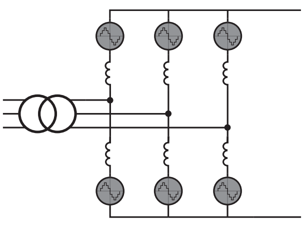
(j) ***Type V Example 1*** *- MMC with three-quadrant valves and DC disconnector*



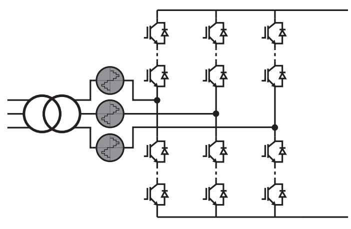
(k) ***Type V Example 2*** *- MMC with three-quadrant valves and DCCB*



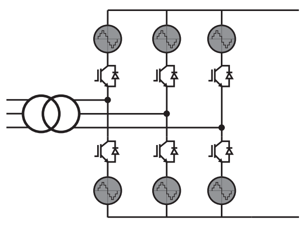
(l) ***Type V Example 3*** *- FFC with DCCB with STATCOM capability*



(m) ***Type VI Example 1*** *- MMC with four-quadrant valves*

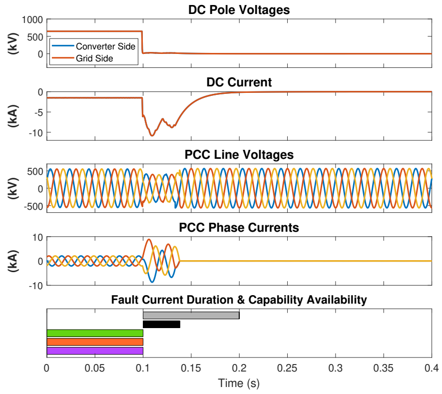


(n) ***Type VI Example 2*** *- Two-Level Converter with AC-side four-quadrant valve*

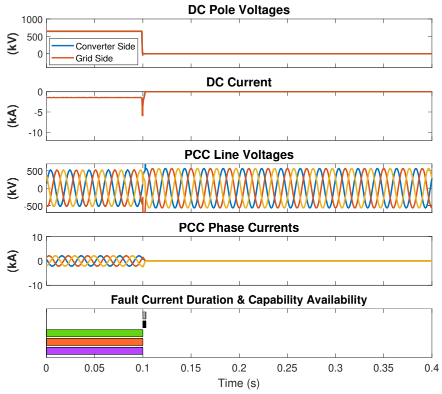


(o) ***Type VI Example 3*** *- Alternate Arm Converter*

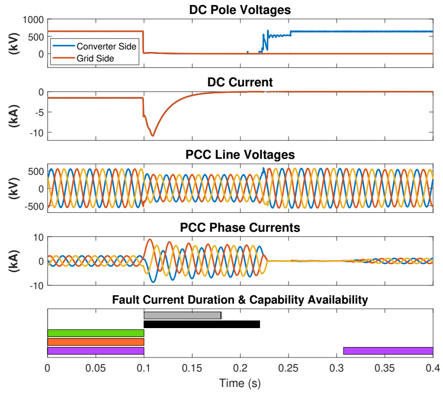
Fig. 5 *Circuit diagrams of example converter station topologies with generalised valve representation that fall into the proposed classification system.*



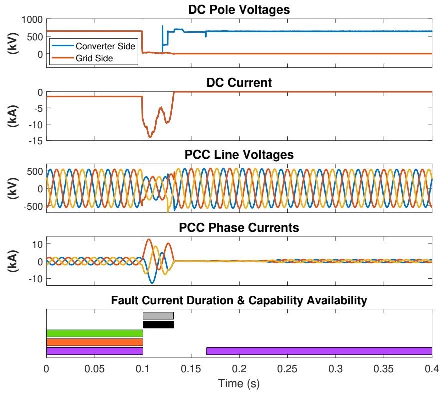
(a) *Type I Example 1*



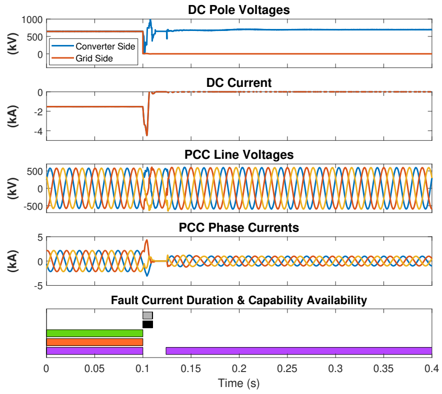
(b) *Type I Example 2*



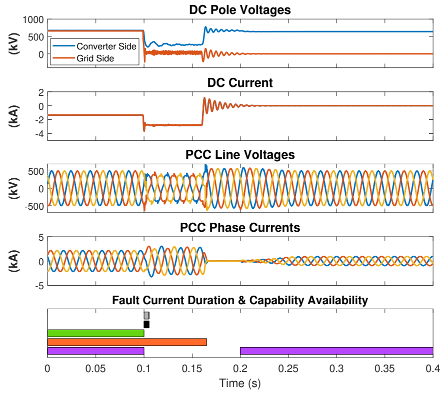
(c) *Type II Example 2*



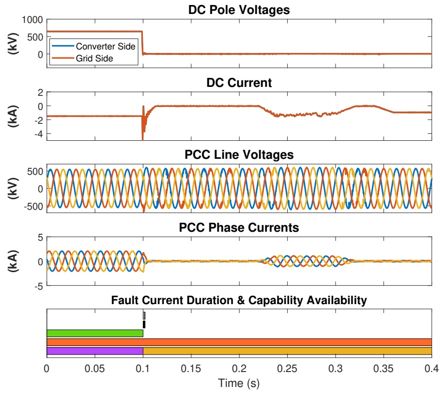
(d) *Type II Example 3*



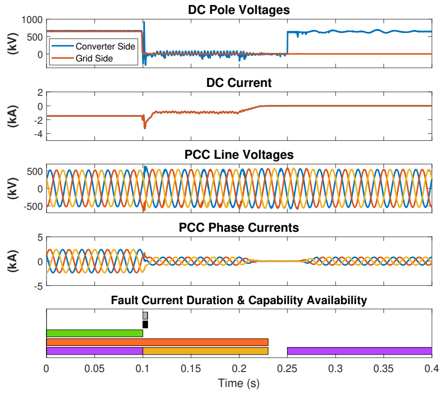
(e) *Type II Example 4*



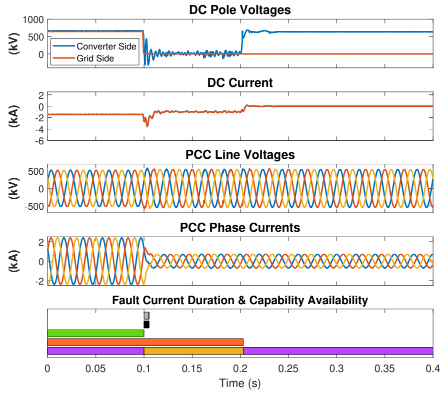
(f) *Type III Example 1*



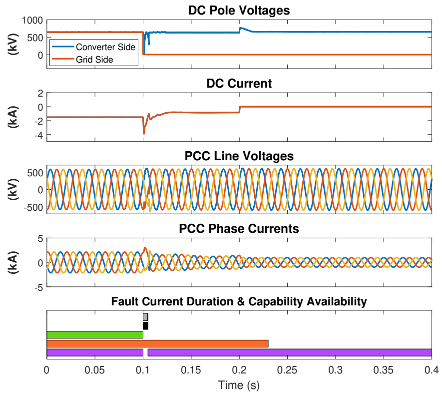
(g) *Type IV Example 1*



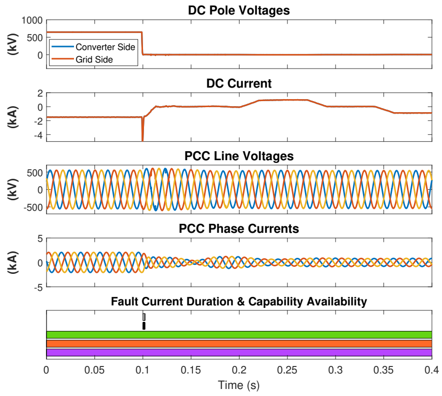
(h) *Type V Example 1*



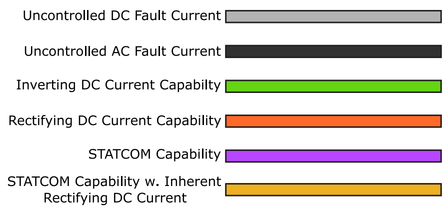
(i) *Type V Example 2*



(j) *Type V Example 3*



(k) *Type VI Example 1*



(l) *Fault Duration & Capability Legend*

Fig. 6 *Simulation results illustrating the response and functionalities of example converter station topologies from each class. Sub-figure labels correspond to the converter station topologies given in Fig. 5.*

blocking of the SMs therefore results in a counter-voltage being imposed which drives the current flowing through the converter arms to zero.

3.2.2 Type II: Five example converter station designs which fall into the Type II classification are shown in Fig. 5c-g. The first example converter station (Fig. 5c) uses an FFC in conjunction with an ACCB to interrupt the AC-side contribution to the DC-side fault [70]. A DC disconnector is used to first isolate the converter's DC terminals from the external grid, before the ACCB can be re-closed and the converter de-blocked, enabling it to move into STATCOM mode. The second example (Fig. 5d) uses an FFC in conjunction with an additional thyristor based crowbar circuit and DC disconnector. During a DC-side fault the crowbar circuit is used to form a low impedance AC-side fault [40, 79], which interrupts the AC-side contribution to the DC-fault, resulting in the DC-side fault current decaying. Thereafter, the DC disconnector can be used to isolate the converter's DC terminals from the faulted grid, allowing the converter to de-block and move into STATCOM mode. The crowbar circuit can be placed on the AC-side of the converter, or in parallel with the converter SMs. The third example (Fig. 5e) uses a thyristor based bypass bridge to divert the AC-side fault current out of the main converter during a DC-side fault [80]. A DC disconnector is then used to isolate the converters DC terminals under zero current conditions. Once this is achieved the thyristor circuit can be de-gated, resulting in the DC fault current being interrupted once the thyristor bridge is commutated by the AC voltage. The fourth example converter station (Fig. 5f) uses an FFC in conjunction with a DCCB, which is not capable of current limiting [104]. The DCCB is relied upon to interrupt the DC-side fault current and isolate the converter's DC terminals. Depending on the speed with which the DCCB opens, the converter may or may not require blocking in order to protect its semiconductors. In the event that the converter blocks, it must be de-blocked before moving into STATCOM mode. The final example (Fig. 5g) uses a blocking converter in conjunction with a DC disconnector. When a DC-side fault is detected, the converter is blocked, thereby driving all currents within the converter towards zero. The DC disconnector can then isolate, under zero current conditions, the converter's DC terminals from the faulted grid, allowing the converter to be de-blocked and moved into STATCOM operation.

Simulation results from three of the example converters station topologies are shown in Fig. 6c-e. In each of the example simulations the converter initially loses current control following a DC-side fault, with subsequent blocking of the converter and uncontrolled rectification of AC current. Once the converter has been isolated from the faulted external grid the converter can be de-blocked, and the DC voltage at the converter's DC terminals re-established, after which STATCOM operation is possible. Re-charge of the DC network using this type of converter station is expected to require pre-insertion resistors due to an inability to control the DC-side currents into a low voltage DC-side. The cases of the FFC with ACCB and DC disconnector, and the blocking converter with DC disconnector are omitted as the results are similar to those shown in Fig. 6a-b, but with a subsequent de-blocking and move into STATCOM mode.

Simulation results for the FFC with AC crowbar and DC disconnector, are given in Fig. 6c. Once the DC-side fault is detected the thyristors are fired, creating a low impedance symmetrical AC fault which interrupts the AC-side contribution to the DC-side fault current. The latter decays to zero in a similar fashion as the type I FFC with AC CBs. The fault is isolated using DC disconnectors after the current has decayed to a level below their residual current capability. The DC voltage is restored in an uncontrolled manner after isolation of the fault, followed by a de-blocking of the converter and move into STATCOM mode.

The FFC with hybrid bypass and fast DC disconnector reduces the fault interruption time compared with the FFC and FFC with AC crowbar and DC disconnector (Fig. 6d). In this case, the converter initially loses current control and blocks itself, moving into natural rectification mode, after which the thyristor bypass branch for each converter arm is activated. Since the bypass branch presents a lower impedance compared with the converter arms, the current is naturally commutated from the latter to the former, thereby driving the current flowing through the converter arms to zero within a cycle. This provides zero current conditions for the DC disconnector located between the converter and the DC connection point of the bypass circuit when isolating the converter from the DC network. Thereafter, the firing signals for the thyristor bypass circuit can be stopped, which results in the DC fault current being extinguished approximately half a cycle after the DC disconnector has opened. Once this has occurred the converters controller can be deblocked and the converter can operate in STATCOM mode after the DC voltage at the converters terminals has been restored.

In the case of the FFC with non-fault-current-limiting DCCB, shown in Fig. 6e, the converter initially loses current control. The DC fault is interrupted by the DCCB, which allows the converter to de-block and move into STATCOM mode. In the case shown the converter blocks itself during the fault, however as discussed in the section above this may not be the case depending on the speed of the DCCB.

3.2.3 Type III: An example of a converter station that meets the classification of Type III is a FFC (e.g. MMC with two-quadrant valve) with a FCL power electronic circuit breaker, shown in Fig. 5h. This converter station uses the FCL functionality of the power electronic circuit breaker to limit the DC-side fault current. During a DC-side fault an uncontrolled fault current is initially conducted through the converter, before the power electronic circuit breaker starts fault current limitation and eventually isolates the fault. Once the DC-side current is zero, the converter station can deblock and provide reactive power to the AC system. When the fault has been cleared (by an external device or by itself in the case of a temporary fault) the converter station can recharge the network. In either case, the power electronic circuit breaker is used in FCL mode during the recharge process.

Simulation results of this example topology are given in Fig. 6f. The converter station is unable to provide reactive power to the AC system while its DC terminals are faulted, but is capable of controlling rectifying DC current. A fault occurs at 0.1 s, after which there is a limited DC-side overcurrent. The hybrid circuit breaker operates in 3 ms and limits the DC-side fault current to 3 kA. During fault current limiting, the converter is blocked. After 60 ms, a control decision is made to isolate the fault and the DC current is reduced to zero. After this point, the converter can begin switching, with capability to source or sink reactive power.

3.2.4 Type IV: A converter station with the functionalities of this type is achieved if a three-quadrant valve, as discussed in Section 2.1, is used in an MMC operated without the use of any auxiliary equipment at the DC or AC side (Fig. 5i). The inability of three quadrant valves to generate voltage in the fourth quadrant implies that, during a DC-side fault, all current flowing through the valves of the converter must be in a rectifying direction. Consequently, active fault current level control in rectifying mode and active recharge of the DC network from zero DC voltage can be achieved. STATCOM mode operation may also be achieved by mapping the AC currents in an upwards direction through each valve, as discussed in [61, 62]. This control mode, however, results in a DC current also being injected into the faulted DC network.

In the example simulation (Fig. 6g), the converter is able to quickly interrupt the DC fault current, and provides STATCOM (with inherent rectifying DC current) and rectifying DC current control capabilities during the full fault clearing process, with the exception of the milliseconds immediately after fault inception. In the example, the converters controllers reduce the DC current to zero at $t = 0.012$ s. Within the time interval of [0.225,0.325] ms, the STATCOM mode operation is accompanied by a DC current circulating between the arms and the fault. After $t = 0.34$, the converter injects DC rectifying current while the reactive AC current component has been set to zero.

3.2.5 Type V: Examples of converter station topologies that fall into Type V are a three-quadrant converter with either DC disconnectors or DCCBs (Fig. 5j-k), or an FFC used in conjunction with an FCL DCCB (Fig. 5l). In the latter case, coordinated control is

IET Research Journals, pp. 1–14

needed to allow the converter to remain actively switching while the DCCB is in FCL mode. Unlike Type IV converter station topologies, the examples of this type based on the three-quadrant topology are able to provide STATCOM mode operation without inherent rectifying DC current if they are isolated by the DC disconnectors or DCCBs. STATCOM mode operation during a DC-side fault prior to this operation results in inherent rectifying DC current. The example topology that uses an FFC in conjunction with an FCL DCCB achieves STATCOM capability without rectifying DC current before isolation. The FCL capability is used to limit the DC fault current to a safe level, as well as keeping the DC voltage at the converter's terminals above the natural rectification voltage, which allows the converter to remain de-blocked, and capable of providing continuous STATCOM mode operation during the DC-side fault.

Simulation results from the three examples of Type V are shown in Fig. 6h-j. The examples of the MMC with three-quadrant valves quickly reduce the DC fault current, before the DC disconnector or DCCBs isolate the converter from the faulted DC bus (Fig. 6h and 6i). Within the interval [0.1,0.2] s, the three-quadrant converters inject reactive current with associated rectifying DC current. At t=0.2 s, the DC disconnector or DCCBs isolate the converter from the faulted DC bus, after which the DC voltage at the converter station terminal re-establishes. The main difference between using DC disconnector and DCCBs is whether the MMC with three-quadrant valves needs to reduce the current to zero or not. Since the DC disconnectors do not have interrupting capability, the DC current has to be driven to zero by the three-quadrant converter. The converter is able to provide STATCOM mode without a rectifying current feeding to the DC bus once the DC disconnector or DCCBs isolates the converter from the faulted DC bus.

The FFC example provides the same current control capabilities as the MMC with three-quadrant valves, whereas in this case the DC voltage is kept around the nominal value by the FCL action of the DCCB (Fig. 6j). The FFC converter is temporarily blocked during the initial stage of the DC-side fault due to overcurrent, then deblocked approximately 0.6 ms after the fault instant when the DC current has been limited to a low level by the FCL operation of the DCCBs. After de-blocking, the converter is operated in STATCOM mode and the DC current is controlled at 0.5 pu by the FCL operation of the DCCBs. STATCOM mode operation while connecting to the faulted DC bus is demonstrated until 0.2 s, then the DCCBs are ordered to open. The converter blocking action can be expected to depend on the breaker opening time, the overcurrent protection level of the converter and the rate of collapse of the DC bus voltage. In this simulation, the breaker opening time and the overcurrent protection setting is 2 ms and 1.6 pu, respectively, and the DC bus voltage collapses immediately after the inception of the DC-side fault. The temporary blocking of the converter in the example results could potentially be avoided by co-designing the DCCB and converter.

3.2.6 ***Type VI:*** Three converter station design examples which achieve the Type VI classification are the MMC with four-quadrant valves, a two-level converter with AC-side four quadrant valves [105], or the alternate arm converter (Fig. 5m-o) [26, 27]. Each of these station designs is capable of remaining in active switched operation during a DC-side fault (i.e., the converter is not blocked, or is temporarily blocked and then de-blocked) and retaining current control over their AC-side, DC-side and internal currents, meaning STATCOM mode operation as well as control over both DC current in the rectifying and inverting operation is possible.

Simulation results for the MMC with four-quadrant valve example are shown in Fig. 6k. The DC-side fault causes a transient initial increase of DC current. The magnitude and duration of this initial increase will be influenced by the response of the current controller to the DC voltage collapse caused by the fault [106]. Current control is re-established shortly and the DC current is then driven to zero. Once the DC fault current is suppressed the ability of the converter to control DC current in both the rectifying and inverting directions is shown, STATCOM mode operation is also demonstrated.

3.3 Time Intervals

To comprehensively specify the response of a converter station during and after DC-side faults, three time intervals are defined in addition to the types. The first time interval is the fault current interruption time, which describes the time interval from the inception of the fault (or alternatively the arrival of the fault wave at the converter station) to the instant at which the DC fault current at the converter station terminals has reached a value at which it can be assumed extinct (i.e., close to zero). The second time interval, known as the STATCOM mode operation time, describes the interval from fault current interruption until the converter station is able to operate as a STATCOM without any restrictions imposed by the circuit or fault clearing equipment. The third time interval is the DC voltage restoration time, which describes the time interval from the clearance of the DC-side fault (after which voltage restoration can be initiated) to the instant at which the voltage is restored to the value at which power flow can be resumed. The terms in the following sections are generalised and not all terms apply to all converter stations, i.e., some terms can be neglected depending on classification type and technology used.

3.3.1 ***Fault Current Interruption Time:*** The fault current interruption time Δt_{int} is the time between the onset of fault current increase at the converter DC terminals (t_{f}) and fault current interruption (t_{int}). It is the sum of the fault detection time Δt_{d}, opening time Δt_{o} and DC-side fault current decay time Δt_{dec}:

$$\begin{aligned}\Delta t_{\text{int}} &= t_{\text{int}} - t_{\text{f}} \\ &= \Delta t_{\text{d}} + \Delta t_{\text{o}} + \Delta t_{\text{dec}}\end{aligned} \tag{1}$$

The fault detection time Δt_{d} is the time between the onset of fault current increase at the converter DC terminals and fault detection, which thus excludes the time it takes for the fault to propagate to the converter terminals. Depending on the technology used for interrupting the DC-side fault, Δt_{o} refers to either the opening time of the ACCB, the opening time of the DCCB or the response time of the converter fault current control.

3.3.2 ***STATCOM Mode Operation Time:*** The STATCOM mode operation time $\Delta t_{\text{Q}\rightarrow\text{Q}^*}$ is the sum of the time intervals of the actions following fault current interruption required for the converter station to be capable of tracking a reactive power set-point Q^*. This time is the sum of the converter station DC isolation time $\Delta t_{\text{isolate}}^{\text{DC}}$, AC reconnection time $\Delta t_{\text{connect}}^{\text{AC}}$, converter deblocking time $\Delta t_{\text{deblock}}^{\text{conv}}$, and converter control action time $\Delta t_{\text{Q}}^{\text{conv}}$:

$$\begin{aligned}\Delta t_{\text{Q}\rightarrow\text{Q}^*} &= t_{\text{Q}^*} - t_{\text{int}} \\ &= \Delta t_{\text{isolate}}^{\text{DC}} + \Delta t_{\text{connect}}^{\text{AC}} + \Delta t_{\text{deblock}}^{\text{conv}} + \Delta t_{\text{Q}}^{\text{conv}}\end{aligned} \tag{2}$$

Depending on the technology used to interrupt a DC-side fault or to provide converter station isolation from the DC side, certain time intervals might not apply (i.e., delay equal to zero). In certain converter station types STATCOM mode operation may not be possible at all, or STATCOM mode operation during a DC-side fault always results in inherent rectifying DC current (Type IV converter stations, and some Type V converter stations before the converter station is isolated from the DC network).

3.3.3 ***DC Voltage Restoration Time:*** The DC voltage restoration time $\Delta t_{\text{V}_{\text{DC}}\rightarrow\text{V}_{\text{DC}}^*}$ is the sum of the time intervals of the actions following fault clearance ($t_{\text{clear}}^{\text{flt,DC}}$) required for the converter station to restore the DC network to its nominal voltage level, assuming the DC voltage has completely collapsed. This time is the sum of the time taken for the converter to reconnect to the network (if disconnected) $\Delta t_{\text{connect,DC}}$, the time taken for the network to passively charge through the converter $\Delta t_{\text{recharge,passive}}$, and the time taken for the converter to actively charge the network to its nominal set-point $\Delta t_{\text{recharge,active}}$:

$$\begin{aligned}\Delta t_{\mathrm{V_{DC}}\rightarrow \mathrm{V_{DC}^{*}}} &= t_{\mathrm{V_{DC}^{*}}} - t_{\mathrm{clear}}^{\mathrm{flt,DC}} \\ &= \Delta t_{\mathrm{connect,DC}} + \Delta t_{\mathrm{recharge,passive}} + \Delta t_{\mathrm{recharge,active}}\end{aligned} \tag{3}$$

Depending on the classification type and technology used, one or both of $\Delta t_{\mathrm{connect,DC}}$ and $\Delta t_{\mathrm{recharge,passive}}$ may be zero as the converter station may remain connected to the fault network throughout the fault and the converter station may capable of actively recharging the network without a passive stage. Further discussion of this is given in Section 3.5.

3.4 Syntax for Presentation of Types and Time Intervals

To support future grid code specification and development, and for ease of comparison between converter station designs, a common syntax for presentation of the type and time intervals associated with a certain converter station is proposed: "$X(\Delta t_{\mathrm{int}}/\Delta t_{Q\rightarrow Q*}/\Delta t_{\mathrm{V_{DC}}\rightarrow \mathrm{V_{DC}^{*}}})$", where X represents the converter station type and the time intervals are specified in milliseconds, considering worst case scenarios (i.e fault instance occurring on point of wave that maximises time taken to interrupt DC fault current). The proposed common syntax serves to describe the characteristics of an existing or prospective converter station in a particular location in an AC/DC system. For example, a type I converter station with $\Delta t_{\mathrm{int}} = 300$ ms, $\Delta t_{\mathrm{Q\rightarrow Q^{*}}}$ not being applicable, and $\Delta t_{\mathrm{V_{DC}}\rightarrow \mathrm{V_{DC}^{*}}} = 80$ ms, would be described as $I(300/-/80)$. A converter station can then be proposed or selected for use in a particular location according to the requirements on both type and time intervals specified for converter stations used at that location. For instance, a requirement for $II(600/100/300)$ would be fulfilled by a $II(100/50/100)$ converter station, and also by a $VI(600/100/300)$ converter station.

3.5 Post-fault Network Recharging Sequences

Following fault clearance, the HVDC network may require recharging before resuming normal operation. Recharging the network from a high-voltage source (i.e. the AC network) requires a sequence of stages to limit the inrush current, which would otherwise damage the converter components. These stages depend on the topology of the converter station that is required to perform the recharging. They can be broadly defined by the converter station action during the recharge, i.e., passive or active, in which the recharging current is limited by passive components or is actively controlled by the converter, respectively. In these simulation cases, the converter station in question is the only device recharging the HVDC network.

Since the characteristics of the recharging are highly dependent on the HVDC network, the examples provided hereunder are solely intended for demonstration of the principles. The following examples are simulated with a DC-side capacitance equivalent to a 500 km 320 kV XLPE HVDC cable for each pole. Two examples of recharging are shown, i.e., a case using passive and active recharging with an FFC and ACCB (Fig. 7a) and a case using solely active recharging with a four-quadrant converter (Fig. 7b). Fault clearance is assumed external to the converter station, either due to the quenching of an arc following a transient overhead line fault, or due to network protection providing fault clearance.

3.5.1 Passive Prior to Active DC Voltage Restoration: This recharge sequence entails a passive recharge stage, in which currents are limited by pre-insertion resistors, prior to an active recharge stage, in which currents are controlled by the converter. It is indicative of the recharging sequence that could be employed by either Type I or Type II converter stations. In the example of the FFC with ACCB (Fig. 7a), the passive recharge stage takes around 250 ms and results in a network charged to the natural rectification voltage of the AC system. In this stage, the current is limited by the pre-insertion resistors. Once the DC voltage reaches a level close to the nominal DC voltage, the active recharge stage commences by bypassing

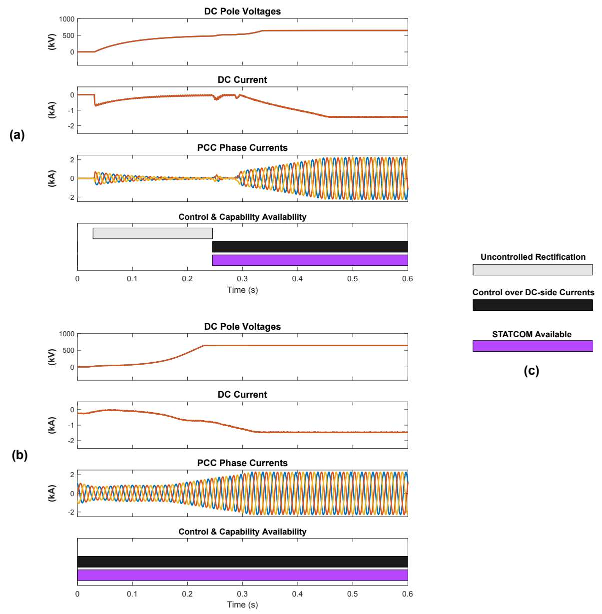


Fig. 7 *Examples of post-fault network recharging. Time relative to the point at which the fault on the network is cleared. (a) Type I - example 1 - FFC with ACCB clearance. (b) Type VI - example 1 - four-quadrant converter. (c) Legend.*

the pre-insertion resistors and starting active switching of the converter. The active recharge stage lasts until the voltage of the system is brought to the nominal voltage.

For this example, the combination of the simulation results in Fig. 6a and Fig. 7b lead to a classification of Type $\mathrm{I}(150/-/350)$. Note that the timings are dependent on the network topology and the implementation of the converter station, and are not necessarily indicative of limitations of the converter station type.

3.5.2 Active DC Voltage Restoration: This process requires no AC or DC switchgear, nor any additional resistors or other auxiliary equipment, and is possible with Type III, IV, V or VI converter stations (i.e those with rectifying DC current control during a DC-side fault). In the example of the four-quadrant converter (Fig. 7b), after the interruption of the DC-side fault current, the converter station remains switching and maintains control over all currents. Once fault clearance occurs, the converter station orders an increase in DC current and performs the recharge using a controlled current. After the network is recharged, the converter maintains control over the DC current and can transfer power as required.

For this example, the combination of the simulation results in Fig. 6k and Fig. 7b lead to a classification of Type $\mathrm{IV}(12/0/210)$. Again, the timings are not necessarily indicative of limitations of the converter station type.

4 Case Study

Fig. 8 shows an example HVDC grid that will be used in a qualitative case study to demonstrate how the proposed classification framework is valuable when specifying the types of converter station required for the various duties in the example grid. In this example, an HVDC grid connects two strong AC systems, 1 and 2, and a weak AC system 3. The HVDC grid is divided into two sub-grids, separated by a DCCB (or DCCBs) on the line between converter stations 1 and 3. Note that the system requirements and associated converter station types presented in this section are to demonstrate a possible use of the classification, and are not part of the classification itself.

A non-selective strategy has been chosen for sub-grid 1, meaning that fault current interruption requires opening the circuit breaker(s) on the line to station 3 and using stations 1 and 2 to interrupt the other contributions to the DC fault current. In a second stage, if the

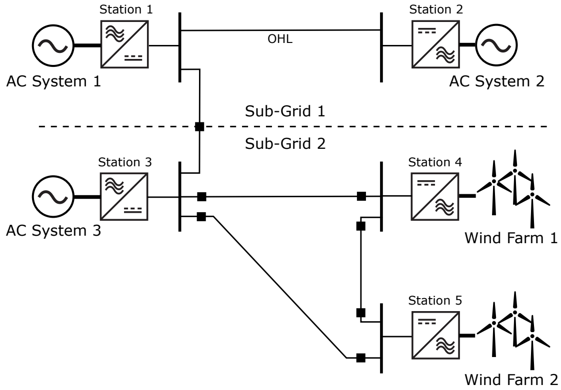


Fig. 8 *Example HVDC grid.*

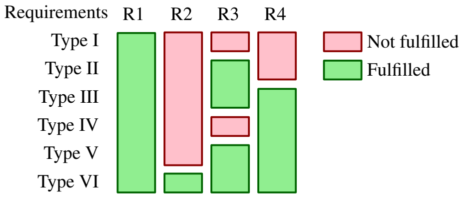


Fig. 9 *Example of mapping of power system requirements and converter types, excluding timing requirements.*

fault is found to be permanent, isolation of the fault is achieved using disconnect switches (without current interruption capability) on the faulted line. If the fault is found to be non-permanent (plausible on an overhead line), converter stations 1 and 2 quickly restore the DC voltage (and power flow) after a prescribed de-ionisation time. A fully selective strategy has been specified for sub-grid 2. This means that DCCBs are installed at the ends of every cable and no special actions are required by the converters.

We assume the system operators of the AC and HVDC grids have determined various requirements for system operation based on their extensive system studies. Four candidate requirements that might be applied have been identified:

R1 - DC current interruption: DC currents must be interrupted by a specified time which may be based on either avoiding high peak DC currents or avoiding pro-longed DC tail currents due to uncontrolled discharge of passive elements.
R2 - Active discharge and polarity inversion: fault currents must be controlled to improve DC-side fault detection and arc extinguishing. This requirement is fulfilled when the converter station is able to discharge the line under both rectifying and inverting conditions.
R3 - Support for weak AC grid: the converter must be able to deliver reactive power while the DC network is faulted. This requirement is fulfilled when reactive power is delivered by a specified time and without simultaneous injection of DC current.
R4 - Controlled DC black start: the converter must be able to restore the DC voltage in a controlled manner to allow for several restoration attempts in quick succession.

The mapping of the converter types and these requirements (excluding timings) is given in Fig. 9, and provides a framework for a structured approach to the selection of the required type for each station in the example HVDC grid. The mapping shows which types are ruled out when certain requirements are to be met. In a further stage, when timings are added to the requirements, some of the converter stations belonging to a certain type may also be ruled out. This demonstrates the usefulness of both the converter types and timings used within the classification framework.

In the example case study, station 1 needs to have fast interruption which may be aided by the ability to control fault current through inverting action that extracts energy from the transmission line which would otherwise flow toward the fault. Further, fast black

Table 3 Candidate converter types for case study, excluding timing requirements

Converter	Requirements	Candidate converters type
1	{R1,R2,R4}	VI
2	{R1,R4}	III-IV-V-VI
3	{R3}	II-III-V-VI
4	{}	I-II-III-IV-V-VI
5	{}	I-II-III-IV-V-VI

start enables a fast recovery after non-permanent faults of the OHL. Station 1 thus has the requirements set {R1,R2,R4} and, as Fig. 9 shows, only Type VI stations can meet this set of requirements. This is recorded in the first line of Table 3. Assuming that for this example, Station 2 is not required to invert, the set of requirements drops to {R1,R4} and the minimally required converter station type is reduced to Type III. In sub-grid 2, given that the stations are not required to perform any protective functions, Station 4 and Station 5 may be of Type I or higher. In this sub-grid, Station 3 is connected to the weak AC system 3 and so the requirement R3 is applied. As a consequence, Type II or higher stations, excluding Type IV due to its inherent injection of DC current, could be considered.

It might be that the required features of the converter station (and hence the required converter station type) may not all come from a strict a priori specification, but may expanded or refined through a study of stability criteria of the overall system. These studies may set the required timings for each of the converter stations, determined as values of Δt_{int}, $\Delta t_{Q \to Q*}$ and $\Delta t_{\text{V}_{\text{DC}} \to \text{V}^*_{\text{DC}}}$. These timings, along with a requirement for a minimum converter station type, could then form the basis of a grid code specification which is not set out in terms of specific technologies and therefore does not preclude future converter or breaker technologies. The interactions between required timings and interoperability between different converter types could also be explored. For example a grid code operator could discover that the overall requirements for system stability are met by either a minimum of I(10/-/100) or a II(30/50/100) converter stations. It is then up to the system operator(s) to decide on the converter station types depending on system stability criteria and other desired features that take account of future grid expansions.

5 Discussion

The classification methodology uses the capabilities during and after a DC-side fault as a main differentiating factor among converter stations. This choice is demonstrated using simulations of selected example converter stations, which confirm that, apart from the time intervals, the converter stations of the same type are able to provide the same capabilities. An overview of example converter station topologies within each type, given in Table 5, demonstrates the merit of the proposed classification; it is the first classification framework which categorises existing and potential future converter station designs according to capabilities rather than technology, and encompasses a wide range of potential converter station designs.

Table 4 Converter Station Classification

Capable of:	Type					
	I	II	III	IV	V	VI
Interrupting AC-side contribution to DC-side faults	✓	✓	✓	✓	✓	✓
STATCOM mode operation during DC-side fault (may require DC-side isolation)	✗	✓	✓	✓	✓	✓
Rectifying DC current control while connected to faulted DC network		✗	✓	✓	✓	✓
STATCOM mode operation while connected to faulted DC network			✗	✓	✓	✓
STATCOM mode operation without inherent rectifying DC current (may require DC-side isolation)				✗	✓	✓
Inverting DC current control while connected to faulted DC network					✗	✓

Table 5 Example Converter Stations

Type	Examples
I	Fault Feeding Converter (FFC) (e.g., MMC with two-quadrant valves or two-/three-level converter) with AC circuit breaker Blocking converter (i.e., MMC or other modular converter with valves capable of generating a negative voltage with blocked operation during DC-side fault)
II	FFC with AC circuit breaker and DC disconnector FFC with hybrid bypass and DC disconnector FFC with AC-side crowbar and DC switch FFC with non-fault current limiting DC circuit breaker Blocking converter with DC disconnector
III	FFC with fault current limiting DC circuit breaker without active DC-side fault ride through control
IV	MMC with three-quadrant valve and active control during fault
V	MMC with three-quadrant valve and DC disconnector FFC with fault current limiting DC circuit breaker and active DC-side fault ride through control MMC with three-quadrant valve and DC circuit breaker
VI	MMC with four-quadrant valves (e.g., full-bridge SMs) Two-Level converter with AC-side cascaded full-bridge SMs Alternate arm converter

One of the main aims of the proposed classification system is to enable technology-independent AC/DC system studies, as illustrated in Fig. 10. Performing studies in this manner would allow a system operator to focus on technical requirements, and investigate the interaction between the capabilities different converter stations could give (included in the classification of the converter types), and the subsequent impact of these capabilities on the stability of the overall power system (as specified by the required timings).

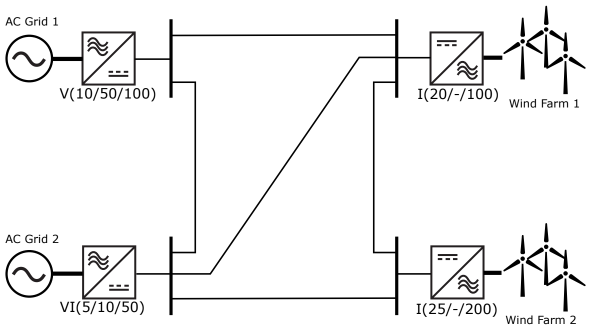


Fig. 10 *Generic system study utilising the proposed classification system.*

6 Conclusion

This paper provides a classification framework that enables VSC HVDC converter station designs to be categorised into six types, which differentiate converter stations based on system-level capabilities (ability to operate as a STATCOM, ability to control rectifying DC current, and ability to control inverting DC current) rather than technology. The classification framework and examples of converter station designs that fall into each proposed type within the framework are summarised in Table 4. The six converter types are extended with three time intervals to fully characterise the converter station from a capability point-of-view. To describe a converter station or a requirement for a converter station, a common syntax is proposed in the following format: $X(\Delta t_{\text{int}}/\Delta t_{Q \rightarrow Q*}/\Delta t_{\text{V}_{\text{DC}} \rightarrow \text{V}^*_{\text{DC}}})$ ms, where X represents the converter station type, Δt_{int} represents the time interval taken to interrupt any DC fault current flowing through the converter station, $\Delta t_{Q \rightarrow Q*}$ represents the time interval taken to track a reactive power set-point, and $\Delta t_{\text{V}_{\text{DC}} \rightarrow \text{V}^*_{\text{DC}}}$ is the time interval taken to restore a fully discharged HVDC network post-fault clearance. We anticipate such a categorisation will prove useful for: (i) Fair and meaningful comparison of new converter station designs, comprising of converter topologies, control, circuit breakers and auxiliary equipment. (ii) Specification of grid codes for the future power system, thereby enabling a multi-vendor market of suppliers. (iii) Enabling technology-independent AC/DC system studies. Future work could focus on system studies using the proposed classification system, as well as the development of technology-independent converter station models based upon the classification.

7 References

[1] P. Bresesti, W. L. Kling, R. L. Hendriks, and R. Vailati: 'HVDC Connection of Offshore Wind Farms to the Transmission System', IEEE Trans. Energy Convers., 2007, 22, (1), pp. 37–43.
[2] N. M. Kirby, L. Xu, M. Luckett, and W. Siepmann: 'HVDC transmission for large offshore wind farms', Power Engineering Journal, 2002, 16, (3), pp. 135–141.
[3] A. E. MacDonald, C. T. M. Clack, A. Alexander, A. Dunbar, J. Wilczak, and Y. Xie: 'Future cost-competitive electricity systems and their impact on us co2 emissions', Nature Climate Change, 2016, 6, pp. 526 EP –, article. [Online]. Available: https://doi.org/10.1038/nclimate2921
[4] N. Flourentzou, V. G. Agelidis, and G. D. Demetriades: 'VSC-Based HVDC Power Transmission Systems: An Overview', IEEE Trans. Power Electron., 2009, 24, (3), pp. 592–602.
[5] D. Van Hertem, O. Gomis-Bellmunt, and J. Liang: 'HVDC Grids:For Offshore and Supergrid of the Future'. Wiley-IEEE Press, 2016).
[6] A. Lesnicar and R. Marquardt: 'An innovative modular multilevel converter topology suitable for a wide power range', in Proc. Power Tech Conference Proceedings, 2003 IEEE Bologna, 3, Jun. 2003, p. 6 pp.
[7] R. Marquardt: 'Modular Multilevel Converter: An universal concept for HVDC-Networks and extended DC-Bus-applications', in Proc. Power Electronics Conference (IPEC), 2010 International, Jun. 2010, pp. 502–507.
[8] T. Xu, M. W. Donoghue, and C. C. Davidson: 'IGBT overcurrent turn-off tests for the MMC-based VSC valves', in Proc. 2013 15th European Conference on Power Electronics and Applications (EPE), Sep. 2013, pp. 1–10.
[9] C. Oates: 'Modular multilevel converter design for VSC HVDC applications', IEEE Trans. Emerg. Sel. Topics Power Electron., 2015, 3, (2), pp. 505–515.
[10] L. Feng, R. Gou, X. Yang, X. Sun, and F. Zhuo: 'Design of high power density sub module in modular multilevel converter for VSC-HVDC project', in Proc. 10th International Conference on Advances in Power System Control, Operation Management (APSCOM 2015), Nov. 2015, pp. 1–6.
[11] H. Chen, W. Coo, Z. Tan, P. Bordignon, R. Yi, and H. Zhang: 'Hardware design and key submodule testing of the world's first single-level press-pack igbt based modular multilevel converter for VSC HVDC', in Proc. 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016), Apr. 2016, pp. 1–6.
[12] M. Spence, A. Plumpton, C. Rout, A. Millington, and R. Keyse: 'Design and Characterisation of Optimised Protective Thyristors for VSC Systems', in Proc. PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, May 2016, pp. 1–8.
[13] J. Chivite-Zabalza, J. Perrier, M. Boden, T. Xu, and J. Outram: 'Development of a Full-Bridge Sub-Module for HVDC and STATCOM Markets', in Proc. PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, May 2017, pp. 1–7.
[14] L. Wang, G. Cheng, T. Bureau, X. Li, D. Zhang, and Y. Fan: 'Automation and control design of overvoltage protection for sub-modules in modular multilevel converter', in Proc. 2017 IEEE 2nd Information Technology, Networking, Electronic and Automation Control Conference (ITNEC), Dec. 2017, pp. 1048–1052.
[15] M. Hagiwara and H. Akagi: 'Control and Experiment of Pulsewidth-Modulated Modular Multilevel Converters', IEEE Trans. Power Electron., 24, (7), pp. 1737–1746.
[16] M. Hagiwara, R. Maeda, and H. Akagi: 'Control and Analysis of the Modular Multilevel Cascade Converter Based on Double-Star Chopper-Cells (MMCC-DSCC)', IEEE Trans. Power Electron., 26, (6), pp. 1649–1658.
[17] B. S. Riar and U. K. Madawala: 'Decoupled Control of Modular Multilevel Converters Using Voltage Correcting Modules', IEEE Trans. Power Electron., 30, (2), pp. 690–698.
[18] S. Fan, K. Zhang, J. Xiong, and Y. Xue: 'An Improved Control System for Modular Multilevel Converters with New Modulation Strategy and Voltage Balancing Control', IEEE Trans. Power Electron., 30, (1), pp. 358–371.
[19] K. Ilves, A. Antonopoulos, S. Norrga, and H. P. Nee: 'Steady-State Analysis of Interaction Between Harmonic Components of Arm and Line Quantities of Modular Multilevel Converters', IEEE Trans. Power Electron., 27, (1), pp. 57–68.
[20] K. Ilves, S. Norrga, L. Harnefors, and H. P. Nee: 'On Energy Storage Requirements in Modular Multilevel Converters', IEEE Trans. Power Electron., 29, (1), pp. 77–88.
[21] M. M. C. Merlin, T. C. Green, P. D. Mitcheson, F. J. Moreno, K. J. Dyke, and D. R. Trainer: 'Cell capacitor sizing in modular multilevel converters and hybrid topologies', in Proc. European Conference On Power Electronics and Applications (EPE'14-ECCE Europe), Aug. 2014, pp. 1–10.
[22] H. Akagi: 'Classification, Terminology, and Application of the Modular Multilevel Cascade Converter (MMCC)', IEEE Trans. Power Electron., 26, (11), pp. 3119–3130.

[23] M. A. Perez, S. Bernet, J. Rodriguez, S. Kouro, and R. Lizana: 'Circuit Topologies, Modeling, Control Schemes, and Applications of Modular Multilevel Converters', IEEE Trans. Power Electron., 30, (1), pp. 4–17.
[24] J. Qin, M. Saeedifard, A. Rockhill, and R. Zhou: 'Hybrid Design of Modular Multilevel Converters for HVDC Systems Based on Various Submodule Circuits', IEEE Trans. Power Del., 2015, 30, (1), pp. 385–394.
[25] G. P. Adam, S. J. Finney, and B. W. Williams: 'Hybrid converter with ac side cascaded H-bridge cells against H-bridge alternative arm modular multilevel converter: Steady-state and dynamic performance', IET Generation, Transmission Distribution, 2013, 7, (3), pp. 318–328.
[26] M. M. C. Merlin, D. Soto-Sanchez, P. D. Judge et al.: 'The Extended Overlap Alternate Arm Converter: A Voltage-Source Converter With DC Fault Ride-Through Capability and a Compact Design', IEEE Trans. Power Electron., 2018, 33, (5), pp. 3898–3910.
[27] M. M. C. Merlin, T. C. Green, P. D. Mitcheson et al.: 'The Alternate Arm Converter: A New Hybrid Multilevel Converter With DC-Fault Blocking Capability', IEEE Trans. Power Del., 2014, 29, (1), pp. 310–317.
[28] P. D. Judge, M. M. C. Merlin, T. C. Green, D. R. Trainer, and K. Vershinin: 'Thyristor-Bypassed Sub-Module Power-Groups for Achieving High-Efficiency, DC Fault Tolerant Multilevel VSCs', IEEE Trans. Power Del., 2017, PP, (99), pp. 1–1.
[29] H. Rao: 'Architecture of Nan'ao multi-terminal VSC-HVDC system and its multi-functional control', CSEE Journal of Power and Energy Systems, 2015, 1, (1), pp. 9–18.
[30] 'Zhoushan five-terminal VSC-HVDC Project', http://www.nrec.com/en/case/-449.html.
[31] 'SGRI Participates in Construction of Zhang-Bei DC Grid Pilot Project_Press Release_C-EPRI', http://www.cepri.com.cn/release/details_66_745.html.
[32] A. Nami, J. Liang, F. Dijkhuizen, and G. D. Demetriades: 'Modular Multilevel Converters for HVDC Applications: Review on Converter Cells and Functionalities', IEEE Trans. Power Electron., 2015, 30, (1), pp. 18–36.
[33] M. A. Perez, S. Bernet, J. Rodriguez, S. Kouro, and R. Lizana: 'Circuit Topologies, Modeling, Control Schemes, and Applications of Modular Multilevel Converters', IEEE Trans. Power Electron., 2015, 30, (1), pp. 4–17.
[34] C. M. Franck: 'HVDC Circuit Breakers: A Review Identifying Future Research Needs', IEEE Trans. Power Del., 2011, 26, (2), pp. 998–1007.
[35] O. Cwikowski, B. Chang, M. Barnes, R. Shuttleworth, and A. Beddard: 'Fault current testing envelopes for VSC HVDC circuit breakers', Transmission Distribution IET Generation, 2016, 10, (6), pp. 1393–1400.
[36] D. Keshavarzi, E. Farjah, and t. ghanbari: 'A Hybrid DC Circuit Breaker and Fault Current Limiter with Optional Interruption Capability', IEEE Trans. Power Electron., 2017, 33, (99), pp. 1–1.
[37] G. Liu, F. Xu, Z. Xu, Z. Zhang, and G. Tang: 'Assembly HVDC Breaker for HVDC Grids With Modular Multilevel Converters', IEEE Trans. Power Electron., 2017, 32, (2), pp. 931–941.
[38] R. Sander, M. Suriyah, and T. Leibfried: 'Characterization of a Countercurrent Injection-Based HVDC Circuit Breaker', IEEE Trans. Power Electron., 33, (4), pp. 2948–2956.
[39] J. Häfner and B. Jacobson: 'Proactive Hybrid HVDC Breakers-A key innovation for reliable HVDC grids', Proc. of Cigré Bologna, Paper, 2011, 264.
[40] X. Li, Q. Song, W. Liu, H. Rao, S. Xu, and L. Li: 'Protection of Nonpermanent Faults on DC Overhead Lines in MMC-Based HVDC Systems', IEEE Trans. Power Del., 2013, 28, (1), pp. 483–490.
[41] S. Cui, S. Kim, J. J. Jung, and S. K. Sul: 'Principle, control and comparison of modular multilevel converters (MMCs) with DC short circuit fault ride-through capability', in Proc. 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, Mar. 2014, pp. 610–616.
[42] L. Huang, X. Yang, P. Xu et al.: 'The evolution and variation of sub-module topologies with DC-fault current clearing capability in MMC-HVDC', in Proc. 2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 - ECCE Asia), Jun. 2017, pp. 1938–1943.
[43] M. Abedrabbo, M. Wang, P. Tielens et al.: 'Impact of DC grid contingencies on AC system stability', in Proc. 13th IET International Conference on AC and DC Power Transmission (ACDC 2017), Feb. 2017, pp. 1–7.
[44] A. Ellis, Y. Kazachkov, E. Muljadi, P. Pourbeik, and J. J. Sanchez-Gasca: 'Description and technical specifications for generic wtg models: A status report', in Proc. 2011 IEEE/PES Power Systems Conference and Exposition, March 2011, pp. 1–8.
[45] S. Debnath, J. Qin, B. Bahrani, M. Saeedifard, and P. Barbosa: 'Operation, Control, and Applications of the Modular Multilevel Converter: A Review', IEEE Trans. Power Electron., 30, (1), pp. 37–53.
[46] J. Hu, R. Zeng, and Z. He: 'DC fault ride-through of MMCs for HVDC systems: A review', The Journal of Engineering, 2016, 1, (1).
[47] L. Zhang, Y. Zou, J. Yu et al.: 'Modeling, control, and protection of modular multilevel converter-based multi-terminal hvdc systems: A review', CSEE Journal of Power and Energy Systems, 2017, 3, (4), pp. 340–352.
[48] T. H. Nguyen, K. A. Hosani, M. S. E. Moursi, and F. Blaabjerg: 'An overview of modular multilevel converters in HVDC transmission systems with STATCOM operation during pole-to-pole dc short circuits', IEEE Trans. Power Electron., 2019, 34, (5), pp. 4137–4160.
[49] M. N. Raju, J. Sreedevi, R. P Mandi, and K. S. Meera: 'Modular multilevel converters technology: a comprehensive study on its topologies, modelling, control and applications', IET Power Electronics, 2019, 12, (2), pp. 149–169.
[50] R. Marquardt: 'Modular Multilevel Converter topologies with DC-Short circuit current limitation', in Proc. Power Electronics and ECCE Asia (ICPE ECCE), 2011 IEEE 8th International Conference On, May 2011, pp. 1425–1431.
[51] J. Zhang and C. Zhao: 'The research of sm topology with dc fault tolerance in mmc-hvdc', IEEE Trans. Power Del., 2015, 30, (3), pp. 1561–1568.
[52] A. Nami, J. Liang, F. Dijkhuizen, and P. Lundberg: 'Analysis of modular multilevel converters with dc short circuit fault blocking capability in bipolar hvdc transmission systems', in Proc. 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), Sep. 2015, pp. 1–10.
[53] R. Li, J. E. Fletcher, L. Xu, D. Holliday, and B. W. Williams: 'A Hybrid Modular Multilevel Converter With Novel Three-Level Cells for DC Fault Blocking Capability', IEEE Trans. Power Del., 2015, 30, (4), pp. 2017–2026.
[54] V. Dargahi, A. K. Sadigh, M. Abarzadeh, S. Eskandari, and K. A. Corzine: 'A New Family of Modular Multilevel Converter Based on Modified Flying-Capacitor Multicell Converters', IEEE Trans. Power Electron., 30, (1), pp. 138–147.
[55] T. A. Meynard and H. Foch: 'Multi-level conversion: High voltage choppers and voltage-source inverters', in Proc. , 23rd Annual IEEE Power Electronics Specialists Conference, 1992. PESC '92 Record, Jun. 1992, pp. 397–403 vol.1.
[56] T. B. Soeiro and J. W. Kolar: 'Novel 3-level Hybrid Neutral-Point-Clamped Converter', in Proc. IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society, Nov. 2011, pp. 4457–4462.
[57] E. Solas, G. Abad, J. A. Barrena, S. Aurtenetxea, A. Cárcar, and L. Zajac: 'Modular Multilevel Converter With Different Submodule Concepts Part I: Capacitor Voltage Balancing Method', IEEE Trans. Ind. Electron., 2013, 60, (10), pp. 4525–4535.
[58] X. Yang, Y. Xue, B. Chen, Z. Lin, T. Q. Zheng, and Y. Li: 'Novel modular multilevel converter against DC faults for HVDC applications', CSEE Journal of Power and Energy Systems, 2017, 3, (2), pp. 140–149.
[59] X. Yang, Y. Xue, B. Chen et al.: 'Reverse blocking sub-module based modular multilevel converter with DC fault ride-through capability', in Proc. 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Sep. 2016, pp. 1–7.
[60] H. Kim, J. Kang, S. Kim, C. K. Kim, and K. Hur: 'DC fault protection for modular multilevel converter HVDC using asymmetrical unipolar full-bridge submodule', in Proc. 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), Jun. 2015, pp. 1083–1089.
[61] X. Yu, Y. Wei, and Q. Jiang: 'STATCOM Operation Scheme of the CDSM-MMC During a Pole-to-Pole DC Fault', IEEE Trans. Power Del., 2016, 31, (3), pp. 1150–1159.
[62] X. Yu, Y. Wei, and Q. Jiang: 'New submodule circuits for modular multilevel current source converters with DC fault ride through capability', in Proc. 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Mar. 2016, pp. 1468–1474.
[63] K. Ilves, L. Bessegato, L. Harnefors, S. Norrga, and H. P. Nee: 'Semi-full-bridge submodule for modular multilevel converters', in Proc. 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), Jun. 2015, pp. 1067–1074.
[64] M. M. C. Merlin, T. C. Green, P. D. Mitcheson, D. R. Trainer, D. R. Critchley, and R. W. Crookes: 'A new hybrid multi-level Voltage-Source Converter with DC fault blocking capability', in Proc. AC and DC Power Transmission (ACDC). IET International Conference On, 2010, pp. 1–5.
[65] P. D. Judge, G. Chaffey, M. M. C. Merlin, P. R. Clemow, and T. C. Green: 'Dimensioning and Modulation Index Selection for the Hybrid Modular Multilevel Converter', IEEE Trans. Power Electron., 2018, 33, (5), pp. 3837–3851.
[66] M. Lu, Q. Zhou, J. Hu, N. Wang, and M. Xiang: 'On hybrid modular multilevel converters with active DC fault ride-through capability', in Proc. 12th IET International Conference on AC and DC Power Transmission (ACDC 2016), May 2016, pp. 1–6.
[67] P. D. Judge, M. M. C. Merlin, T. Green, D. R. Trainer, and K. Vershinin: 'Thyristor/diode-bypassed sub-module power-groups for improved efficiency in modular multilevel converters', IEEE Trans. Power Del., 2018, pp. 1–1.
[68] Working group B4.37, 'VSC Transmission', 269, (().
[69] P. Haugland, 'It's time to connect: Technical description of hvdc light® technology', 2008.
[70] A. Hassanpoor, Y. Häfner, A. Nami, and K. Vinothkumar: 'Cost-effective solutions for handling dc faults in VSC HVDC transmission', in Proc. 2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), Sep. 2016, pp. 1–7.
[71] Cigré Joint Working Group A3-B4.34: 'Technical Requirements and Specifications of State-of-the-art HVDC Switching Equipment'.
[72] B. Yang, D. Cao, W. Shi, W. LV, W. Wang, and B. Liu: 'A novel commutation-based hybrid HVDC circuit breaker', in Proc. Proc. Cigré 2017 Canada, Winnipeg, Canada, 30 Sep. - 6 Oct. 2017.
[73] W. Grieshaber, D. Dupraz, J.P.and Penache, and L. Violleau: 'Development and test of a 120 kV direct current circuit breaker', Paris, France, 24 – 29 Aug. 2014.
[74] L. Ängquist, S. Norrga, T. Modeer, and S. Nee: 'Fast HVDC breaker using reduced-rating power electronics', in Proc. Proc. IET ACDC 2017, Manchester, UK, 14.
[75] F. Dijkhuizen and B. Berggren: 'Zoning in high voltage DC (HVDC) grids using hybrid DC breaker', in Proc. Proc. EPRI HVDC and FACTS Conf., Palo Alto, USA, 2013, pp. 1–8.
[76] K. Tahata, S. Ka, S. Tokoyoda et al.: 'HVDC circuit breakers for HVDC grid applications', in Proc. Proc. Cigré AORC Technical Meeting, Tokyo, Japan, 2014.
[77] Y. Wang and R. Marquardt: 'Future hvdc-grids employing modular multilevel converters and hybrid dc-breakers', in Proc. 2013 15th European Conference on Power Electronics and Applications (EPE), Sept 2013.
[78] B. Xiang, L. Zhang, K. Yang et al.: 'Arcing Time of a DC Circuit Breaker Based on a Superconducting Current-Limiting Technology', IEEE Trans. Appl. Supercond., 2016, 26, (7), pp. 1–5.
[79] A. A. Elserougi, A. S. Abdel-Khalik, A. M. Massoud, and S. Ahmed: 'A New Protection Scheme for HVDC Converters Against DC-Side Faults With Current Suppression Capability', IEEE Trans. Power Del., 2014, 29, (4), pp. 1569–1577.

[80] I. A. Gowaid: 'A Low-Loss Hybrid Bypass for DC Fault Protection of Modular Multilevel Converters', IEEE Trans. Power Del., 2017, 32, (2), pp. 599–608.
[81] ENTSO-E, European Commission: 'Establishing a network code on requirements for grid connection of high voltage direct current systems and direct current connected power park modules', 2015.
[82] H. G. Sarmiento, G. Pampin, and J. D. de Leon: 'Feasibility Studies for Dynamic VAR and STATCOM Applications to Prevent a Fast Voltage Collapse', in Proc. IEEE/PES Transmission and Distribution Conference, May 2006, pp. 1420–1425.
[83] B. Singh, R. Saha, A. Chandra, and K. Al-Haddad: 'Static synchronous compensators (STATCOM): A review', IET Power Electronics, 2009, 2, (4), pp. 297–324.
[84] E. N. Lerch, D. Povh, and L. Xu: 'Advanced SVC control for damping power system oscillations', IEEE Trans. Power Syst., 1991, 6, (2), pp. 524–535.
[85] S. Johansson, G. Asplund, E. Jansson, and R. Rudervall: 'Power system stability benefits with VSC DC-transmission systems', in Proc. CIGRE conference, Apr. 2004, pp. 1–8.
[86] Q. Deng, X. Liu, R. Soman, M. Steurer, and R. A. Dougal: 'Primary and backup protection for fault current limited mvdc shipboard power systems', in Proc. 2015 IEEE Electric Ship Technologies Symposium (ESTS), June 2015, pp. 40–47.
[87] G. Chaffey and T. C. Green: 'Low speed protection methodology for a symmetrical monopolar HVDC network', in Proc. 13th IET International Conference on AC and DC Power Transmission (ACDC 2017), Feb. 2017, pp. 1–6.
[88] D. Jovcic, W. Lin, S. Nguefeu, and H. Saad: 'Full bridge MMC converter controller for HVDC operation in normal and DC fault conditions', in Proc. 2017 International Symposium on Power Electronics (Ee), pp. 1–6.
[89] Siemens, 'HVDC PLUS – the Decisive Step Ahead').
[90] J. Dorn, P. L. Seta, F. Schettler et al.: 'Full-bridge VSC: An essential enabler of the transition to an energy system dominated by renewable sources', in Proc. 2016 IEEE Power and Energy Society General Meeting (PESGM), Jul. 2016, pp. 1–5.
[91] P. Münch, D. Görges, M. Izák, and S. Liu: 'Integrated current control, energy control and energy balancing of Modular Multilevel Converters', in Proc. IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society, Nov. 2010, pp. 150–155.
[92] M. Wang, W. Leterme, G. Chaffey, J. Beerten, and D. Van Hertem: 'Pole Rebalancing Methods for Pole-to-ground Faults in Symmetrical Monopolar HVDC Grids', IEEE Trans. Power Del., 2018, early online access
[93] R. Dantas, J. Liang, A. Adamczyk, C. Barker, and R. Whitehouse: 'Protection Strategy for Multi-terminal DC Networks with Fault Current Blocking Capability of Converters', in Proc. Proc. IET ACDC 2017, Manchester, UK, 14–16 Feb. 2017.
[94] B. Pauli, G. Mauthe, E. Ruoss, G. Ecklin, J. Porter, and J. Vithayathil: 'Development of a high current HVDC circuit breaker with fast fault clearing capability', IEEE Trans. Power Del., 1988, 3, (4), pp. 2072–2080.
[95] C. Peng, J. Wen, X. Wang, Z. Liu, and K. Yu: 'Development of DC Transfer Switch for Ultra High Voltage DC Transmission Systems', Proceedings of the Chinese Society for Electrical Engineering (CSEE), 2012, 32, (16), pp. 151–156.
[96] T. Eriksson, M. Backman, and S. Halén: 'A low loss mechanical HVDC breaker for HVDC grid applications', in Proc. Proc. Cigré Paris, Paris, France, 24.
[97] J. Magnusson, R. Saers, L. Liljestrand, and G. Engdahl: 'Separation of the Energy Absorption and Overvoltage Protection in Solid-State Breakers by the Use of Parallel Varistors', IEEE Trans. Power Electron., 2014, 29, (6), pp. 2715–2722.
[98] P. Skarby and U. Steiger: 'An ultra-fast disconnecting switch for a hybrid HVDC breaker - a technical breakthrough', in Proc. Cigré 2013 Canada Conf., Calgary, Alberta, Canada, 9.
[99] C. Petino, M. Heidemann, D. Eichhoff, M. Stumpe, E. Spahic, and F. Schettler: 'Application of multilevel full bridge converters in HVDC multiterminal systems', IET Power Electronics, 2016, 9, (2), pp. 297–304.
[100] G. Asplund, K. Eriksson, and K. Svensson: 'Dc transmission based on voltage source converters', in Proc. Proc. CIGRÉ SC14 Colloquium, South Africa, 29-30 Sep. 1997.
[101] WG B4.37: 'Technical Brochure 269: VSC Transmission'. CIGRE, 2005).
[102] R. Dantas, J. Liang, C. E. Ugalde-Loo, A. Adamczyk, C. Barker, and R. Whitehouse: 'Progressive fault isolation and grid restoration strategy for mtdc networks', IEEE Trans. on Power Del., 2018, 33, (2), pp. 909–918.
[103] J. Chongxue, Lu Yu, Wang Nannan, Wang Hui, Wang Jiacheng, and Zhao Xicai: 'Comparative Analysis of DC Line Fault Recovery Technology in VSC HVDC', in Proc. CIGRE SC A3, B4 and D1 Colloquium, Winnipeg, Canada, Oct. 2017, p. 13 pages.
[104] D. S. Loume, A. Bertinato, B. Raison, and B. Luscan: 'A multi-vendor protection strategy for HVDC grids based on low-speed DC circuit breakers', in Proc. Proc. IET ACDC 2017, Manchester, UK, 14–16 Feb. 2017.
[105] G. P. Adam, S. J. Finney, and B. W. Williams: 'Hybrid converter with ac side cascaded h-bridge cells against h-bridge alternative arm modular multilevel converter: steady-state and dynamic performance', IET Generation, Transmission Distribution, 2013.
[106] M. Winkelnkemper, L. Schwager, P. Blaszczyk, M. Steurer, and D. Soto: 'Short circuit output protection of MMC in voltage source control mode', in Proc. 2016 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 1–6.