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Review article

Control and protection of MMC-based HVDC systems: A review

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ABSTRACT

The voltage source converter (VSC) based HVDC (high voltage direct current system) offers the possibility to integrate other renewable energy sources (RES) into the electrical grid, and allows power flow reversal capability. These appealing features of VSC technology led to the further development of multi-terminal direct current (MTDC) systems. MTDC grids provide the possibility of interconnection between conventional power systems and other large-scale offshore sources like wind and solar systems. The modular multilevel converter (MMC) has become a popular technology in the development of the VSC-MTDC system due to its salient features such as modularity and scalability. Although, the employment of MMC converter in the MTDC system improves the overall system performance. However, there are some technical challenges related to its operation, control, modeling and protection that need to be addressed. This paper mainly provides a comprehensive review and investigation of the control and protection of the MMC-based MTDC system. In addition, the issues and challenges associated with the development of the MMC-MTDC system have been discussed in this paper. It majorly covers the control schemes that provide the AC system support and state-of-the-art relaying algorithm/ dc fault detection and location algorithms. Different types of dc fault detection and location algorithms presented in the literature have been reviewed, such as local measurement-based, communication-based, traveling wave-based and artificial intelligence-based. Characteristics of the protection techniques are compared and analyzed in terms of various scenarios such as implementation in CBs, system configuration, selectivity, and robustness. Finally, future challenges and issues regarding the development of the MTDC system have been discussed in detail.

Contents

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1. Introduction

Although traditional HVAC is less complicated and inexpensive, due to the rapid advancement in power electronic devices, researchers have paid more attention to HVDC for long distance transmission (Ding et al., 2008). The first 20 MW HVDC project went into commercial operation in 1954 between the mainland of Sweden and the island of Gotland (Wang, 2010). Meanwhile, the world is going towards renewable energy sources such as hydro, wind and solar to meet the electric power demand. It becomes a big challenge for researchers to integrate all renewable energy sources (RES) with conventional sources through some efficient mechanism. The HVDC system can provide a mechanism where wind power can be integrated into the existing AC grids efficiently (Wang, 2010; Li et al., 2020b). The HVDC has a lower cost as compared to HVAC for long distance transmission. Moreover, HVDC has lower transmission losses due to the absence of high reactive charging current, particularly for long distance overhead transmission lines and underwater cables. Unlike AC cables, DC cables are free from skin and proximity effect problems (Li et al., 2018). Mainly, DC transmission lines' efficiency and power carrying capacity depends on the type of converter used to convert one form of the power (AC/DC) to another form (DC/AC). The choice of a well-designed converter used in HVDC applications will give the advantages of reduced harmonics, increased power capability and robustness to tolerate the faults through the line (Van Hertem and Ghandhari, 2010). With the advent of power electronics, two power converter technologies were introduced, namely a line commutated converter (LCC) and a VSC to convert the power from AC into DC and DC into AC (Schettler and Huang, 2000; Hasan and Saha, 2013). Currently, the MMC, which is actually an updated version of the VSC, is popular in the development of the MTDC network.

1.1. LCC-based HVDC

Due to its extensive use in the past, LCC-based HVDC has become a mature technology and is often referred to as a classic HVDC system (Haileselassie, 2012). This offers a bulk power transmission at long distances with high efficiency (Hannan et al., 2018; Zou et al., 2017). The LCC is referred to as a current source converter (CSC) because it permits DC current to flow in only one direction (Alassi et al., 2019). Researchers have not shown much interest in using this technology for future HVDC systems because of some unavoidable limitations, such as limited reactive power control and complicated master control. In addition, the inability to change the direction of the current in DC link is also a big disadvantage of this technology which causes the inability of power flow direction (Oni et al., 2016; Alyami and Mohamed, 2017; Zhang et al., 2018b).

1.2. VSC-based HVDC

VSC technology was introduced in late of 1999s (Hannan et al., 2018; Oni et al., 2016) and has significant benefits over conventional LCC type converter (Cao et al., 2013), such as the ability to change the direction of power flow without reversing the polarity of the voltage, enabling the concept of MTDC systems (Xu et al., 2008). This technology has significant advantages like independent control of active and reactive power, improved power quality, reduced losses, reactive power support, and black start capability (Song et al., 2021). Commutation failures can be eliminated or even avoided in VSC-HVDC. Moreover, it enables the interconnection of weak ac systems such as offshore wind farms without synchronous generators (Alyami and Mohamed, 2017) and requires less space on converter stations (Hannan et al., 2018).

1.3. MMC-based HVDC

Although, the VSC-HVDC has posed major advantages over the LCC-HVDC, the conventional two-level or three-level VSCs result in some considerable drawbacks like higher switching losses and unimproved AC waveform. Therefore, it has been observed and realized to propose the multilevel converter in order to overcome these two major issues. The idea led to the further development of the advanced VSC technology, MMC and was first introduced in 2000 by Professor R. Marquardt for high voltage applications such as HVDC systems (Lu et al., 2018; Zhao et al., 2015). Scalability and modularity are attractive properties of MMC converters compared to conventional two or three-level VSCs. The scalability allows the facility to scale up or scale down the voltage levels to any desired level and modularity makes the maintenance easy (Lesnicar, 2003). Unlike the two-level or three-level VSC, the MMC type converter has low switching losses, lower harmonic contents, better fault blocking capability and high reliability. Also, the need for huge filters at the AC side and AC transformers is abridged when an MMC type converter

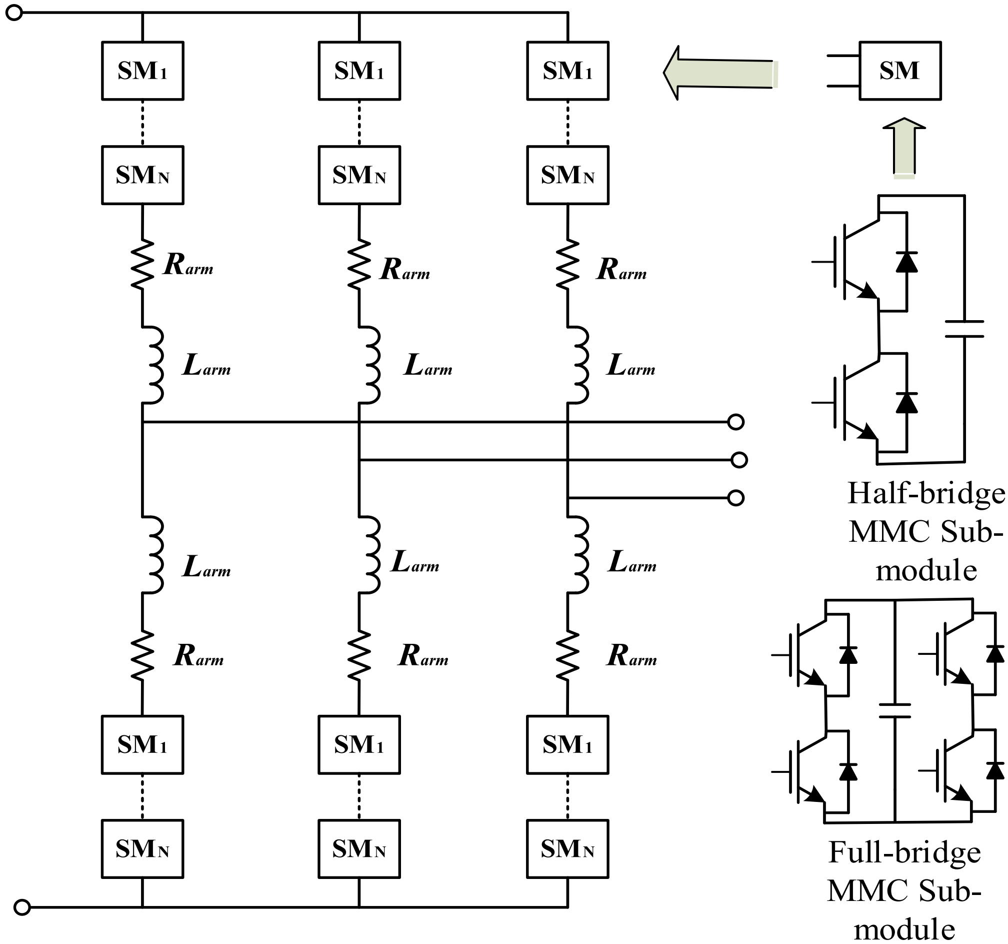

Fig. 1. Schematic diagram of MMC and its different sub-module topologies (Zhang et al., 2017).

is used in an HVDC system (Tu et al., 2019). Moreover, switches in MMC have lesser stress, so that they can be used in high voltage applications (Nakanishi et al., 2014). Besides, its attractive feature of the good quality waveform has made this topology the most advantageous configuration in medium and high power applications (Priya et al., 2019). Due to these attractive features, the MMC has become the cornerstone of the development of the MTDC system and DC grids. The schematic of MMC diagram is shown in Fig. 1.

The Nan'ao three-terminal VSC HVDC system has been upgraded with MMC technology and is now the first MTDC system with five terminals. The summary of other commercial MMC-based HVDC projects in Asia and Europe is provided in Table 1.

This paper gives a comprehensive review of the control of MMC-based HVDC systems. Moreover, advanced and latest control schemes have also been discussed in detail, incorporating the features of basic control strategies applied to DC voltage control and their critical analysis. Besides, protection schemes of MMC-MTDC under DC fault conditions have been presented thoroughly in this paper, including the DC fault analysis, detection and location, and interruption. The structure of the paper is as follows: Section 2 presents the problems and challenges associated with the development of the MTDC system, highlighting the issues of modeling, control and protection. Section 3 provides an in-depth review of existing control strategies applied to the MMC-MTDC system and discusses various challenges. The existing protection methods are presented in Section 4 and the limitations related to them. Section 5 provides future recommendations to address the problems presented in Sections 3 and 4. Finally, Section 6 presents the conclusion.

2. Issues and challenges associated with development of MMC-based MTDC system

MMC-based MTDC system is becoming more popular due to its numerous advantages over the AC transmission and LCC-based HVDC system. Despite its superiority over the AC transmission system and conventional HVDC technology, the MMC-based MTDC network is yet to be realized in practice. Modeling, operation and control of such MMC-based technology are arguably the most challenging issues that academicians and industrialists are currently engaged in.

2.1. Modelling issue

VSC-based HVDC is a growing technology in the power industry and has more advantages such as flexible control, easy development of multi-terminal DC grid, and easy integration of weak grids like an offshore wind farm. MMC-HVDC has more preference than two-level VSC HVDC due to modularity, scalability, lower losses and good quality of voltage and current waveforms (Debnath et al., 2015). Half-bridge sub-module MMC shown in Fig. 1, is a more dominant topology in MMC-based HVDC systems because it has lower losses and cost advantages. In the event of a short circuit fault on the DC side, the HB-MMC cannot block the fault fed from the AC side. Different SM structures for MMC have been introduced to increase its fault-handling capability, which includes the full-bridge (FB) shown in Fig. 1, the clamp-double (CD) SM, 3-level cross-connected (3LCC) SM, 5-level cross-connected (5LCC) SM, and modified switched-capacitor SM (MSCSM) (Ali et al., 2021). Different configurations

Table 1
Commercial MMC-based HVDC projects in Asia and Europe.

Name of project	Manufacturer	Commissioning year	Terminals	Power (MW)	Rated DC Voltage (± kV)
Nan'ao, China	CSG	2013	3	200/100/50	160
Zhoushan, China	CEPRI	2014	5	400/300/100/100/100	200
Zhangbei, China	SGCC	2020	4	3000	500
Xiamen, China	C-EPRI	2015	2	1000	320
Chongqing-Hubei, China	C-EPRI	2018	2	2500	420
Nanhui, China	C-EPRI	2011	2	18	30
BroWin1, Germany	ABB	2011	2	900	320
HelWin2, Germany	Siemens	2015	2	690	320
DolWin2, Germany	ABB	2016	2	916	320
North Sea Link, UK	ABB	2021	2	1400	525

and SM circuits of MMC have different design considerations and operating behaviors. For a large scale MMC MTDC network, it is very necessary to look into dynamic behavior, reliability and stability, fault analysis and protection, and control design based on modeling and simulation analysis to satisfy the development and operational standards (Wang et al., 2016). In order to investigate how such HVDC grids should be implemented practically and to find possible solutions to technical challenges, efficient simulation models are very important. Without computationally efficient and accurate simulation models of MMC, it is not possible to analyze the transient behavior of such grids. Accurate models are therefore required for the complex MMC-HVDC systems for research and development (Beddard and Barnes, 2015).

Several hundred sub modules are typically employed per valve arm in large-scale-MMC MTDC systems. The employment of detailed switching modeling (DSM) for such type of MMC HVDC results in unrealistically long simulation times, and the computational burden for such models will be very high due to a large number of switching components. To overcome these issues, equivalent models are needed (Ahmed, 2018). Meanwhile, the use of average modeling (AM) of MMCs is not able to study the transients on the dc side. Further, detailed equivalent circuit models (ECM) have been proposed in the literature. Such ECM models have the capability to compute the capacitor voltages for HB-MMCs, but are not applicable for FB-MMC sub-modules. Therefore, there is still a need to develop a more computationally efficient model for large-scale power grids which guarantees a fast simulation speed. These models create a computational load that emphasizes the need to propose simplified models that offer similar behavior and dynamic response.

2.2. Reliability and stability issue

MMC-based HVDC system utilizes the large number of SMs. Damage of any SM could result in shutdown of entire network or significantly affect the performance of converter. However, the inherent fault blocking capability of MMC can be used to potentially improve the performance and reliability of a system with proper design and control. Various methods have been presented in the literature to improve the reliability of MMC based HVDC network. Redundancy design (Tu et al., 2019), post-fault control, fault detection/location and periodic maintenance methods have been presented for reliability improvement. Though the redundancy design is a well-known method for the reliability improvement of MMC but it requires additional SMs which leads to higher cost (Alharbi et al., 2018). Therefore, it is still challenging to propose such approaches which estimate and improve the reliability of MMC-HVDC accurately and cost-efficiently.

In order to improve the entire system performance, it is very necessary to investigate the stability of MMC-HVDC system and increase the stability of both AC & DC systems (Alsseid et al., 2011). Moreover, the stability analysis of MMC-MTDC system depends on the magnitude of DC voltage. Therefore, it is handled differently from HVAC. To guarantee the dynamic and transient stability of a system, detailed state–space modeling of the system components and proper systematic analysis is required. In an MMC-MTDC system, the MMC can provide the energy storage capability that can be used for damping the power oscillations (Taffese et al., 2017). Though internal dynamics of MMC may impact the stability of the MTDC system and thus they pose serious challenges to stability. MMC may cause large second harmonic currents if such dynamics are not controlled. In order to overcome such harmonics, the circulating current suppression controllers (CCSCs) are used in the MMC-MTDC system (Xu et al., 2019). However, on the DC side of the converter, these types of CCSCs may cause poorly damped oscillations. In consequence, the use of MMC in MTDC provides enhanced and flexible ancillary services for stability improvement. Therefore, properly designing the internal dynamics of MMCs and their controllers is important to achieve increased stability.

2.3. Protection issue

Although the VSC-based MTDC system has great advantages over conventional HVDC system, it has some drawbacks like sensitivity to DC faults, lower power ratings, and high losses, typically around 1.6% (Candelaria and Do Park, 2011). In an MMC-MTDC, it is important to ensure that the fault on one AC side should not spread to other connected AC network and that the dc side fault should not contribute to the AC side fault. In case DC fault current occurs, normally fault current spreads to all interconnected power converters and as a result, their DC output voltage is reduced, which results in the stoppage of power flow. Hence to operate the MMC MTDC system reliably, the proper protection strategies are needed which must satisfy the requirements like reliability, sensitivity, selectivity, robustness and system's speed of operation.

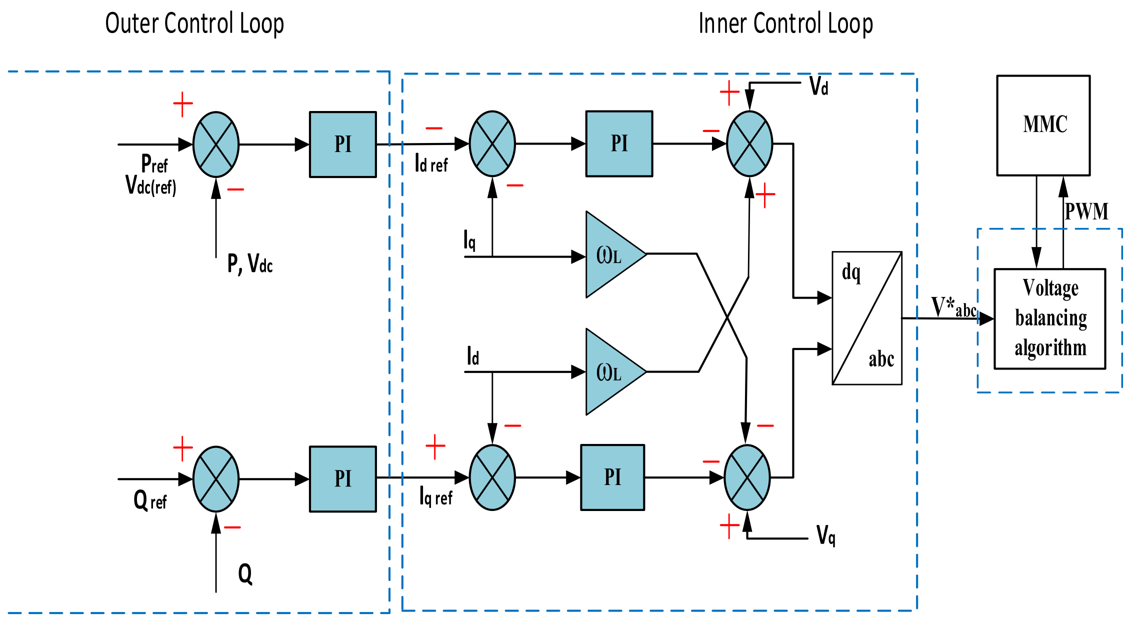

Fig. 2. DC voltage and power flow control scheme for VSC (Vanfretti et al., 2014).

As discussed above, the HB-MMC is the dominant topology in HVDC system due to its advantages. However, like a conventional two level VSC-HVDC it has similar DC fault blocking characteristics. If a fault happens on the DC side, the fault current cannot be blocked by both the conventional two-level VSC and the HB-MMC because the freewheeling diodes allow fault current to be flowed through them Ali et al. (2021). Therefore, proper protection schemes are needed to design and deploy in HB-MMC MTDC network. In order to block the fault current, fault blocking capability can be inserted into HB MMC by employing a fault blocking sub module. However, these solutions are non-selective or partially selective, which will interrupt the power flow of healthy lines. Therefore, they may only be suitable for two-terminal HVDC system. Another solution can be the use of DC circuit breakers to isolate the faulty lines (Li et al., 2018b). However, both aforementioned solutions increase the losses and costs. Thus, it is still challenging to propose the most cost efficient protection method for MMC-MTDC system, which may be achieved with the coordination of converter, DC CBs, and some other protection devices.

3. Control strategies for MMC-based MTDC system

The MMC is the advanced version of the VSC. So, similar control strategies can be implemented for both conventional two-level VSC converter and MMC converter (Zou et al., 2017). However, the control of MMC is more complex than the two-level VSC converter due to a large number of switches. The control strategies ensure the effectiveness of the MMC-based MTDC system. The control system of MMC-based MTDC may be divided into two level parts, valve-level control and station-level control. The valve level control part is in fact, the basis for the stable operation of the converter and mainly includes circulating current suppression and sub-module capacitance–voltage balancing control strategies. On the other hand, the station-level control part determines the operating mode of the system and is mainly composed of two control layers, an inner control loop and an outer control loop (Dong et al., 2019) shown in Fig. 2 whereby the DC voltage control and power flow control can be achieved for the stable operation of VSC or MMC-MTDC system.

Two control tasks, the control of DC voltage and AC side auxiliary control, should be considered in order to ensure the proper and efficient control of MMC-based MTDC system (Gavriluta et al., 2015b). Regulation of the DC voltage is actually the main control challenge in MMC-based MTDC system, since it is used to stabilize the operations of the DC grid. However, DC voltage is directly associated with the balance of active power and power flow, similar to frequency parameters in AC grid systems. But, unlike frequency which is often considered a universal parameter, the dc grid voltage varies throughout the system depending upon the power injection at each node (Gavriluta et al., 2015a). In addition, power decoupling and fast response are also attractive features of the MMC-type converter stations which can offer auxiliary support to the AC network and greatly improve its performance and stability. Moreover, the current control schemes which apply to VSC-MTDC through inner and outer control loops are also applicable to the MMC-MTDC system (Ansari et al., 2020).

3.1. DC voltage control

An outer control loop is responsible for controlling the DC voltage. In MMC-based MTDC, DC voltage control is known to be too important to achieve effective MTDC control. This is because of the fact that in the DC network, the energy flow between the terminals of the network is controlled by DC voltage of the terminals. In other words, the DC voltage varies because of the power flow, which is regulated by the difference between the grid voltage and bus voltage. In contrast to the AC system, in which the frequency is kept at the nominal value throughout the system, the DC voltage level in the MTDC cannot be kept at the same level for all terminals. Therefore, a control strategy must be established to regulate the DC voltage in the MTDC system in such a way that the desired power flow can be achieved between the DC terminals (Rouzbehi et al., 2015). There are three main control strategies for controlling DC voltage in the MTDC system: master–slave, voltage margin and voltage droop. Moreover, these three methods can also be categorized as centralized and decentralized control strategies (Chen et al., 2017). A brief introduction regarding these three strategies is described as follows:

3.1.1. master–slave control

In this approach, one of the converters is the master controller responsible for controlling the DC voltage profile and the rest

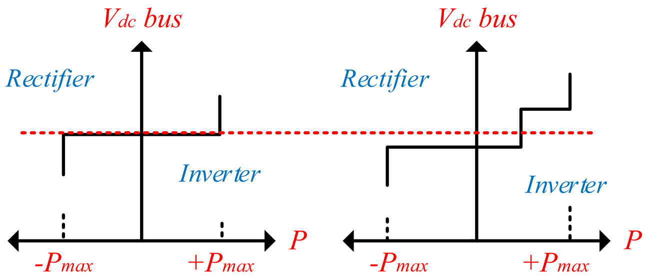

Fig. 3. Characteristics of voltage margin control.

of the converters control the power flow. However, this strategy presents instability problems because it lacks reliability, so the DC voltage control is completely compromised and the correct operation cannot be guaranteed if the master converter fails (Rekik et al., 2018). Moreover, in this control strategy, the master converter should be connected to a strong AC grid in order to ensure the fast conditioning of DC grid so that negative impacts can be avoided on the AC grid. According to standard IEC 60870-5-101 and IEC 60870-5-104, which is widely used in power generation where master and salve converters can be termed as server and client, respectively (Item-no et al., 2021).

The master–slave control is an appropriate method for practical multi-terminal projects such as current Zhangbei, Nan'ao, and Zhoushan HVDC projects in China; because this kind of control is easy in dispatching power, the backup converter of dc voltage control is often developed in master–slave control for fault conditions (Zhao and Tao, 2022).

3.1.2. Voltage margin control

This control scheme is an extension of the master–slave control shown in Fig. 3. There are dedicated converters termed as clients in the voltage margin control that ensure the DC voltage control when the power limit is exceeded (Di Wang et al., 2015). Moreover, if the main converter, which can be termed as the server, reaches its power limitations or is off-line then one of the reserved converters performs the function of DC voltage regulation. This control strategy suffers from the same drawback of instability as in the master–slave control, where one master converter is responsible for controlling at one time and the shifting of the master converter will cause the generation of oscillations in the DC voltage (Rault et al., 2012). The magnitude of voltage margin in this control scheme should be chosen properly, because too small value will cause unnecessary shifting of the master converter, while too large value may lead to underutilization of the MTDC system. Additionally, determining the voltage margins becomes too much challenging in this scheme when the number of converter stations increases (Chaudhuri et al., 2014).

To implement the control functionalities, the Zhoushan, China MTDC transmission project uses the conventional voltage margin method (VMM) technique. However, due to the nature of the control and the fact that only one VSC at a time controls DC voltage, the dynamic responses are comparatively slow. Additionally, the response accuracy and power efficiency are both really poor. Therefore, the novel control approaches are simulated and tested in the literature in this project to address the aforementioned issues (Xu and Zhang, 2016).

Direct-current control with double closed-loop control is used in the Xiamen 320 kV VSC-HVDC transmission demonstration project. It is primarily made up of the phase-lock synchronization controller, the valve-based controller (VBC), the inner-loop current controller, and the outer-loop power controller (Guo et al., 2016).

3.1.3. Voltage droop control

Unlike master–slave and voltage margin control strategies which are based on centralized control, the droop control is the decentralized control strategy shown in Fig. 4 and is complicated as compared to the above-mentioned control schemes (Gavriluta et al., 2015b). Droop control strategy is applied to the MMC-based MTDC to facilitate power-sharing after a converter outage. This method allows multiple converter stations for controlling DC voltage to maintain power balancing and voltage stability (Spallarossa et al., 2014). This control principle is similar to the power frequency droop control of the AC system (Haileselassie and Uhlen, 2012a). In addition, this control scheme is more reliable because the various converter stations can work together to maintain the power balance and simultaneously control the DC voltage (Di Wang et al., 2015). Apart from reliability, there are no oscillations. In this type of method, multiple converters stations can be used as server and client at time.

The aforementioned DC voltage control strategies pose different limitations when applied to MMC-based MTDC system. It becomes necessary for researchers and industrialists to propose such control strategies which incorporate the features of these three strategies. In order to utilize the advantages of above mentioned three basic control strategies, different improved and modified control schemes have been proposed by the researchers in the literature. Based on DC voltage margin control, Ref. Chai et al. (2015) proposed an improved control scheme that actually overcomes the drawback of the conventional voltage margin strategy. In the proposed control strategy, the steady state power flow is regulated precisely. Based on the characteristics of both the voltage margin and the voltage droop control Ref. Cheng et al. (2019) proposed a new control strategy, the adaptive droop control of the DC voltage margin. It has been applied to 6-terminal MTDC systems. The proposed strategy offers good performance in transient and steady-state when the power fluctuations of the DC grid are small. Moreover, some of the converters in this strategy switch to adaptive droop control when the power fluctuation of the DC grid is larger. An improved droop control strategy is proposed in Ref. Zhang et al. (2019b), which can reduce the DC voltage deviation and improve the stability and reliability of the MTDC system. Master auxiliary coordinated control strategy has been proposed in Di Wang et al. (2015), which incorporates the features of voltage margin control and voltage droop control in which stable DC voltage can be achieved through the control parameters of each converter station. Moreover, this strategy can guarantee power distribution capabilities and suppress high-power fluctuations. Ref. Li et al. (2021) conducts research on the particular requirements for control and protection systems to guarantee the proper functioning of the VSC-HVDC grid. A number of important control methods are created, examined, and investigated in accordance, such as coordinated control for Zhangbei VSC-HVDC.

Notwithstanding the popularity of the voltage droop control, it has some limitations for certain converter stations; this scheme cannot perform fixed DC voltage and power control in some modes of operation. In order to overcome the disadvantage described, a control strategy was proposed in Ref. Rouzbehi et al. (2015), which deals with the uniform control strategy for regulating the DC voltage and the power sharing in VSC-MTDC networks. This control scheme incorporates the implementation of generalized voltage droop (GVD) control at the primary level of the MTDC system with a two-layer hierarchical architecture. In addition, the power-dependent droop-based control strategy has been proposed in Stamatiou and Bongiorno (2017), in which the proposed new control structure keeps the grid DC voltage close to its nominal value and also preserves the power flow in the DC grids, thus eliminating contingencies such as faults or

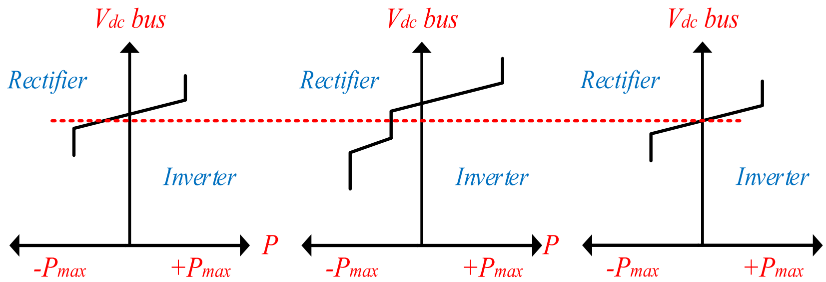

Fig. 4. Characteristics of voltage droop control.

disconnection of converter stations. Ref. Li et al. (2019) suggested the multipoint strategy for coordinated voltage control, which focuses on AC grids properties for a VSC-based MTDC system. This control strategy can provide satisfactory performance for dynamic DC voltage control with a reduced power deviation of converter stations and minimal power deviation from the steady state of converter stations. For autonomous power sharing and DC voltage regulation in a multi-stage DC grid, the new adaptive droop control strategy is proposed in Kumar and Padhy (2019). This control scheme can facilitate sharing of power between the terminals without putting a burden on any converter during converters outage. Moreover, this approach in DC grid, also reduces the DC voltage deviations from its nominal values. Dead-band droop control and undead-band droop control strategies have been reviewed in Simiyu et al. (2019). Dead-band droop control incorporates the characteristics of voltage droop control and voltage margin control in each terminal of converter to improve the dynamic performance and flexibility in VSC-MTDC system. In addition, this scheme works as the voltage margin in constant power or constant current mode if dead-band in normal operation; otherwise, it operates in droop if it is outside the dead-band. Unlike the dead-band control strategy, the undead-band neglects constant mode control of current/power and provides the droop constants specified for normal operation in the MTDC system. In Song et al. (2021), the cost-based adaptive droop control scheme is proposed. As compared to other adaptive droop control strategies, this scheme considers the advantage of the fact that it tries to reduce the generation cost of AC system and provide robust control. Based on droop control, an improved control strategy for VSC-MTDC is proposed in Qian et al. (2019), where an equivalent circuit of VSC-MTDC has been established in d–q reference frame and employed for designing this strategy. Moreover, this control scheme is a communication free method where its droop parameters consisting DC voltage droop, AC voltage droop and frequency droop are chosen optimally. Since the proposed method has the capability of sharing active and reactive power, and in case of sudden changes, it can also control the DC voltage, AC voltage and frequency of AC/DC grids without any need for communication infrastructure.

3.2. Power flow control and sharing among the converter stations

In classical AC system, maintaining the power balance between the generation side and load side is achieved by monitoring the frequency of the system. Though, this type of control mode is not applicable to MTDC system, where the frequency of the system is zero. So it is possible to redistribute the power sharing between the AC and MTDC system by controlling the power converters. Non-coordinated control strategies can be implemented in two terminal HVDC systems to eliminate the power imbalances. Nevertheless, when multi-terminal DC networks are considered and significant power variation is expected with a large number of buses then DC voltage droop control strategies are employed to control the power flow and sharing in MTDC system (Kotur and Stefanov, 2019). As a fact, the meshed structure is the preferable structure for MMC-MTDC system. The uncontrolled flow of power can generate system losses and can affect the stability of the entire system. Thus it becomes necessary to design the power flow controller since its significance paves the way for further development of MMC-MTDC system and DC grids (Wu et al., 2021). The flow of power and sharing in an MMC-based MTDC network are controlled by the DC voltage of each terminal, as shown in Fig. 5. In this regard, voltage droop control strategies are employed for the efficient control of power flow and sharing in MTDC system under any kind of variations on the generation or load side (Aragüés-Peñalba et al., 2012).

The voltage drops in DC line and converter losses have major impact on the control of the power flow in VSC or MMC-based MTDC system that resulting in large power flow deviations in the network. An approach is proposed in Haileselassie and Uhlen (2012b) to get precise control of power flow in the MTDC system, which can eliminate the power deviations that occur due to the DC line resistance and converter losses. Flexible power flow control using a DC–DC converter for DC networks is provided in Rouzbehi et al. (2016), and the DC–DC converter is connected to DC transmission line in cascade form hence named as cascade power flow controller. In this system, two layers control method is designed with novel differential voltage droop control at the primary level. This strategy enables the cascade power flow controller to control the power flow in the HVDC transmission. Based on the DC voltage deviation factor and power sharing factor, another adaptive voltage droop method is proposed in Wang et al. (2019b). The DC voltage rating and power loading of each converter within their limits are ensured by this strategy during large disturbances. Also, the capability of power sharing of the complete MTDC system remains high. Further, four terminal MTDC system has been designed in the PSCAD/EMDTC to validate the effectiveness of this control strategy under different kind of disturbances. For accurate power sharing, a new control strategy has been proposed in the Kirakosyan et al. (2018) where accurate power sharing has been ensured between the droop controlled power converter stations. With the help of Power Sharing index (PSI) communication between the adjacent converters, the exact droop control operation is achieved by the proposed scheme independent of DC system topology and line parameters like lengths and line resistances. For comparison, the Pilot Voltage Droop (PVD) based controller has been taken as the base case, which is an alternative communication-based scheme for getting precise power sharing. Though, the conventional voltage droop control schemes in MTDC system for power sharing lead to the deviation of the voltage from nominal value. Further, there is inaccurate power sharing in droop controlled based MTDC system. In order to get equal power sharing automatically among the converter stations and to compensate for the voltage deviation, the secondary controller with distributed architecture is recently proposed in Zhang et al. (2020). This work

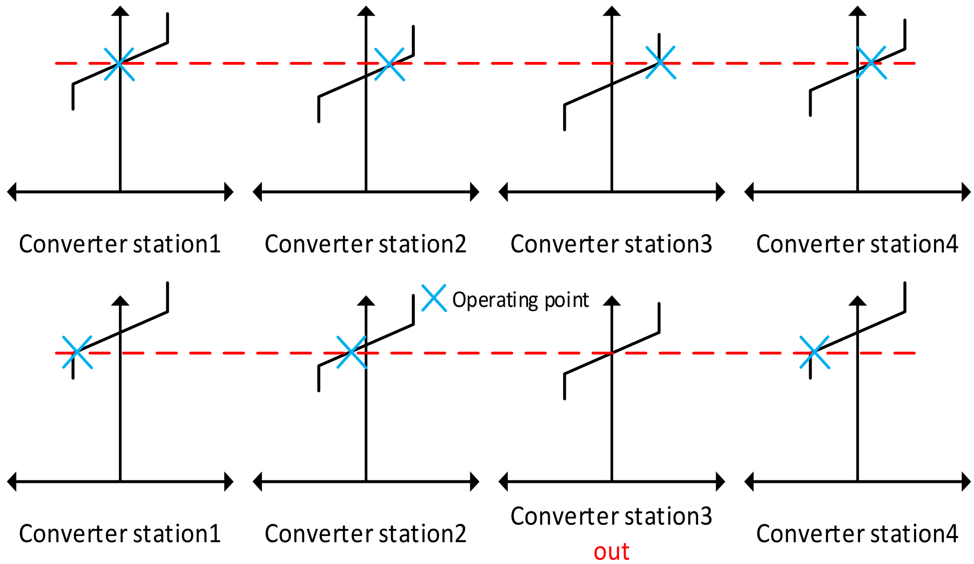

Fig. 5. Power sharing characteristics in four-terminal MTDC system (Zhang et al., 2017).

presents a nonlinear secondary control method for regulating the average voltage of the complete MTDC system to reference and for sharing the power mismatch based on power ratings of the converters in the system. In this proposed method, the droop-based primary controller is improved in terms of voltage deviation and power sharing mismatch because the designed controller has been added as an additional controller to the primary droop controller. In Yadav et al. (2020), a control scheme with the combination of adaptive droop control and linear quadratic regulator (LQR) control is designed in order to achieve an appropriate power distribution between the converter connections. This approach reduces overshoots/undershoots, as it improves the dynamics of the closed loop system. Hence, it also reduces the time required to reach a steady state. This approach facilitates the power sharing between the terminals as per the converter rating and reduces the oscillations in both power and voltage deviation signals.

3.3. Power oscillations damping

As discussed earlier, the VSC-MTDC system is a promising solution for the integration of renewable energy sources (RES) like large-scale off-shore wind farms (OWFs) (Liang et al., 2009). Several two terminal VSC-based HVDC links are connected to develop a VSC-based MTDC system to make better power sharing between the multiple RESs and asynchronous AC system. As the classical control strategies like master–slave and DC voltage droop control only focus on the stable operation of the DC grid (Cheng et al., 2019). However, the equivalent inertia of the whole power grid could be reduced by the integration RESs into power system as power electronic-interfaced RESs (VSC-interfaced) have very negligible or even no rotating mass (Nahid-Al-Masood et al., 2016). The systems with such low inertia may face more stability issues such as large frequency deviation, power oscillations and so on Liu and Chen (2015). Some low frequency oscillations issues have become more and more significant when there is large scale interconnected power system. Low frequency oscillations are divided into two categories inter-area oscillations and local oscillations (Li et al., 2015). Inter-area power oscillations are more difficult as compared to local oscillations as a large number of generators are involved in this type of oscillation mode. Inter-area oscillations mode can cause more serious harm as continuous and equal, or increasing amplitude oscillations occur. Moreover, these inter-area oscillations have caused wide-scale blackouts and may become the reason for separation and cascading failure in power systems (Pai and Stankovic, 2013). Therefore, attenuating the inter-area power oscillations is too much important in the power system.

Because of their flexibility and usually quick response, the VSC-MTDC applications with some modified control approach can provide a significant advantage to control the transmission system like inter-area power oscillations damping (Vural, 2016). The VSC-MTDC can also provide additional control features such as power oscillations damping, transient stability, fault recovery and sub-synchronous damping enhancement to improve the dynamic performance of the system (Liu and Liu, 2016). For the MTDC system, it provides the opportunity to integrate the power oscillation control into its DC power control. The basic idea is that by modifying the DC power reference value, oscillations of the AC system can be compensated (Pipelzadeh et al., 2013). It is also known that the active and/or reactive modulation capabilities of the MTDC system can be used in conjunction with several other signals to suppress inter-area power oscillations (Vural, 2016) effectively.

Ref. Preece and Milanović (2012) proposed the work to dampen the power oscillations in meshed AC network by the use of active power modulation at different converter stations in MTDC system. In this work, a power oscillation damping (POD) controller with a novel Modal Linear Quadratic Gaussian approach is designed. Based on the $\boldsymbol{H}_\infty$ mixed-sensitivity formulation in Linear Matrix inequality framework a robust damping controller has been designed for the MTDC in Banerjee and Chaudhuri (2016). In Li et al. (2017c), based on frequency characteristics of inter-area oscillations, the controller is designed to damp the oscillations in the MTDC system. In Banerjee et al. (2018), a new approach to damping inter-area power oscillations is presented by developing an additional robust controller with multiple inputs and multiple outputs for MTDC systems integrated into AC networks. A nonlinear model predictive control scheme (NMPC) is presented in Fan et al. (2018) for an MTDC system to damp inter-area in the power grid. In this work, the Ensemble Kalman Filter (EnKF) method was used to generate future forecasts based on a nonlinear model in a finite horizon. Unlike existing control methods, this approach retains full non-linearity in the AC-MTDC system. In addition, a modified two-domain, four-machine system and a modified IEEE New England system were selected to validate the proposed approach. In Lian et al. (2018), wide-area demand side control is developed to mitigate the inter-area oscillations by directly modulating the real power of end user loads. In this, the implementation of the control strategy is carried out in hierarchical manner. Ref. Wilches-Bernal et al. (2020) proposes a novel method using the loads, demand side of the system in order to damp the inter-area oscillations. The aggregator-level load modulation signal is determined by this novel methodology, where the loads are grouped into clusters and controlled as a unit. A coordinated control strategy for VSC-HVDC integrated with OWF has been proposed in Liu and Lindemann (2015), which aims to provide synthetic inertia. In Nie et al. (2019) the analysis of low frequency oscillations is proposed for AC/DC system with offshore wind power plant integrated through MMC-based HVDC system. Ref. Thakallapelli and Kamalasadan (2020) proposes the measurement-based wide area damping of inter-area oscillations based on multi-input multi-output (MIMO) identification, which facilitates estimating such oscillation frequencies. The wide area damping controller (WADC) design is based on the combination of the discrete linear quadratic regulator and Kalman filter to dampen the inter-area oscillations. This proposed method overcomes the demerits of earlier linearization-based methods presented in the literature.

The aforementioned damping control methods for VSC-MTDC can also be applicable to MMC-MTDC system. Though, the MMC topology has the advantage of internal energy storage, which can be utilized to damp the inter-area power oscillations (Trinh et al., 2014). Various methods to utilize the inherent energy of the MMC to damp the power oscillation are presented in the literature. The method utilizing the internal energy of MMCs to damp the low frequency power oscillations has been proposed in Barker et al. (2017). To effectively damp the power oscillations with virtual capacitance support of MMC is proposed in Taffese et al. (2020), where the effective DC grid capacitance is increased by using the stored energy of MMCs. It has been observed that various efficient power oscillations damping (POD) methods can be proposed by utilizing the internal dynamics of the MMCs for MMC-MTDC network. But there is still lack of work to be done in order to know the interaction of such dynamics. As the MMCs are more complex in terms of control than that traditional two-level VSCs. Therefore, there is a need for a more complex internal control architecture to properly control the internal dynamics of MMCs. In addition, the enhanced stability of AC system as well DC network may be achieved by utilizing the MMCs internal energy storage effectively.

4. Protection methods for MMC-based MTDC system

The big challenge in the development of MMC-based MTDC system is its protection under dc fault conditions. Fault current can flow from the AC grid to the DC side through the freewheeling diodes under DC fault conditions in half bridge (HB) MMCs, a more common converter configuration for MTDC systems. Therefore, if a DC fault occurs, a low short circuit impedance can cause a sharp increase in short circuit current, which can lead to severe damage to power converters or the complete shutdown of the whole system (Chen et al., 2011). However, HB-MMC configuration is widely preferred in the MTDC system, but it cannot block the dc fault under fault conditions and this behavior of HB-MMC is similar to the conventional two-level VSC, as shown in Fig. 6.

Fault handling of DC systems is similar to faulty handling of AC systems, which includes fault detection and location as well as fault interruption. The propagation rate of the fault in a DC system is much faster than in an AC system. Therefore, the fault clearing must be done rapidly in order to limit the effect of fault on the neighboring DC lines. Therefore, the time required to clear

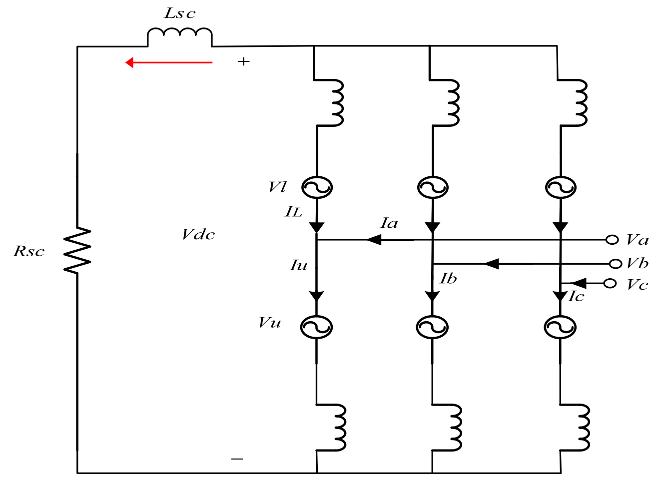

Fig. 6. Equivalent circuit of the HB-MMC system during DC-side short circuit fault (Qin et al., 2015).

the DC fault should be in the range of milliseconds which can be achieved with the employment of fast DC breakers (Taisneh et al., 2011). As discussed earlier that in event of DC fault, both HB-MMC and the conventional two-level VSC have similar behavior and cannot block the fault currents. Therefore, DC fault Analysis, Detection and Location methods for VSC-MTDC can also be used for MMC-MTDC system.

4.1. DC fault analysis

Analysis and calculation of short circuit current are necessary for a protection design of MTDC system. In literature, the DC fault types and characteristics for general VSC-based MTDC systems have been investigated by Chang et al. (2015), Bucher and Franck (2016), Guo et al. (2021), Li et al. (2020a) and Dessouky et al. (2019) in detail, which is also applicable to the MMC-based MTDC system. DC fault analysis of MMC-based MTDC system and two-level VSC has been proposed by the Cui et al. (2011) and Zhang and Xu (2016). Meanwhile, the results are based on the simulation of electromagnetic transients (EMT), which actually takes a long time when a large and complex DC network is taken into account. In Ref. Yang et al. (2011), the dynamics of two level VSC based network have been analytically studied. Ref. Ye et al. (2021) proposes the characteristics analysis and efficient estimation method for short-circuit current in MMC-MTDC system. In Li et al. (2017b), a generic fault current calculation method is proposed for DC grid, where the fault matrix of the entire Dc grid is established. However, this algorithm cannot provide clear analytical expressions of the fault current and also the parameters which affect the fault current. Further, a comprehensive review of DC short-circuit fault current analysis and suppression techniques has been carried out in Qin et al. (2020).

4.2. DC fault detection and location algorithms/ relaying algorithms

Various DC fault detection and location methods are known as relaying algorithms that have been presented in the literature to protect the MTDC system. These methods are categorized as non-communication/local measurement based and communication-based algorithms. The communication-based methods use only locally available measurements for fault detection and communication-based methods use the information from both ends to take the decision. The communication-based

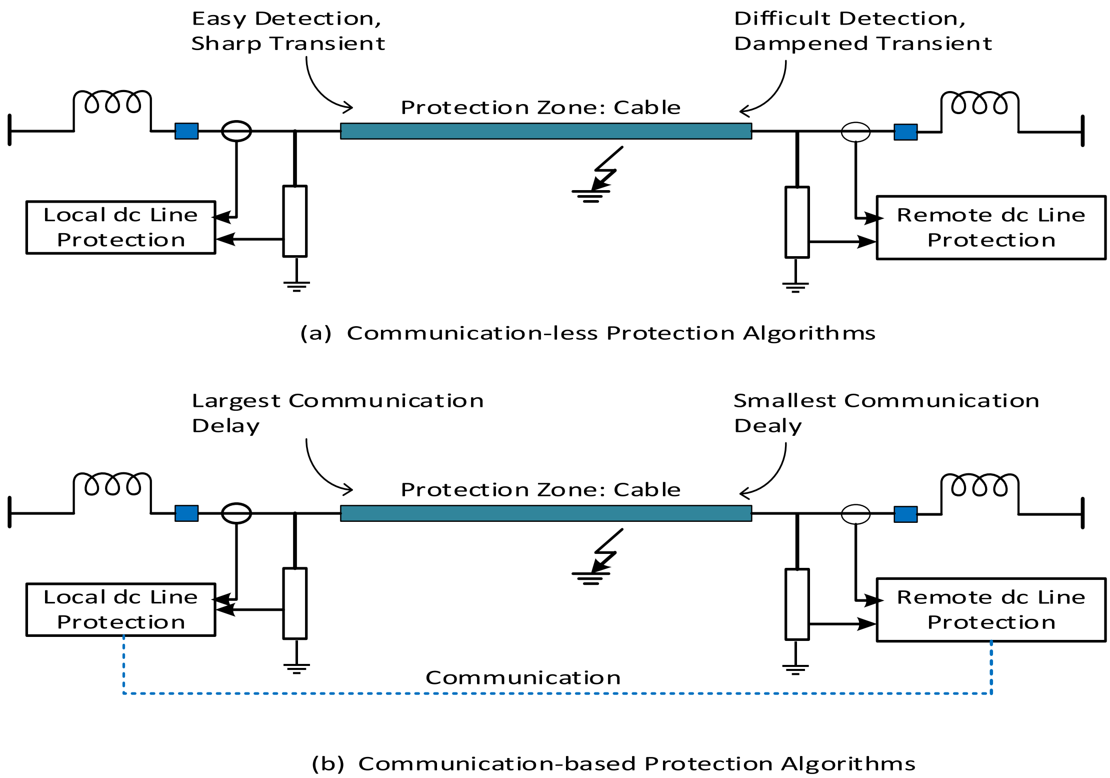

Fig. 7. A comparison of protection algorithms (Leterme et al., 2019).

algorithm is often called two-ended method, while communication less methods are known as single-ended methods. The basic concept can be understood from Fig. 7.

The local measurement-based algorithms are very fast since they take the information from a single end, but lack selectivity. Some of the examples include Undervoltage, overcurrent, rate of change of voltage and rate of change of current. Communication based algorithms are inherently selective, but they pose a slow response due to the communication channel. System based on these may go into a non-operative state if any problem is found in communication channel. The most common methods among these are directional-current and differential-current. Some other methods like traveling wave based and artificial intelligence based have also been discussed in the literature. Ref. Taisneh et al. (2011) describes differential, overcurrent and distance methods and their difficulties when applied to a high voltage direct current (HVDC) grid. In Naidoo and Ijumba (2004), Zhang et al. (2012), Li et al. (2017a) and Sneath and Rajapakse (2016), the traveling wave, voltage derivative and dc voltage level protection methods have been discussed. A detailed review of various fault detection and location algorithms is presented below:

4.2.1. Tarvelling wave-based

The concept of traveling wave-based fault location methods for the transmission line is explained in Baseer (2013). Refs. Jiang et al. (2018), Wang and Hou (2020), Li et al. (2018a) and Zhang et al. (2021) propose fault detection and location methods based on traveling waves. A traveling wave detection technique based on communication between two terminals was proposed in Azizi et al. (2014) and Leterme et al. (2016). The fault type and location can be precisely determined by calculating the traveling wave propagation time between two terminals. Although flexible HVDC grids need a faster protection speed than a typical HVDC system, it will be constrained by communication delay. In Zhang et al. (2021), a single-ended TW based protection method has been proposed for VSC HVDC with the integration of renewable energy. The proposed approach includes the theories of wavelet transform modulus maximum and phase-mode transformation for dc lines in the system. The results show high sensitivity to high resistance faults and remote faults. Ref. Jamali and Mirhosseini (2019) proposes the traveling wave based method for VSC HVDC where the traveling waves generated by fault events are filtered through series inductor. The filtered voltage is processed by a morphological gradient to design the single-ended protection. This method does not require communication and is capable of detecting and distinguishing high resistance faults. For MMC-MTDC grids, Ref. Zhang et al. (2019) suggests a novel single-ended line protection. The initial values of the traveling positive-sequence voltage traveling waves (PSVTWs) produced by the fault are initially examined using the symmetrical component analysis. Based on these, a fast protection scheme is proposed and tested under various fault conditions. However, in these methods, wave head detection is a major challenge in identifying the faults occurring on DC lines (He et al., 2014). In addition, methods based on traveling waves are not able to detect high-resistance faults, and their practical implementation is not easy due to the high-sampling method (Li et al., 2017a).

4.2.2. Natural frequency based

Natural frequency-based fault location and detection techniques have also received interest in HVDC. In these methods, there is no need to detect the wave head as with the traveling wave methods (He et al., 2014). Refs. Song et al. (2011) and Liao et al. (2013) propose the fault location methods based on the natural frequency of the traveling wave, which has the capability of locating the dc fault occurring on the HVDC lines accurately and quickly.

Ref. He et al. (2014) employs the natural frequency to locate the fault in a bipolar CSC-based HVDC system where the dominant natural frequency is used to calculate the fault distance by computing the velocity of traveling wave and reflection coefficient. The authors of Song et al. (2011) describe a fault location approach in a two-terminal VSC-based HVDC system by extracting the fault current's natural frequency. Because of the fault's high transient energy, the DC line will produce more natural frequency components. However, these methods are not applicable for time-varying transients. Additionally, the accuracy of measurement decreases when fault distance increases. Voltage and current frequency spectra can be utilized to propose an efficient method of protection.

4.2.3. Wavelet Transform based

The Wavelet Transform (WT) is a powerful method for extracting information from current and voltage signals (Robertson et al., 1996). WT-based protection schemes can be seen in Murthy et al. (2008), De Kerf et al. (2011) and Pérez et al. (2012). Wavelet transform based protection methods are categorized as continuous wavelet transform (CWT) and discrete wavelet transform (DWT) based methods. The DWT methods can easily be implemented compared to CWT, the discrete wavelet transform and pose less computation time (Yeap et al., 2017). In Saleem et al. (2018), DWT is used to locate and detect the fault in the DC system. The proposed method has been verified and tested for different fault types at different locations.

The Zhangbei four-terminal HVDC grid is used as an example in Kong et al. (2017) for the analysis and design of a DC line fault protection scheme. A lifting wavelet-based non-unit protection scheme has been proposed that can locate the fault within a few milliseconds. The validity and reliability of the suggested protection approach are verified under various fault resistances, locations, and fault types. In these methods, however, the wavelet coefficient for detecting the fault is predetermined. The fault entry angle and the fault's resistance can influence the methods' efficiency based on the coefficients of wavelets. In addition, these methods are not fast enough compared to others and may not show suitability for stand-alone protection schemes

4.2.4. Transient based

The transient-based protection method is presented in Zheng et al. (2012a), in which the difference in transient energy of the rectifier and inverter sides is used to detect the internal and external fault and differentiate them in a bipolar HVDC network. The method to detect and differentiate between the internal and external faults in two pole HVDC is proposed in Zheng et al. (2012b), where a transient harmonic current is used. However, its sensitivity can be affected by the resistance of fault and its location. Therefore, it needs information about transient current harmonics at both ends to distinguish one fault from another. Ref. Abu-Elanien et al. (2017) proposes the method of identifying the fault at a terminal using the high-frequency transient signal. Shunt capacitors installed at the bus bar are used to differentiate between the internal and external faults. In this way, high-frequency transients that originate from external faults can be eliminated. Meanwhile, the use of shunt capacitors add up the cost, but the requirement of communication system can be reduced as single end measurement is used for making the decision. Ref. Li et al. (2020a) proposes the fault detection method based on transient average current for MTDC system. Using the average transient value of current, a non-unit DC fault detection method having low complexity and high sensitivity is developed. In Abu-Elanien et al. (2016), a method for fault detection in VSC-MTDC is presented. The work is focused to use energy index difference and which can be determined from transient current signals with high frequency measured at both terminals. However, the accuracy in detecting the fault may not be possible practically by taking only the fault affected transient signals because similar transients can also be generated by switching or/and other transient events. In addition, transient-based fault location and detection methods are not sensitive to faults with high resistance.

4.2.5. Voltage and current derivative based

Refs. Wang et al. (2015) and Sneath and Rajapakse (2016) present protection methods based on the voltage derivative and current derivative. Voltage and current derivatives, namely the rate of change of voltage or current signals are considered an effective criterion for designing the dc fault analysis method for MTDC system. If the change rate of dc voltage or current exceeds the preset threshold value, a fault can be identified. Based on the dc voltage and current derivatives a fault detection method for radial MTDC is presented in Marvik et al. (2015b). However, the robustness of this method is not verified for meshed-MDTC system. A communication less protection scheme for HVDC radial transmission with three connections and a bipolar configuration is presented in Marvik et al. (2015a), which is based on the threshold limit of DC current derivatives and using DC CBs. However, its practical implementation is not feasible because the DC CBs are not yet available on the market. Ref. Meghwani et al. (2017) presents the work to detect and distinguish the fault in DC micro grid by using first and second derivatives of the fault current. Refs. Mirhosseini et al. (2021), Le Blond et al. (2016) and Haleem and Rajapakse (2018) present and review the fault detection and location methods based on voltage and current derivatives. Ref. Wang et al. (2019c) suggests a protection method for bipolar VSC-HVDC grids equipped with DC circuit breakers based on the Zhangbei HVDC grid project. The protection process is initiated, faults are quickly identified using the voltage gradient, and internal and external faults are distinguished using the voltage derivative criterion. Based on the propagation characteristics between the line- and zero-mode voltages, two different faulty pole identification techniques are suggested, guaranteeing the selectivity of the protection. However, these schemes depend upon the system topology and parameters such as capacitance and resistance. In addition, they have low accuracy for high resistance faults.

4.2.6. Overcurrent based

Over-current based protection methods have been proposed for VSC-HVDC in Baran and Mahajan (2007); the issue with this scheme is that it requires a high current threshold value to achieve the desired fault discrimination. Therefore, it will require a long span of time for the breaker to reach the completely open position. Additionally, the fault may not be detected if there exists a high impedance fault in the DC system. Moreover, overcurrent, under voltage and differential protection schemes have been established for the point–point HVDC system. However, the first two methods have the capability to detect the faults within 2 or 3 ms but are not able to detect the high resistance faults. Communication-based protection methods are applied to the Nan'ao three terminal MMC-HVDC project in literature. The boundary components (line inductors) used in the Nan'ao project are 10 mH. Under these weak boundary conditions, Ref. Guo and Liu (2018) uses overcurrent protection in conjunction with current differential protection to discriminate between internal and external faults. Ref. Yang et al. (2010) proposes an overcurrent protection for a radial VSC-MTDC. The current magnitude is compared to a threshold of 2.1 p.u. Further, an inverse time OC method has been suggested in Torres-Olguin and Hoidalen (2015) for three-terminal MTDC where the magnitude of the current is inversely changed with time.

Although, a differential protection scheme can detect high resistance faults but meet the speed requirements of DC protection, it relies on a fast communication link. Even when high-speed communication link is used, such as an optical link, the applicability of the differential scheme is determined by the length of the cable or line (Le Blond et al., 2016).

Table 2
DC fault detection and location methods.

Protection method	Advantages	Limitations
Handshaking method	Cheaper than DC CBs Practically applicable	Not suitable for multi-terminal HVDC system Long down time for the entire DC network
Traveling wave-based	More suitable for DC transmission because the traveling wave is present at any point, Provides the high speed protection	The detection of wave head is challenging in identifying the faults, Sensitive to noise and current capacitive distributions in differential protection
Natural frequency-based	No need to detect the wave head as in traveling wave, Can use any post fault data	May not be applicable for time varying transients Algorithms are not fast enough and stable as compared to other methods
Wavelet-based	Band pass filters can be avoided as it consists of filter banks	The fault resistance and fault inception can affect the effectiveness May not be applicable for stand-alone systems
Transient/derivative	Can use changes in both voltage and current Able to detect external faults due to high selectivity	May not be suitable for MDTC due to presence of multi-resonance frequencies in the system Depending on system parameters (resistance and capacitance) and system topology Not applicable for high resistance fault due to low accuracy
Overvoltage/overcurrent	Provide tolerable results as a backup protection	Low accuracy and selectivity thus cannot be used as main protection scheme in MTDC
Artificial Intelligence (AI)-based	Provides fast and accurate results in simulations	Practical implementation is difficult as it is not robust enough
Harmonic-based	Can discriminate between the external and internal faults	More suitable for 2, 3 level converters but difficult to detect on MMC

4.2.7. Handshaking method

Refs. Tang and Ooi (2007) and Ashouri et al. (2018) propose the handshaking method to detect the dc fault in VSC-MTDC system. The concept of handshaking was firstly introduced in Tang (2003). This scheme uses AC circuit breakers and Dc switches. The handshaking method can be applicable to two terminal HVDC network. However, for the MTDC system, when the fault occurs, the AC CB will perform the function and all the converters have to be shut down, and because of this, the power flow in the entire network can be interrupted. In addition, transient phases such as capacitor discharge and diode freewheeling stages take place very rapidly, and could cause the damage of semiconductor components and other devices if reasonable care is not taken. Further, fault detection and location methods are summarized in Table 2.

4.3. DC fault interruption methods

In Barnes et al. (2020) the AC CBs coordinating with DC switches are employed to clear the Dc fault in Dc grid which is also called handshaking-based protection method. However, the AC CBs have a slow response; this solution cannot meet the fast requirements of Dc grids. In this regard, the MMCs with fault blocking capability can provide more feasible choices for DC fault interruption in MTDC system. In consequence, three ways are practicable to clear the DC faults in MMC-MTDC system. They can include the use of DC CBs, the integration of an MMC converter topology with fault blocking capability, and the coordination of converters with DC CBs and some other protection components.

4.3.1. Use of DC circuit breakers

There are mainly three types of DCCBs which include mechanical, solid-state and hybrid DCCBs have been introduced in the literature for DC systems as shown in Fig. 8. The basic operating principles and configuration of DC CBs are studied and reviewed in Barnes et al. (2020) and Mohammadi et al. (2021). The DC CB actually needs to create zero crossing switching in order to interrupt the fault current and dissipate the energy stored in the system. In Ref. Eriksson et al. (2014), the mechanical DC CB is employed in high power dc grid to isolate the fault. The configuration of the mechanical DC CB basically consists of a normal current path, commutation path and energy dissipation path, as shown in Fig. 8(a). During the normal operation, the current flows through the CB and when the fault occurs, it will be commutated through commutation path. Mechanical DC CBs are inexpensive and have the advantage of low on state losses. However, their operating time is around 30 to 100 ms, so they are not preferred in VSC-based HVDC applications.

The other category of DC CB is solid state DC CBs which basically employ the semiconductor switches as both are normally conducting and breaking elements. For the implementation of solid-state DC CBs, various combinations of semiconductor switches and ancillary circuits with an ultra-fast operating speed are used (Meyer and De Doncker, 2006). Solid-state DC CBs have the ability to interrupt the fault current rapidly and their typical operating time is less than 1 ms. Therefore, these CBs can be used when high speed fault isolation is needed. However, the solid-state DC CBs have high on-state losses and a high cost (Pei et al., 2016).

One of the DC CB configurations in the discussion today is hybrid DC CB which typically stands out from the former two. This type of DC CB is implemented with the combination of mechanical DC CBs and solid-state DC CBs, which essentially includes the negligible on-state losses of mechanical switches with the advantages of power semiconductors. Refs. Li et al. (2016) and Ahmad and Wang (2000) present the operation of hybrid DC CBs and their application to the HVDC grid. The general and typical configurations of hybrid DC CBs are shown in Fig. 8(b) and (c), respectively.

In Shukla and Demetriades (2015), operational principles of the hybrid DC CBs are analyzed, and their various configurations are summarized too. The fault isolation method based on hybrid DCCB for DC grid is presented in Hajian et al. (2013). In the hybrid DCCBs, the total protection time and peak breaking time are responsible for the size of surge arrestors and other power electronic devices. Ref. Wang and Marquardt (2015) presents a fast hybrid DC CB with scalability and modularity properties. Moreover, the use of semiconductor switches in hybrid DC CBs makes them able to provide high-speed fault isolation, and their operating time is 2 ms. As a fact, the mechanical DC CBs have the capability to provide low loss conduction paths but take a

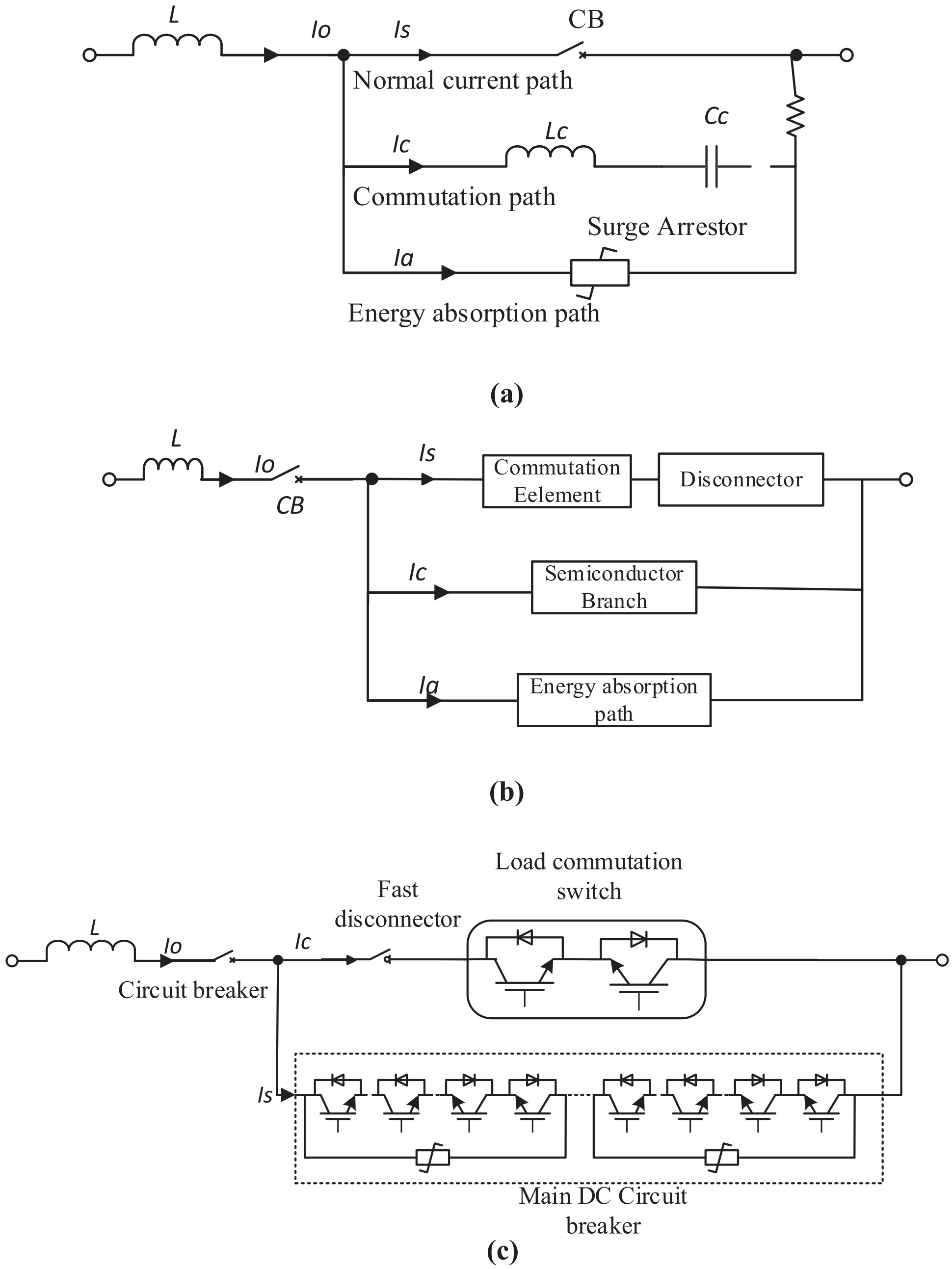

Fig. 8. (a) Basic configuration of mechanical DC CB (b) general configuration of hybrid DC CB (c) typical specific configuration of hybrid DCCB (Callavik et al., 2012).

long time to clear the faults. On the other hand, the solid state DC CBs have a faster switching speed and can clear the faults in less than 1 ms but have more on-state losses as compared to the mechanical DC CBs. Consequently, the hybrid DC CBs have lower on-state power losses than the solid state DC CBs and faster speed than the mechanical DC CBs.

4.3.2. Use of MMCS with fault blocking capability

Researchers today have an interest in taking advantage of the in-built fault-ride through the capability of MMC converters by modifying their sub-modules (Yadav et al., 2017; Huang et al., 2017). The modified sub-module can generate the voltage with reverse polarity to eliminate the fault in the DC network and recover very quickly, as it can avoid the contribution of the AC side to the DC fault current. In addition, modified converters can improve the system stability, since they also work as wave shaping circuits and can regulate the AC current while riding through a DC fault.

Therefore, the protection schemes based on the converter topologies provide the alternative to replace the expensive CBs completely. Owing to the benefits of fewer switches and lower losses, the HB MMC topology is more dominant topology in HVDC application. However, it has no fault blocking capability, so when the fault occurs on the DC side, the fault current can flow from the ac side through antiparallel diodes. However, it has no fault blocking capability, so that in the event of a fault on the DC side, the fault current can flow through anti-parallel diodes from the AC side. In order to address this matter, it is necessary to propose the MMCs with inherent fault-blocking capability.

Ref. Zhang et al. (2018a) proposes an enhanced HB sub-module configuration which not only has the ability of protection but also employs a reduced number of power thyristors of lower cost and has lower losses than the conventional HB sub-module in

MMC. A novel bidirectional blocking SB (BBSM) is proposed in Xue et al. (2017) to clear the fault; the fault current is completely transferred to the bypass thyristor when all IGBTs are switched off. However, the cost and volume are significantly increased by employing additional thyristors. The HB sub-module with a bi-directional control switch is designed in Zhang et al. (2019a) and is known as a hybrid double direction blocking sub-module (HDDB) for reducing power losses in the MTDC system. In Yao et al. (2020), a new type of double reverse sub-module is proposed, which contains less power devices with the same voltage. A novel flexible an over-head HVDC transmission converter station topology is proposed in Huo et al. (2020), wherein blocking sub-modules are added onto the positive and negative side of DC buses of a traditional HB SM converter station. The proposed work provides the rapid fault current blocking in the event of DC bus short circuit. In order to avoid the concerning flaws of the double thyristor-based fault clearing method on DC side, a protection technique based on the new MMC sub-module topology is proposed in Li et al. (2020c). In this work, RC absorber, a group of inverse-series IGBTs and diodes are added to the sub-module. Ref. Zhu et al. (2019) proposes the full bridge director switch based MMC topology, which has the features of DC side fault blocking capability and is more compact. Also, it provides a more effective predictive control strategy in order to reduce the error of sub-module capacitor voltage and output AC current. However, there are more power losses, especially with the increase in the number of SMs. Presently, various MMC topologies with fault blocking topologies have been proposed in the literature. Although the proposed topologies efficiently block fault current, the large number of switches and other control circuits results in additional power losses. Various hybrid design strategies have been proposed to optimize the MMC design in terms of fault blocking capability, power loss and cost.

4.3.3. Use of coordination of the MMCS with DC CBS

The MMCs with fault blocking capability SMs are not cost-effective solutions to clear the fault in MTDC network due to their high cost and high losses. Moreover, there is still a need for DC CBs to isolate the faulty lines reliably in MTDC system. However, the only use of DC CBs is not even a possible solution for interrupting the DC fault current because a large number of CBs are needed in meshed MTDC network (Wang et al., 2019a; Liu et al., 2017).

Therefore, the coordination of MMC topologies with hybrid DC CBs can provide a potential solution (Wan et al., 2020). In Zhao et al. (2019), two novel coordination methods have been presented for dc fault suppression and clearance. Ref. Wang et al. (2017) proposes the coordination strategy to discontinue the fault current by hybrid DC CBs without blocking the MMC. Also, it ensures the continued operation of a healthy system. An assembly of DC CBs and a corresponding control strategy have been proposed in Liu et al. (2017). Based on the coordination of Dc CBs and HB MMCs, a protection strategy has been proposed in Tejas Gaidhani and Thakre (2020) to prevent the overcurrent and suppress the dc fault current in MMC arms.

5. Future development prospects of MMC-based MTDC system

Significant developments have been made in SM topologies, modeling, control, modulation techniques, and MMC applications over the past decade. In recent years, MMC has received more attention from various industrial applications and has become an integral part of new HVDC systems, integration of various RES into the grid, medium voltage drives, FACTs and storage systems. In addition, MMC-based HVDC systems have become an emerging technology that will lead to the development of the concept of super grids in the future. However, it suffers from several problems that must be resolved in order to expand its scope. This allows new SM topologies to be proposed to reduce the cost and size of the back-to-back MMC structure. With medium voltage inverters, there is a problem with the voltage ripple of SM capacitors. High value capacitors are needed to reduce these ripples during low frequency operation, which actually increases the cost and space of the entire system. To solve this problem, an efficient control method is needed. There are control and protection problems in the MMC-MTDC system; if they are met, a new search gateway could open. New control methods have to be developed in order to increase the output performance of the MMC and also to decrease the communication load. Further, enhanced hierarchical control architectures are also required to be proposed to integrate the system properly. To develop the large-scale MTDC system, more computationally efficient models of MMCs would be required. More research on the internal dynamics of MMCs would be needed to be carried out for the development the efficient methods to dampen the power oscillations in MTDC system.

A fast and robust protection system for MMC-MTDC systems is highly required. Therefore, there is still a need to develop fast and robust dc fault detection and location algorithms that can take the decision within the first few milliseconds. A combination of the different algorithms can provide better protection performance. Therefore, the combination of local measurement based and communication-based algorithms is still a challenge that can be further instigated. The use of only DC CBs for the protection of MTDC system is not an economical solution. The coordination DCCBs with MMC for the development of an effective protection system is highly recommended. However, coordinated protection strategies with decreased switching losses and overall cost are required to be developed for the future MTDC system.

The use of semiconductor material in MMCs plays a vital role in its performance. Nowadays, silicon-based semiconductor devices are widely used, but the combination of silicon and silicon carbide (SiC) (Leterme et al., 2019) could pave the way for a great future for the development of new SMs in future. In addition, the combination of these components can offer advantages such as the use of small capacitors, lower power losses, increased efficiency and fault handling capability, and full control under normal and high conditions fault.

6. Conclusion

This paper provides a review of the control and protection system of the MMC-MTDC system. The basic DC voltage control strategies have been discussed in detail. Further, coordinated control strategies have also been reviewed, and their critical analysis is presented. Besides, it covers the protection of MMC-MTDC under dc fault conditions. The protection part mainly discusses the various aspects of the relaying algorithms and fault interruption methods. Various Relaying algorithms have been discussed in terms of different characteristics and applications.

It can be concluded that new control schemes need to be developed to improve MMC output performance and reduce communication load. To properly integrate the system, the enhanced, hierarchical control architectures are also required to be addressed. Coordinated-droop control with other control schemes may be the best solution for future MMC-based MTDC control strategies to improve the performance of AC and DC systems. There is still a need to utilize the internal dynamics of the MMC to design an efficient method to reduce the power oscillations.

Further, various types of dc fault detection and location algorithms have been discussed in detail. Various methods such as voltage based, currently based and traveling wave based have been discussed. Their main characteristics and features are compared and summarized. The local measurement-based algorithms are fast but lack selectivity. Moreover, they need the limiting inductors in order to improve the selectivity and set the protection zones. Also, these inductors reduce the peak value of fault current; this allows the use of CBs with a lower rating, which can avoid the higher energy dissipation. Meanwhile, the communication-based algorithms provide high selectivity, but their application is limited by the communication delay and channel's correct operation.

It can be concluded that the protection of the MMC-MTDC system predominantly incorporates the local-measurement based algorithms. Further, HB-MMC configuration and fully selective strategies with hybrid DCCBs are highly recommended for the future development of the MMC-MTDC system. In addition, combining the different protection algorithms can benefit the system's protection performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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