A Comprehensive Review of the Protection Methods Applied to the MTDC Systems

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***Abstract*— With the recent development in voltage source converters (VSC), modular multi-level converter (MMC) topology has been recognised as the most suitable topology for building multi-terminal direct current (MTDC) grids. Today, several MMC-based MTDC projects have been commissioned. The primary motivation to construct such advanced MTDC grids is to ensure the reliable and economical operation of the interconnected power system. Protection of MTDC grids is a vital task, requiring effective protection algorithms to detect the transients in milliseconds and isolate the healthy and unhealthy parts quickly. The emerging technology of hybrid direct current circuit breakers (DCCBs) assures the de-energization of the faulty section in an MTDC system. However, such a solution is uneconomical and produces increased power losses. This research work provides a comprehensive review of different protection devices and fault detection methods for MTDC systems. In addition, the effects of measuring and communication devices on protection methods are also discussed. Finally, the challenges for existing protection systems are discussed and some future recommendations are presented.**

Keywords—MTDC Systems, HVDC Grids, MMC, Protection Methods, DC Circuit Breaker

I. Introduction

Word-wide integration of renewable energy resources for electricity generation increases day by day. With this rapid development, the demand for a secure and reliable high power transmission system is emerging [1]. The bulk and long-distance power AC transmission system possesses high capacitance and huge power losses. A high voltage direct current (HVDC) transmission system has been identified as the most reliable and economical solution to transmit electric power from offshore power plants [2]. MMC-based HVDC systems are widely adopted to integrate offshore power plants, the connection of weak AC grids, and the integration of asynchronous grid ties [3]. A multi-terminal direct current (MTDC) HVDC system provides numerous advantages over point-to-point interconnection, such as flexibility, reliability, redundancy, and improved fault ride-through capability [4, 5]. Due to the robust features of MMC, it has been recognised as the most suitable topology to build MTDC systems. With the improvement in MMC technology, MTDC systems can now provide independent control of active and reactive power, which makes them more suitable for building smart grids [6]. An illustration of a four-terminal Zhang-Bei MMC-based MTDC system is shown in fig. 1 [19].

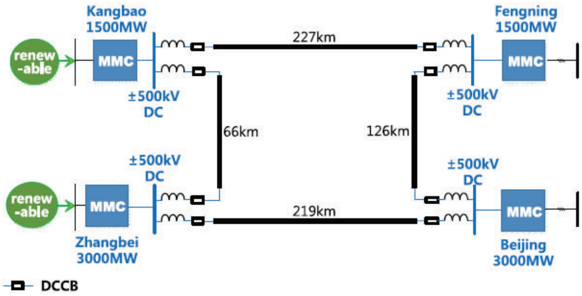

Fig. 1. Zhang-Bei MMC based MTDC system [19]

Protection of DC grids is not an easy task compared to AC grids. Because of the low resistance and zero reactance of dc lines, they are more venerable to DC faults. This limits the use of impedance-based protection methods [7]. The most common protection algorithms designed for MTDC systems are voltage and current derivative, travelling waves, and signal processing-based methods [6, 7].

However, these techniques suffer from various drawbacks. These include the requirement of a fast communication medium for differential protection, poor efficiency of travelling wave methods for high impedance faults, and low accuracy of voltage & current derivative-based methods [6]. For DC side transients, several protection methods are proposed in the literature, such as the implementation of fault-blocking submodules [8], DCCBs [9], and coordination of fault blocking MMCs with DCCBs [14]. However, all such methods increase the overall cost and power loss in an MTDC system. Therefore, for an MTDC system, designing a proper protection scheme is still a big challenge, which requires the design of an economical and efficient protection scheme with appropriate coordination of MMC, DCCBs, and other protective devices. This article provides a comprehensive review of existing protection methods of MTDC systems. At first, various DCCB topologies are discussed. After that, an in-depth critical analysis of existing fault detection and isolation methods for MTDC systems has been provided. The challenges for the protection of MTDC systems and the effects of measurement & communication devices on protection systems are discussed in detail. Finally, some future recommendations are discussed. The rest of the paper is organized as follows. Section II discusses the development of protection devices, section III gives a brief overview of various protection methods, section IV discusses the impact of measurement and communication devices on protection systems, section V discusses issues and challenges pertaining to the protection of MTDC grids, section VI provides authors' recommendations and section VI concludes the outcomes of the review.

II. PROTECTION DEVICES

With the commercial integration of MTDC systems, the demand for the realization of the DC circuit breaker (DCCB) is increased. Today, multiple DCCB topologies are invented. However, their commercial realization is still a big challenge for power industries [28]. This includes numerous technical and economic limitations. In this section, the development of DCCBs and their challenges for their commercial realization are discussed in detail.

A. Mechanical DCCB

The isolation of a DC line is challenging compared to an AC line because of the absence of zero crossing in DC. Today several DCCBs are available in the market. The mechanical DCCB is an economical solution to interrupt DC short circuit current and possess lower on-state losses [24]. It creates a zero current crossing using a resonant circuit. It is more suitable for the protection of medium voltage systems. A DCCB with a resonant circuit is the simplest mechanical DCCB used for HVDC systems. A mechanical DCCB may be classified as an active resonant mechanical DCCB, which utilizes a pre-charged capacitor for active commutation and passive resonant mechanical DCCB, which uses a non-pre charged capacitor for passive commutation [30, 31]. In [32], the optimal design of the commutation branch is proposed for the active resonant mechanical DCCB, which reduces the overall commutation period. In [33], an active resonance circuit for mechanical DCCB is proposed using multiple series gaps. In [34], the bidirectional current carrying capability of mechanical DCCB is studied. In [35-38], different topologies have been proposed to improve the overall performance of a mechanical DCCB. In all these designs, the slow opening of DCCB leads to high arc currents, which may cause the failure of the interruption process [30]. The current limiting reactors increase the overall cost and power losses for a VSC-based HVDC system. However, exemption of current limiting reactors leads to the requirement of a large capacity of inductors and capacitors [30]. The development of semiconductor devices has restricted mechanical DCCBs for MTDC systems [31]. Owing to its higher operating time, this type of circuit breaker is not suitable for VSC based HVDC and MTDC systems where the fault current interruption time is the most critical element [26, 30]. An active resonant circuit for mechanical DCCB is shown in fig. 2 [30].

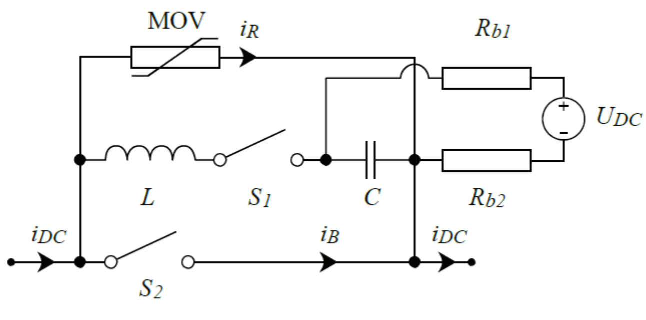

Fig. 2. Active resonant circuit for mechanical DCCB [30]

B. Solid-State DCCB

The solid-state DCCBs use semiconductor switches as conduction and breaking elements. Because of lower conduction losses, insulated gate bipolar thyristor (IGBT) and insulated gate commutated (IGCT) are preferably used in solid-state DCCBs [28]. Two topologies of SSCB are presented in literature 1. SSCBs with surge arrestors and SSCBs with freewheeling diodes [31]. These two topologies are discussed in detail in [39]. In a surge arrestor based SSDCB, the current flows through IGBTs in normal operating conditions. The IGBT is turned off in case of a fault, and the surge arrestor starts conduction. The current conduction by the surge arrestor results in the blocking of any abnormal grid voltage. In the other type of SSDCB, a freewheeling diode is connected in parallel with the IGBT to protect it against voltage spikes in a fault condition. In addition, the surge arrestor is also employed to dissipate the heat caused by the fault current [31]. The typical operating time of a solid-state DCCB is less than one millisecond. Thus, it is recommended for systems where high-speed fault isolation is required [24]. The number of valves in a solid-state DCCB depends upon its voltage and current rating. The high voltage MTDC systems require the design of high voltage CB valves, which involves a chain of IGBTs. This results in higher design costs and higher operating losses. Due to fast operating time, the conduction losses in a solid-state DCCB are excessive compared to mechanical DCCBs. Due to these reasons, their application to high voltage MTDC systems is restricted [30]. The typical arrangement of a solid-state DCCB is shown in fig. 3 [28].

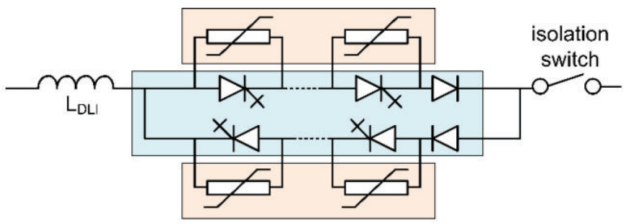

Fig. 3. Typical arrangement of a solid-state DCCB [28]

C. Hybrid DCCB

The hybrid DCCB combines the advantages of both mechanical and solid-state DCCB. In a hybrid DCCB, the normal current flows through a mechanical switch and a power electronic switch. IGBTs are switched off using an auxiliary breaker, and the fault current travels to the main breaker in case of a fault. The auxiliary breaker is isolated using a mechanical switch. The main breaker is then opened to isolate the fault current [26, 28]. The operating time of hybrid DCCB is two milliseconds, having higher current breaking capability and reduced power losses. [26, 28, 30]. The extensive use of power semiconductor devices in a hybrid DCCB make it more expensive. They are more suitable for protecting VSC and MMC based HVDC systems. However, when it comes to an MTDC system, the overall cost of the protection system is increased [24]. Moreover, due to its complex structure, its failure rate is high compared to ACCBs [31, 40]. ABB[9] and Alstom [41] are the major manufacturers of hybrid DCCB. A schematic diagram of ABB hybrid DCCB is shown in fig. 4 [50].

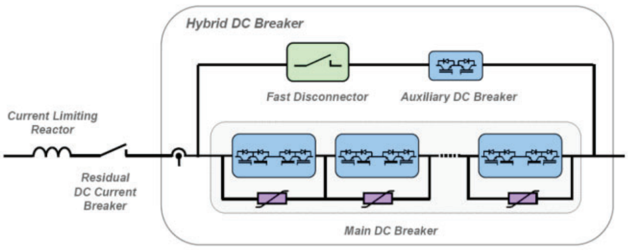

Fig. 4. Schematic diagram of hybrid DCCB proposed by ABB [50]

D. *Hybrid DCCB With Fault Current Limiters*

Hybrid DCCBs can effectively handle the DC fault transients. However, the increasing trend of high voltages in HVDC systems leads to the severe magnitude of fault currents and a longer operating time may exceed the capacity of hybrid DCCB. To avoid this fault, current limiters (FCLs) may be combined with the hybrid DCCBs. FCLs reduce the magnitude of fault current to ensure the satisfactory operation of hybrid DCCBs. FCLs may be used as independent circuits, or their features may be embedded in the design of hybrid DCCBs to suppress the fault currents [42]. Two types of FCLs are discussed in the literature, i.e. superconducting FCLs and non-superconducting FCLs [43]. In [42-45], the design of hybrid DCCBs combined with FCLs is discussed. For VSC and MMC-based MTDC systems, hybrid DCCBs combined with FCLs would be feasible to interrupt fault currents. However, the practical implementation of FCLs possesses various technical and economic challenges, which include power loss and an increased cost of DCCB [31]. The control strategy for a hybrid DCCB proposed by ABB is shown in fig. 5 [26].

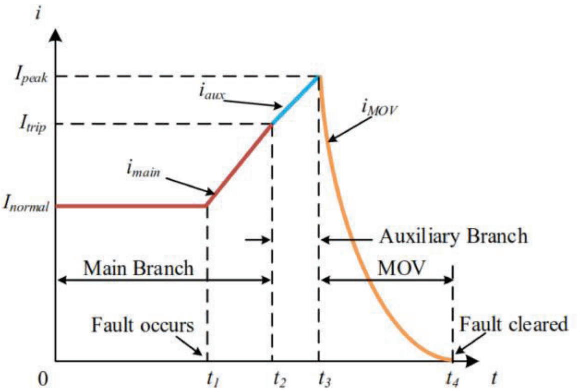

Fig. 5. Control strategy of a hybrid DCCB proposed by ABB [26]

The mechanical DCCBs possess a considerable operating time, ranging from 60 to 100 milliseconds. For hybrid DCCB, it is less than 30 milliseconds. However, the working time of a solid-state DCCB is relatively low, which is less than one millisecond [28, 31]. Compared to a VSC station, the mechanical DCCBs possess negligible power loss because of the low voltage drop across the breaker's contacts. The power loss inside a hybrid DCCB is less than 1% of VSC station power losses. However, a solid-state DCCB causes an increased power loss compared to other DCCB topologies [28, 31]. It is because of power electronic switches in the main current path. Experimentally, mechanical DCCBs are tested up to a voltage rating of 550kV, while hybrid DCCBs are designed for a 120kV rating. However, the solid-state DCCBs have not been designed for higher voltage ratings still. By looking at the increasing utilization of power semiconductor devices in DCCBs, it is expected that SSCB would be realized for a commercial rating of 800kV in future [31]. The current interruption rating of a hybrid DCCB is the highest among all DCCB topologies [28]. A detailed comparison of different DCCB topologies parameters is given in [31].

III. PROTECTION METHODS FOR MTDC SYSTEMS

Protection algorithms are responsible for detecting and locating faults. These can be classified into local measurement and communication-based algorithms [17]. The local measurement-based protection algorithms utilize the magnitude of direct current & voltage and their derivatives for fault discrimination [46]. Over-current, under-voltage, di/dt and dv/dt algorithms are considered as local measurement algorithms [17, 46]. Communication-based protection algorithms include differential current and current directional algorithms. They are selective but at the cost of increased time delay produced by the communication medium. Additionally, they are not suitable for long-distance transmission lines [47]. However, such methods can be effectively used for high impedance faults where the speed of operation is not critical [48]. The protection methods based on travelling wave theory and artificial intelligence (AI) for detecting faults can be local measurements or communication-based algorithms. The travelling wave methods utilize mathematical techniques such as wavelet and Fourier transforms to extract the fault current information [46]. Artificial neural network (ANN), an example of AI, is a robust approach for detecting and locating faults in an HVDC system. The speed of operation of ANN is breakneck [49]. However, it requires complex training algorithms, which causes an increased computational burden [46]. In [24, 46, 47], the different fault detection and location methods are discussed. A summary of various fault detection and location methods is given in table I.

TABLE I. SUMMARY OF FAULT DETECTION AND LOCATION METHODS

Fault Detection Method	**Measurement Algorithm**	**Suitability as Main/ Backup Protection**	**Limitations**
Over Current and Under voltage	Local Measurement algorithm	Backup Protection	Low accuracy & selectivity, and limited speed of operation
Differential Current	Communication-based Measurement algorithm	Primary protection for short transmission lines. Backup protection for long transmission lines	Effective for short transmission lines only. Communication delays affect the speed of operation. Require synchronised measurements
Directional Current	Communication-based measurement algorithm	Main Protection	Communication delay affects its speed of operation
ROCOV	Local Measurement algorithm	Main protection	The low cable impedance and increased line length affect its speed of operation and selectivity. Sensitive to noise

ROCOC	Local Measurement algorithm	Main protection	Affected by noise. Reduced selectivity for high impedance internal faults
Travelling Wave	It may be a local measurement or communication-based measurement algorithm	Main protection	The detection of wave head is challenging in identifying the faults, Sensitive to noise. The incapability of detecting close-up faults. Require a high sampling rate
Artificial Intelligence (AI)-based	It may be a local measurement or communication-based measurement algorithm	Main protection	Complex training algorithm leads to additional computational burden. Hardware implementation is not economical

A. *Overcurrent and Under-Voltage*

In an overcurrent protection algorithm, the magnitude of fault current is monitored locally and compared with a threshold value. The speed of operation of an overcurrent protection algorithm is fast but a cost of reduced selectivity [52]. The selectivity can be improved by employing the directional current criterion. However, it may cause false tripping of adjacent relays. It is best suited for backup protection combined with other protection schemes [50]. In the under-voltage protection algorithm, faults are characterized by low voltages, which cause the under voltage relay to operate. Like the overcurrent protection algorithm, directionality cannot be achieved using an under-voltage protection algorithm. This method is also employed for backup protection combined with other protection schemes [47].

B. *Directional Current Algorithms*

A current directional algorithm is a communication-based algorithm [47], which detects the fault when it is located in the forward direction. It works on monitoring the current polarity. If the relays of the protected line detect a fault in the forward direction, the trip signal is sent to the CB [52, 56]. Such a method of protection is selective. However, the communication medium produces a time delay [47].

C. *Current Differential Protection*

A differential current algorithm sums the input and outputs a current of a DC link or bus bar [52]. For DC lines, the current value is measured locally at each end of the line and communicated to the other end's relay. In this way, each end of the line possesses information about both measured currents. At any end, the difference between both currents is compared with a pre-defined threshold, and if it exceeds the threshold, the fault is detected [47, 57]. This algorithm is robust and selective [58]. However, the communication medium produces a time delay for a DC line, affecting its operation speed [46]. Communication time delay can be more with the increasing length of DC line, which restricts its utilization in HVDC systems with long transmission lines [47]. It is more suitable for short-distance transmission lines, backup protection and high impedance faults [46].

D. *Voltage And Current Derivative Algorithm*

Voltage derivative algorithm or rate of change of voltage (ROCOV) is widely adopted for LLC based HVDC systems. In a voltage derivative method, the rate of change of voltage is measured at various instants to detect any abnormality in DC voltage. It is fast enough to detect faults [51]. Additionally, it can discriminate between internal and external faults [46]. To achieve the discrimination between internal and external faults, the value of ROCOV is compared with a predefined threshold [52]. The low cable impedance and increased line length affect its speed of operation and selectivity [51]. The current derivative or rate of change of current (ROCOC) method utilises the initial rate of fault current to detect the abnormality. Ideally, the ROCOC should be zero during normal operating conditions. However, practically the fluctuations in current affect its selectivity. To ensure selectivity, the value of the present derivative is compared with a pre-defined value [46]. The ROCOC provides faster detection than the overcurrent algorithm. However, the ROCOC for remote internal faults with a high impedance may be lower than the ROCOC for external faults [51]. A general illustration of the fault detection method is shown in fig. 6 [24].

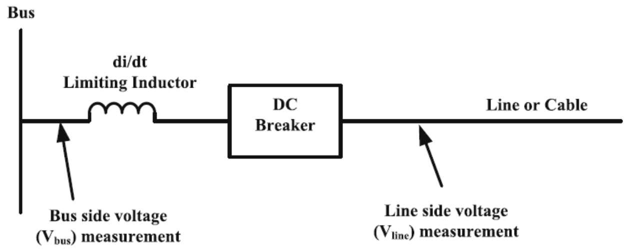

Fig. 6. Illustration of fault detection [24]

E. *Travelling Wave*

When a fault occurs in the HVDC network, the voltage and current waves propagate rapidly across the entire network. These waves contain essential information about the voltage and current surges. Such information is utilized by travelling wave-based methods to detect the fault. A travelling wave method detects the initial wavefront [47, 54]. To do this, samples for voltage and current are measured at various instants with high sampling frequencies. The result is recorded if the difference between two consecutive measurements exceeds the pre-defined value. In this way, subsequent measurements are taken, and if all samples witness similar behaviour, the fault is detected [47].

The most crucial signal processing tools based on the travelling wave method are Fourier transform and wavelet transform. A Fourier transform is a powerful signal-processing tool that extracts the frequency content of a travelling wave to detect the fault [54]. Discrete Fourier transform (DFT) and fast Fourier transform (FFT) are the two power tools of Fourier transform. A Fourier transformed signal does not contain the time information [46]. However, an FT requires ample time for monitoring the signal, which affects the speed of operation for fault detection. Additionally, important information may be lost for the monitored signal, which affects its reliability. These shortcomings may be fulfilled by wavelet transform [47]. A wavelet analysis works on a time-scale basis [55]. It can detect any abrupt or local changes in the signal. Wavelet transform (WT) detects the fault current's first minimum or maximum co-efficient to indicate any fault condition. Discrete wavelet transform (DWT) and continuous wavelet transform (CWT) are the two significant types of the wavelet transform. As compared to CWT, the computational burden of DWT is less. Due to this reason, it is preferred for fault detection in HVDC networks [47].

F. Artificial Intelligence-Based Algorithms

Artificial intelligence (AI) is a promising approach for fault detection and location due to its superior pattern recognition capabilities. There are several AI methods proposed in the literature for fault detection that include Artificial Neural network (ANN), Fuzzy Logic (FL), Expert System (ES) and Genetic Algorithm (GA) and some other hybrid approaches. The artificial neural networks (ANNs) are adaptive to evolving situations and improve their performance based on the information gathered [53]. They can diagnose the system's behaviour from the data extracted from the fault signal. They are robust and fast enough to detect and locate the fault in an HVDC system [54]. However, the complex training algorithm of ANNs leads to an extra computational burden.

IV. . IMPACT OF MEASUREMENT AND COMMUNICATION DEVICES ON PROTECTION METHODS

The performance requirements for an effective protection system are selectivity, sensitivity, speed of operation and accuracy [14, 15]. Today, a single vendor usually provides the protection and control devices. Hence, the fault detection algorithms for an MTDC system are provided in a single intelligent electronic device (IED) [16]. The local measurement algorithms are very fast to detect the fault. However, they are not selective and are less sensitive to external faults [17, 18]. To improve the selectivity of local measurement algorithms, limiting inductors are placed at both ends of the protection zone. These algorithms use a threshold value to compare the measured values for discrimination between internal and external faults. A higher threshold value increases the selectivity but at the cost of reduced sensitivity [19]. Communication-based algorithms are selective. However, they require a communication channel to send and receive data, which imposes a time delay [17, 20]. A time delay in communication-based algorithms is the most unwanted parameter [21]. Additionally, any fault in the communication channel will cause the failure of the protection system. Hence, such algorithms may not be feasible to be used as primary protection. However, they are suitable for secondary protection systems [22]. Using advanced fault current limiting methods, communication-based algorithms can provide primary protection when the fault current is limited. This will reduce the rising rate of fault current, and hence speed of operation would not be mandatory [19]. Combining resistive type superconducting fault current limiter (RSFCL) and DCCB can effectively reduce the rising fault current rate [23]. For the reliable and economical operation of MTDC systems, a fast-acting protection system is necessary. Today the complete protection system requires to be implemented in distributed IEDs. This requires designing protection algorithms having wide bandwidth and high speed.

V. CHALLENGES FOR PROTECTION OF MTDC SYSTEMS

In an HVDC system, the fault may occur at various locations such as AC side faults, internal converter faults, and DC side faults. For a reliable protection system, it is necessary that fault current may not propagate on either side of the converter station [10]. For AC side faults, usually, distance relays are used to protect the MTDC system [24]. The fault inside the converter station may cause loss of a load or generation, which affects the overall stability of an interconnected system [10]. For the VSC and MMC-based HVDC systems, under pole-to-pole short circuit conditions, the fault current may rise ten times the standard operating current, which may cause severe damage to the converter station. Hence, the primary concern relevant to converter level protection is controlling the rising rate of fault current [29].

HVDC lines are more venerable to DC side transients. For a line-commutated converter (LCC), a DC side fault is not very severe because of the presence of large reactors, which reduce the amount of fault current. However, it is more challenging for VSC & MMC based systems because of fast rise time, high peak and steady fault current [24, 25]. Developing cost-effective and robust protection strategies for MMC-based MTDC systems is challenging. The increasing number of terminals and converter levels in VSC found HVDC systems have put the researchers' focus on DC side protection. Half-bridge MMC (HB) is the dominant topology for reduced cost and higher efficiency, but it can not block DC short circuit currents. To reduce the rising rate of DC short circuit currents, full-bridge MMC (FBMMC) and its different variants are proposed in the literature. However, these solutions increase overall cost and losses in an MTDC system [11]. To interrupt the DC short circuit current, various DCCBs are available in the market, such as mechanical DCCB, solid-state DCCB and hybrid DCCB. However, using only DCCBs to interrupt fault current is not economical. It is because, for a meshed MTDC system, several DCCBs are required. This would also produce a complex communication system [12, 26, 27]. The coordination of fault blocking MMCs with DCCBs provides an optimal solution for dc short circuit currents [13]. The coordination strategies presented in the literature need improvement due to higher switching losses.

VI. RECOMMENDATIONS

MTDC systems are more venerable to DC faults because of the low impedance and high capacitance of DC lines. DC faults induce high currents, which converter stations cannot tolerate. Implementing conventional protection schemes such as overcurrent, distance, and differential current schemes is unsuitable for protecting MTDC systems [24]. The development of fast-acting protection algorithms is highly recommended. The communication-based fault detection algorithms are highly-selective but at the cost of increased time delay. However, the local measurement algorithms are fast enough to detect the faults but at the expense of compromised selectivity. The selectivity of local measurement algorithms can be improved by employing current limiting inductors. This provides robust discrimination between internal and external faults [46]. Further research is required to optimize the overall cost and size of FCLs. A protection system based on fault blocking MMCs and hybrid DCCBs can be an ideal solution for MTDC systems. However, this will increase the overall cost and power losses of an MTDC system.

In future, cost-effective coordination methods are required to handle the DC short circuit currents. This involves the development of fault blocking MMCs with increased fault current limiting capacity & reduced switching losses to reduce the number of hybrid DCCBs in a meshed MTDC system. Additionally, the integration of renewable energy resources in an MTDC system requires the development of adaptive fault detection methods based on AI and travelling wave theory [24]. Moreover, due to continuous development in MTDC systems, protection standards for advanced DC protection methods are essential to be developed.

VII. CONCLUSION

This paper is intended to present a comprehensive review of existing protection methods applied to MTDC systems. The various topologies of HVDC CBs for fault isolation are also discussed in detail. The advantages and limitations of different protection methods are summarized based on the local measurement and communication-based algorithms.

It can be concluded that for an interconnected MTDC system, a single protection method cannot fulfil its protection requirement. A combination of various fault detection methods is required for a robust protection system. The local measurement-based algorithms are fast but lack selectivity. Selectivity can be achieved by employing communication-based protection algorithms but at the cost of time delay introduced by the communication medium. The current limiting inductors may be placed at both ends of a DC line to improve its selectivity. This will reduce the size of DCCBs but will cause an increased power loss. Self-blocking converters can reduce the fault current but at the cost of increased power loss. The superior features of hybrid DCCB have improved the fault isolation requirements of an MTDC system, but its overall worth is high. Coordination of converter stations with hybrid DCCBs seems an optimal choice for fault isolation. In the future, the design of cost-effective hybrid DCCBs and advanced coordination methods must be developed for their integration in combination with fault blocking converter stations.

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