Review

A Comprehensive Survey of HVDC Protection System: Fault Analysis, Methodology, Issues, Challenges, and Future Perspective

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Abstract: The extensive application of power transfer through high-voltage direct current (HVDC) transmission links in smart grid scenarios is due to many factors such as high-power transfer efficiency, decoupled interconnection, control of AC networks, reliable and flexible operation, integration of large wind and photovoltaic (PV)-based off-shore and on-shore farms, cost-effectiveness, etc. However, it is vital to focus on many other aspects like control, protection, coordinated operation, and power management to acquire the above benefits and make them feasible in real-time applications. HVDC protection is needed to focus further on innovative and devoted research because the HVDC system is more vulnerable to system faults and changes in operational conditions in comparison to AC transmission because of the adverse effects of low DC-side impedances and sensitive semi-conductor-based integrated power electronics devices. This paper provides a comprehensive review of the techniques proposed in the last three decades for HVDC protection, analyzing the advantages and disadvantages of each method. The review also examines critical findings and assesses future research prospects for the development of HVDC protection, particularly from the perspective of smart-grid-based power systems. The focus of the review is on bridging the gap between existing protection schemes and topology and addressing the associated challenges and issues. The aim is to inform power engineers and researchers about potential research avenues to tackle the challenges in HVDC protection in smart-grid-based power systems.

Keywords: high-voltage DC (HVDC); high-voltage AC (HVAC); protection; fault current limiter (FCL); voltage source converter (VSC)

1. Introduction

1.1. General Overview

The first inception of the transmission and distribution of electrical energy in the year 1882 was based on direct current (DC) and a 50-kilometer-long DC transmission line realized utilizing DC machines between Miesbach and Munich in Germany. Later, due to the flexibility of AC transmission and distribution, alternating current (AC) dominates the DC-based approach in the power sector to date. However, many associated factors related to AC transmission links attract the use of DC technology, such as the inductive and capacitive influence of overhead lines and cables, charging current having an adverse impact on the frequency and loss in system operation, particularly in the case of AC

cables, making it not feasible to connect two systems with different frequencies, which easily leads to system instability because of high short-circuit levels or undesirable power scenarios. Due to the above reason, DC transmission is always considered a supplement to AC transmission. Figure 1 demonstrates the step-by-step improvement of high-voltage DC (HVDC) transmission [1]. Broadly, there are two types of HVDC: the classic technology based on thyristors for conversion and HVDC light based on voltage source converter (VSC) technology using transistors for conversion. At present, the research is focused on DC support in AC grids with renewable energy sources.
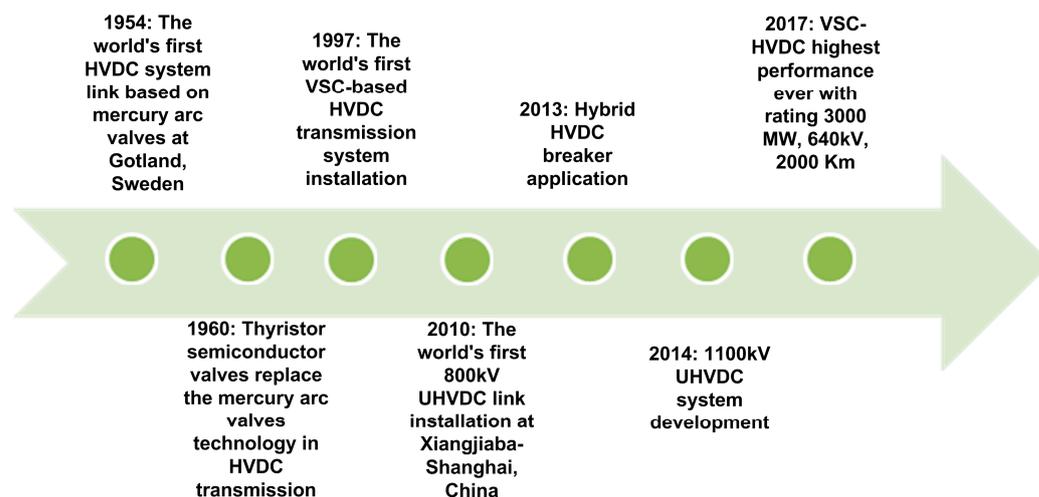

Figure 1. Evolution of HVDC technology deployment.

HVDC technology presents several operational benefits over conventional HVAC technology, standing as a promising alternative to bulk power transfer at high voltage levels [2]. The attractive features making it more realistic to power system are (i) secure and cost-effective solutions for future extensions of the grid or new interconnections [3], (ii) substantial reduction in transmission power loss, (iii) significant installation cost reduction in long-distance power links, (iv) keeping the same amount of power transfer, HVDC fetch fewer electrical conductors with a smaller diameter and lower weight [3], (v) having the capability to transmit power over a long distance through underground or undersea cables, (vi) with an HVDC link it is easy to interconnect two asynchronous grids, (vii) overall system stability is enhanced because of controllability and flexibility of the power flow even under AC transients, (viii) flexibility to integrate with fluctuating and renewable power sources without sacrificing the operational efficiency and stability, (ix) independent active and reactive power controllability, and (x) acting as a firewalling of AC grids against cascading blackouts. These factors justify the larger application of HVDC transmission, shortly, in comparison to HVAC transmission.

1.2. Motivation and Incitement

HVDC-based transmissions are having a significant impact on power grid operation even with the integration of supplementary sustainable and renewable-source-based generation [1–4]. In the era of renewable power generation, HVDC can be applied in the grid connection of remote offshore wind-power plants, photovoltaic (PV)-based large solar generation, and interconnections among nations. Operationally, HVDC technology is ideally preferable to maintain and enhance sustainability, efficiency, and reliability with greater control and protection of power supply systems. HVDC has gained its preference for many applications as a transmission link through submarine cables, land cables, and overhead lines. Apart from that, the major HVDC functions at the smart transmission and distribution system level are connecting remote generation, interconnecting grids for bulk power transfer, power from shore, DC links in AC grids, city-center infeed, multi-terminal applications, and connecting remote loads. In real-time implementation, each transmission

link has its own set of requirements concerning the choice of HVDC. The major prominent factors are asynchronous interconnections, long-distance water crossing, lower losses, controllability, environmental concerns, limited short-circuit currents, and lower investment costs. However, the operation of HVDC transmission for better performance needs to be associated with better HVDC control and protection strategies.

The implementation of the protection scheme in DC circuits is too challenging for the following reasons.

- Generally, mechanical circuit breakers exploit natural zero crossings of fault current to interrupt the current. However, the absence of natural zero crossings of DC fault current creates many problems for performance [5].
- In the case of a DC fault, the fault current level is considerably high with a low voltage level across the entire grid because of significantly low DC line impedances.
- Location of fault in DC grids is comparatively not easy because of low DC line impedance.
- Under the condition of DC voltage dropping to around 80–90% of nominal value, there is a high possibility of blocking of VSCs [4].
- In the DC systems, as cables are used extensively, there is a considerable amount of shunt capacitance impedance. Apart from that, the integration of converter DC-side capacitors and filters further added capacitance to the circuit. This capacitance presence in the circuit may have an adverse impact under transient and faulted conditions.
- All the VSCs, DC/DC converters, and DC CBs present in the DC circuit have very small thermal constants and a very small over-current rating. This factor leads to putting hindrance to clearing DC faults in a short time [4].

The DC fault current has a large peak and steady values within a few milliseconds. As a result, it is crucial to employ high-speed fault detection and isolation techniques to manage the critical implications that arise in an HVDC grid. The black-out incident in the UK in August 2019 [6] was a significant event that highlighted the importance of protection schemes in HVDC systems, particularly in the context of renewable energy integration. The incident was triggered by a series of cascading failures in wind generation, which caused a critical drop in the system's frequency excursion (RoCoF). This led to the activation of low-frequency demand disconnection (LFDD) protection schemes, which disconnected large parts of the grid to prevent a total system collapse. The incident demonstrated the potential consequences of inadequate or poorly designed protection schemes, which can lead to large-scale blackouts and disruptions to the energy supply. It underscores the need for robust and reliable protection schemes in HVDC systems, particularly as more renewable energy sources are integrated into the grid. By ensuring that protection schemes are up to date and adequately designed, the risks of blackouts and other disruptions can be minimized, and the transition to a cleaner, more sustainable energy system can be facilitated. These factors motivate this study to carry out an in-depth survey of HVDC protection.

1.3. General Literature Review

The above issues make the design and implementation of HVDC protection more complex. In addition to that, the HVDC grids similar to HVAC are also not failure proof. Hence, very fast and reliable protection systems are required in the case of HVDC to avoid adverse effects on the system components. The in-built protection scheme must be capable of fault detection, location, and clearance in a very short span of time according to the specified standard specification in the order of 10 ms. Hence, fast protection algorithms and HVDC circuit breakers (CBs) need to be designed and implemented with a suitable fault-clearing strategy adaptation to minimize the impact of fault conditions in the HVDC systems. Looking at the importance and urgency of HVDC protection in the recent power grid scenario, this study intends to discover the opportunities and limitations for further development.

Even though many innovative and effective modeling and design protection strategies related to HVDC have been suggested in recent times, still many issues arise because of rapid changes in topology and dynamics for the up-gradation of the power sector in the

direction of smart and microgrid concepts. To be aware of and provide information to the researchers about the developments and related issues, many review articles are published on HVDC protection [7–12]. Candelaria and Park [7] presented a comprehensive review of different protection methods used in VSC-HVDC systems. However, the article has a limited scope, as it only focuses on VSC-HVDC systems and does not cover other types of HVDC systems. Additionally, the article was published over a decade ago, so it may not reflect the most current protection methods used in VSC-HVDC systems. Zhang et al. [8] provide a comprehensive review of the modeling, control, and protection of modular multilevel converter (MMC)-based multi-terminal HVDC systems. The article provides an in-depth analysis of various MMC configurations, control strategies, and protection schemes. The article's strength is that it provides a detailed review of the MMC-based MTDC system's modeling, control, and protection. Authors in [9] have covered various DC fault protection methods, including DC circuit breakers, fault current limiters, and DC fault detection and isolation methods. The article's strength lies in its comprehensive and detailed review of the DC fault protection methods for HVDC grids, covering different types of protection methods and discussing their advantages and disadvantages. One limitation of the article is that it only focuses on DC fault protection and does not cover other types of protection methods used in HVDC grids, such as AC fault protection. Li et al. [10] provide a comprehensive review of protection methods for multi-terminal VSC-HVDC grids and its emphasis on the importance of reliable protection mechanisms for the grid's safe and stable operation. The authors provide a critical analysis of each protection method and compare their performance in different scenarios. They also discuss the challenges associated with protection in multi-terminal VSC-HVDC grids and suggest potential solutions. However, one limitation of the article is that it focuses solely on multi-terminal VSC-HVDC grids and does not cover protection methods for other types of HVDC grids. Chang et al. [11] discussed the impact of fault detection methods on pre-emptive VSC-HVDC dc protection performance. The authors present a detailed review of different fault detection methods used in VSC-HVDC systems, including the use of traveling wave signals, wavelet transform, and artificial intelligence techniques such as fuzzy logic and neural networks. Perez-Molina [12] reviewed the protection approaches of MT-HVDC in two groups such as local measurements or communication channel assisted. In conclusion, a comparison was made between the key features of the protection algorithms that were reviewed. These features included the system configuration, converter technology, fault-clearing strategy, circuit breakers used, and the size of the limiting inductors.

Upon reviewing the aforementioned literature, it is apparent that a significant number of papers predominantly focus on providing fundamental descriptions of HVDC faults, fault interruption devices, and conventional protection strategies. Furthermore, numerous review articles accentuate the criticality of integrating renewable energy, which has resulted in the substantial proliferation of HVDC systems. Nonetheless, there remain certain research gaps that prompt us to undertake a new review article in the same field.

- The literature on HVDC transmission protection has provided only limited exploration of the issues and challenges involved in protecting HVDC transmission systems. More attention needs to be given to issues such as DC fault protection, protection coordination, and the impact of power-electronics-based converters on protection schemes.
- It is worth noting that while renewable energy integration with HVDC protection is an important area of research, the current literature does not deeply analyze this topic. Further research is needed to fully understand the implications of renewable energy integration on HVDC protection and to develop effective protection schemes that can accommodate the variability and intermittency of renewable energy sources.
- In addition, the use of signal processing and machine learning techniques for HVDC protection has not been significantly analyzed in the current literature.

1.4. Major Contribution

This review paper is formulated to add the new techniques proposed recently and technical information not presented in past review papers on HVDC protection. While several review papers on this topic have been published, this paper provides a comprehensive analysis of recent advancements and challenges in the field. Building on the existing literature, this review paper aims to consolidate gaps in the protection solutions on various system-faceted topics, which had been missing in previous literature reviews. The paper seeks to provide a more up-to-date and in-depth analysis of the current state of the art in HVDC transmission, with a focus on addressing these gaps in the literature (as mentioned in Section 1.3). Additionally, this paper also highlights the current research gaps and future directions for HVDC transmission in smart grid applications.

- In this paper, an attempt has been made with an extensive discussion and analysis based on the associated issues and challenges of HVDC protection.
- The pros and cons of all the existing methods and the recently suggested approaches are detailed to provide a motivation for further research that needs to be carried out in this direction.
- The major crucial factors to which the paper is devoted are (a) the evolution of HVDC protection and its implementation challenges, (b) the performance of traditional HVDC protection schemes (fault-clearing strategies) and their associated hurdles, (c) the possibilities of integration of the advanced protection schemes with the traditional architecture, (d) extensive summarization after a thorough investigation of every operating condition and mode of operation, (e) types and performance comparison of different existing circuit breakers (CBs), and (e) suggestions to all possibilities and requirements to do further research for a better solution as a futuristic direction with smart intelligent methods and designs.
- The above factors make this review paper different from all the review papers published to date.

This manuscript is organized as follows. In Section 2 is discussed HVDC protection issues and challenges. Section 3 describes the classification of DC faults in HVDC systems. Section 4 presents different fault-clearing strategies for HVDC systems. Sections 5 and 6 present HVDC protection solutions implemented in the traditional power system and recently suggested by various researchers and technocrats. Critical discussions based on the major findings are presented in Section 7. The future scope and possibilities on HVDC protection are discussed to provide the focus of the researchers in this field. At last, the paper is concluded in Section 8 with a summary of the work accomplished in this study.

2. Issues and Challenges for the Protection of HVDC Transmission

Like HVAC systems, HVDC transmission systems are not absolutely failure proof. Many issues and challenges need to be focused on for future HVDC grids, as follows [3]:

- During certain fault conditions, the voltage drops suddenly, and the current also increases to an undesirable high value very rapidly. Some components, such as VSCs and others, may differ greatly in this regard, including their ability to sustain a current value up to twice their rated value. These are disconnected as a result of self-protection, which may lead to blackouts. To solve the above problem, the HVDC links need to be protected with a fast, reliable, and fast-detecting system that can detect, locate, and remove any faults within 10 milliseconds.
- It is imperative to design and coordinate circuit breakers (CBs) that can minimize the adverse effects of fault conditions in both the AC and DC systems associated with HVDC links by following the appropriate fault-clearing strategies.
- In voltage measurement devices, achieving high operational bandwidth can be limited by the presence of stray inductances in the capacitive part of the system. This is due to the resonance effects that occur in the connected parallel RC groups of the voltage divider that is used to reduce the primary voltage amplitude. These effects can restrict

the operational bandwidth of the device, particularly at higher frequencies [13,14]. Similarly, in the case of DC measurement devices, the bandwidth is limited to a range of a few kHz to MHz because of the dependence on fiber optic cables. This is because fiber optic cables can experience signal attenuation and dispersion, which can limit the bandwidth and accuracy of the measurement.

- The conventional methods for HVDC protection lack effective strategies in terms of selectivity and are not as efficient for detecting external faults. Aside from this, the protection-based algorithms are working by the pre-setting of limited values chosen through substantial simulations. However, it is always difficult to choose the appropriate optimal value because a higher value improves the selectivity but reduces the sensitivity of the algorithm.

- In the case of a communication-based protection algorithm, the major issue is the dependency of performance on the communication channel medium and the associated time delay in it. The first factor reduces the overall reliability because a problem in the communication channel makes the overall protective system nonfunctional, and that always needs to be accompanied by backup protection. The second factor restricts the operation to not being fast enough, which is a mandatory characteristic for an ideal implemented protection strategy [15].

- For the communication-based protection algorithms, improved fault-limiting techniques are implemented to limit the rapid rise of current and are used as primary protection, particularly for short transmission lines and to protect against high impedance fault scenarios. However, this reduces the requirement for speed.

- HVDC transmission links are protected from DC faults using AC CBs located on the AC side because of advanced technology and cost-effectiveness in comparison to the HVDC CBs. However, these CBs have less operational speed and take more time for disconnection because of mechanical restrictions and take several cycles, up to tens of milliseconds.

- The disconnection of converters by the use of AC-CBS because of DC side faults is not appropriate, particularly for the DG's integrated multi-terminal HVDC grids.

- A larger size of indictors is connected in the HVDC-CBS, and there is a need to dissipate a larger amount of energy that later affects the ability to acquire the stability of the overall system.

- The main conduction branch, the communication branch, and the energy absorption branch are connected parallel branches. Under normal operation, the current flows through the main conduction branch, while the current is forced to flow to the commutation branch because of the need to be interrupted during the occurrence of the fault. Under this condition, a large amount of stored energy loss occurred at the connected surge arresters located in the energy absorption branch.

- HVDC protection requires advanced fault-detection systems that can operate many times faster than required for an AC system. This is because of the low inertia property of DC systems, and because of that, faults propagate very fast across the network.

- Speed, selectivity, and time delay are the three most challenging issues that need to be focused on for HVDC protection. High-speed DC CBS (much faster than an AC system frequency cycle) is required to clear the fault currents rapidly because of the rapid increase in energy to be dissipated. The standard tripping time including the time delay of the associated hardware in the loop is standardized as less than 1 millisecond. The second challenge selectivity is the major concern to identify correctly the faulted section to clear among several DC lines forming a DC network. The third challenge in the form of communication time delay arises because of long HVDC transmission lines. This in turn might have made the current differential protection much slower than the speed of requirement of a DC grid.

- The interaction of AC/DC in the HVDC connection as a transmission link may bring many operational issues, such as the HVDC block leading to a power shift to AC sys-

tems and making it more intense, a blackout from AC/DC interaction, and abnormal AC voltage leading to HVDC commutation failure or blockage.

- The probability of commutation failure is increased substantially when going for a high-voltage-level power transfer, particularly for DC in the case of a multi-infeed HVDC link.

3. Taxonomy of HVDC Faults

Faults associated with HVDC systems may be classified as (i) AC-side faults, (ii) DC-side faults, and (iii) internal converter faults (ICFs) [16]. The AC-side faults generally occur in AC transmission lines connected with current source converter (CSC)-based HVDC stations, which may be symmetrical or asymmetrical in nature. The occurrence of AC faults at the transmission line can lead to communication failure followed by DC voltage collapse [17]. Distance relay schemes and AC circuit breakers are usually used to protect the transmission system from these external faults or AC faults. The ICFs generally occur because of converter misfire, DC-link capacitor failure, flashover, etc. [18]. A brief analysis of the existing protection schemes for ICFs is presented in Section 6. The faults that occur on the DC side are classified as (i) pole-to-pole (P2P) faults, (ii) pole-to-ground (P2G) faults, and (iii) pole-to-pole-to-ground (P-P2G) faults. DC faults are more harmful to the VSC-HVDC system compared to CSC-HVDC lines. The fault current associated with the CSC-HVDC system is limited by large DC reactors at the DC terminals, whereas the fault current associated with the VSC-HVDC system is of large magnitude, is steady in nature, and has a very fast rise time [19]. Owing to the growing installation of multi-terminal VSC-HVDC systems worldwide, the research toward the development of DC fault protection schemes has gained huge attention in the last decade. An extended study on DC faults can be extracted from the literature [20–26].

3.1. Pole-to-Pole (P2P) Faults

P2P faults are considered as the severest compared to P2G faults in a VSC-HVDC network. When a P2P fault occurs, in the initial phase, the DC link capacitors react to it by a discharging action. After that, within a few μ-seconds, the converter valves are closed to protect them from over-current. Then, the free-wheeling diodes (FDs), which are connected in anti-parallel across the semiconductor switches, start conducting in the opposite direction to protect the valves from over-voltages. In the second stage, the DC link voltage falls; however, the link inductance compels a flow of current through FDs, albeit in the absence of DC voltage. Due to this, a huge spike can be observed in the current signal. In the subsequent stage, the short-circuit current is supplied from the AC network via FDs. In a multi-terminal DC network, any DC link coupled to the same bus will continue to supply the fault current. In this case, the converter is unable to block this current as it does not lie in the fault current path [27]. To show the voltage and current behavior during this fault, a simple HVDC model as shown in Figure 2 is simulated in MATLAB. Figure 3 shows a sample of graphs for both voltage and current signals during P2P faults with different fault distances from the converter (VSC1) end. It can be observed that the voltage is dropped and the current is elevated after the fault occurs; however, the rate of change of voltage and current is decreased when the fault distance increases. Moreover, it can be seen that although the fault distance is too far from the converter, the fault current is increased approximately twice the steady-state value within a few milliseconds.
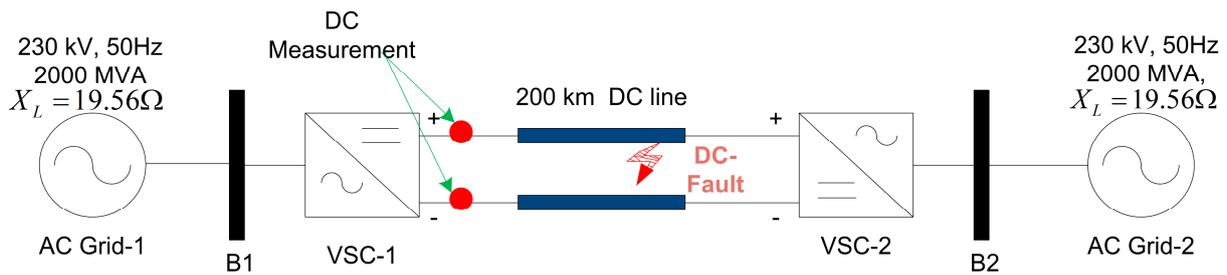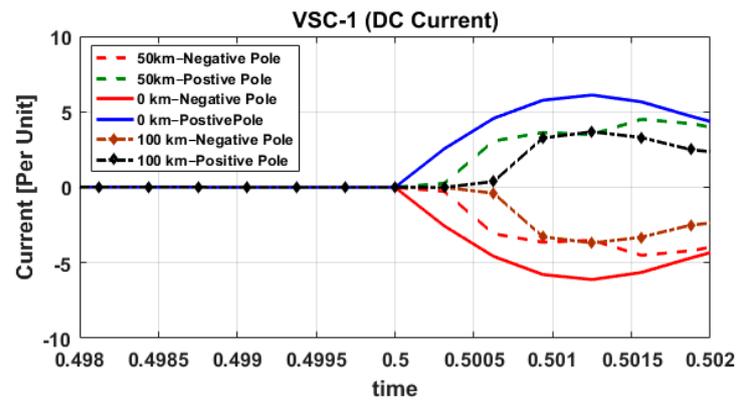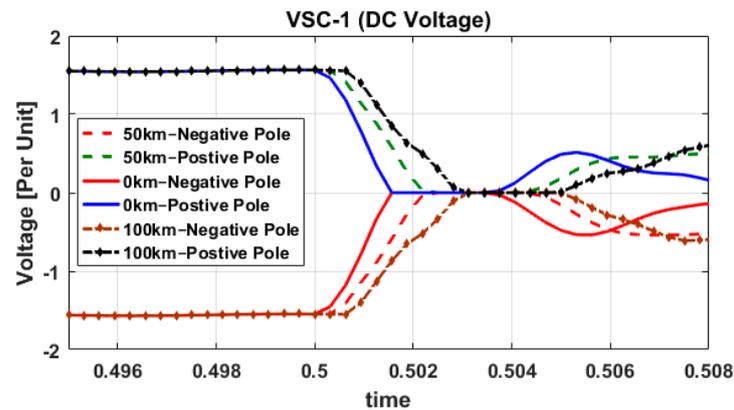
Figure 2. A simple HVDC test model.

(**a**)

(**b**)

Figure 3. P2P fault for different distances from the VSC-1 (fault occurred at 0.5 s): (**a**) DC current waveform (**b**) DC voltage waveform.

3.2. Pole-to-Ground Faults

In HVDC systems, the severity of a fault depends on various factors, such as fault type, location, duration, system configuration, and protection scheme. While P2G faults may occur more frequently than P2P faults in some HVDC systems, it cannot be assumed that they are always less severe. The impact of a fault should be evaluated on a case-by-case basis to determine the appropriate protection measures to be implemented. The response of P2G faults is majorly dependent on the grounding of the system, for example, the grounding of the neutral point on the step-up transformer on the AC side and the grounding of the mid-point on the DC link. The P2G faults are either positive pole-to-ground or negative pole-to-ground faults. Likewise to P2P faults, the P2G faults can be described in two phases: the discharging of DC link capacitor and the feeding of AC side currents. Identical to the P2P fault, at first, the DC link capacitor, if in existence, will supply

the short circuit to the ground by means of the grounding fault impedance. Furthermore, the fault current contribution can be seen from the grid via the power converter. In this case, the converter behaves like an uncontrolled rectifier as the current passes through the FDs. In the subsequent phase, the total inductive reactance corresponding to the combination of cable internal inductance, transformer self-inductance, and grounding inductance plays a role in the increased fault current. The FDs operate as soon as the DC voltage falls below the AC supply. Ultimately, the system operates in a steady state, having the fault current consisting of the AC input and any DC link still nourishing the faults [21]. Figure 4 shows a sample of graphs for both the voltage and current signals during P2G faults with different fault distances from the converter (VSC1) end.
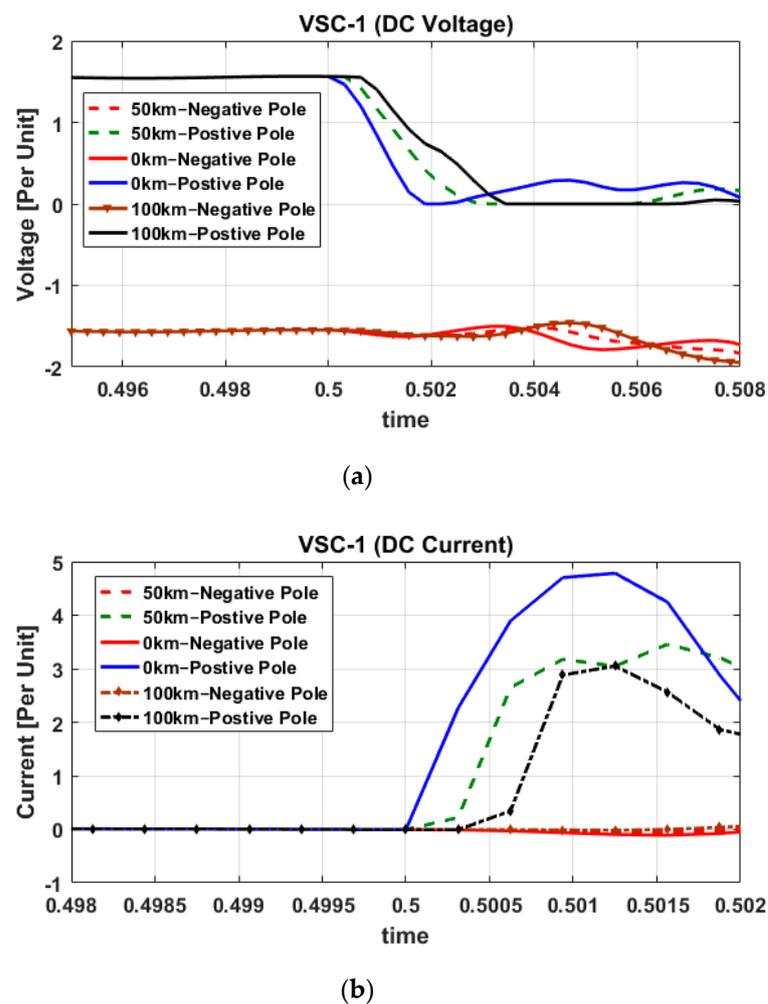

(**a**)

(**b**)

Figure 4. Positive pole-to-ground (P2G) fault for different distances from the VSC-1 (fault occurred at 0.5 s): (**a**) DC voltage; (**b**) DC current.

3.3. Pole-to-Pole-to-Ground Faults

A pole-to-pole-to-ground (P-P2G) fault in an HVDC line is a fault condition where one or more of the HVDC conductors (poles) of a bipolar transmission line come into contact with each other or with the ground. This can occur for a variety of reasons, including insulation failure, lightning strikes, or physical damage to the transmission line. In a pole-to-pole-to-ground fault, current flows from one pole to the other through the ground, causing a significant increase in ground potential and potentially damaging nearby equipment. The fault can also cause a rapid decrease in the voltage at the fault location, which can lead to a loss of power transmission in the affected section of the HVDC line. The probability of P-P2G fault occurrence is much less and almost unfeasible if both the positive and

negative conductors are placed in different cables [27]. However, if the fault occurs then the process of fault current can be accomplished in three stages. The first one is the capacitor discharging stage, where the DC voltage is discharged to zero. The rate of discharge is inversely proportional to the fault distance. The second phase is all about the conduction process of FDs, which results from an unusual growth of DC fault current followed by steady-state magnitude. In the final stage, the fault current contribution is observed from the grid.

4. HVDC Fault Interruption Devices

Tang and Ooi [28] proposed a handshaking method, where they utilized a coordination strategy between the AC-side circuit breakers (CBs) and DC-side fast switches to clear the DC grid faults. Although this method is reliable for locating and isolating the DC fault, it may be unable to meet the fast response commitments of the DC grid because of the larger switching time of AC-CBs [8]. According to the modular multilevel converter (MMC)-based multi-terminal DC system, the following three alternatives are available for clearing the DC faults: (i) converter topology with embedded fault-blocking capability, (ii) DC-CBs, and (iii) efficient coordination between CBs, converters, and other protective devices [8].

4.1. Converter Topology with Faulting Blocking Capability

MMCs are considered an improved technology for the potential VSC-HVDC grids, as they are more advantageous than the two- or three-level VSCs [9]. A sample representation of the MMC station is shown in Figure 5 with six converter arms [8]. Each converter arm is comprised of several half-bridge (HB) sub-modules (SMs). Owing to the modular architecture of the SMs, the MMC can be customized to higher voltage levels. As the voltage and current of the MMC circuit have the least impact on harmonics, the need for extra AC side filters is very trivial [9,10,29,30]. Moreover, the switching frequency of MMC is usually in the scale of (0.001–0.2) kHz, which leads to very low switching power losses in comparison to other two- or three-level VSCs. The MMC with the HB SMs is the major converter topology for the application of VSC-HVDC systems. During DC-side faults, the fault currents flow from the AC section to the DC section via the FDs. To get rid of these issues, several fault-blocking sub-modules based on HB SMs have been suggested and explored, for example, full-bridge (FB), unipolar voltage full-bridge (UFB), clamped double (CD), three-level cross-connected (3LCC), five-level cross-connected (5LCC)SM circuits, and hybrid SMs [8,31]. A schematic diagram of all these topologies is presented in Figure 6 [7]. Once the semiconductor power devices are blocked during the DC faults, the sub-module capacitors of these SM architectures provide a negative supply to the fault current flowing from the AC side, which then rapidly suppresses the AC side current to zero. For example, Figure 7 shows the fault current path during a DC-side fault having MMC with FB SM, where all power devices in the FB-MMC system are blocked/switched off, and the fault current flows via the FDs and is then opposed by the SM capacitor voltages [8]. During steady-state situations, the magnitude of the AC-side phase–phase voltage is comparatively less than the summation of the voltage of the capacitor in the short-circuit loop (refer to Figure 7). Thus, the fault-blocking facility of MMC can be potentially utilized for both AC and DC networks for fault interruption.
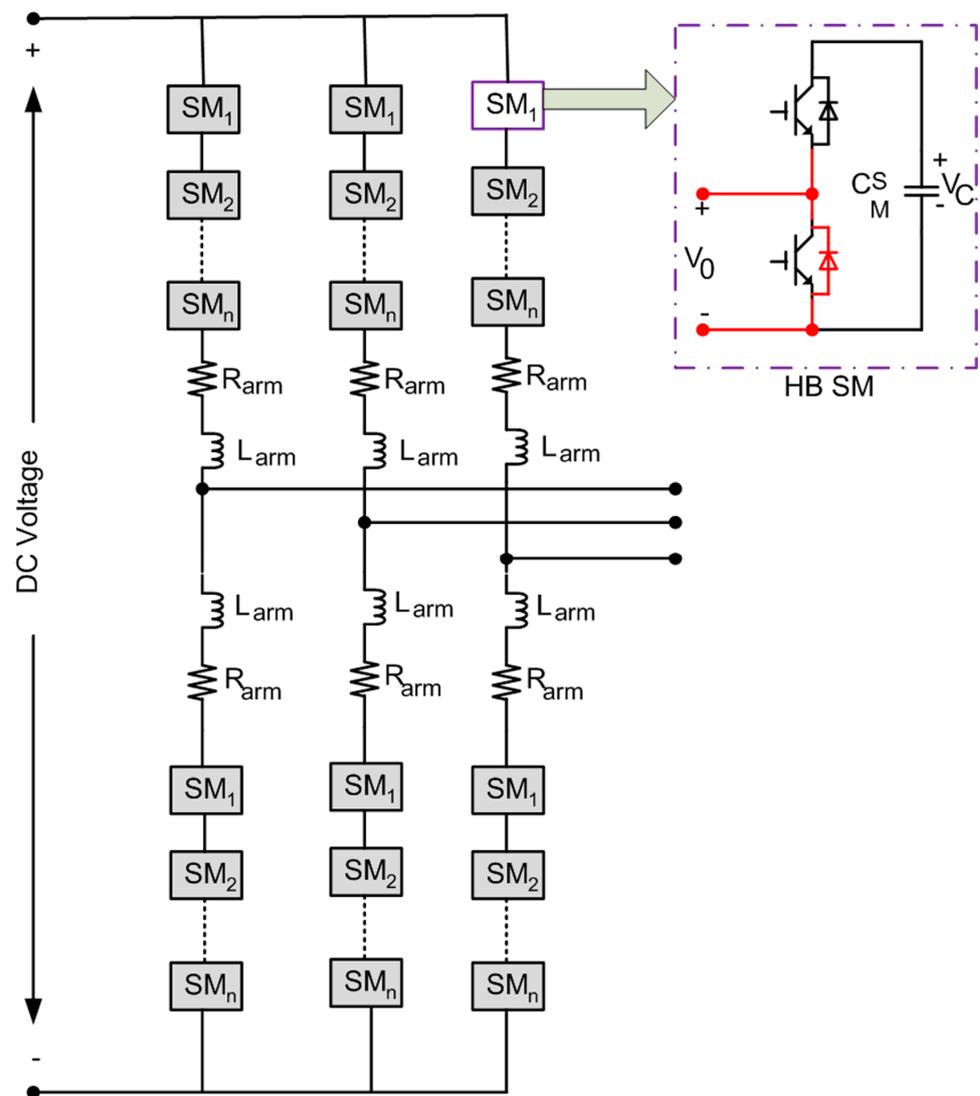
Figure 5. A sample representation of the MMC station.
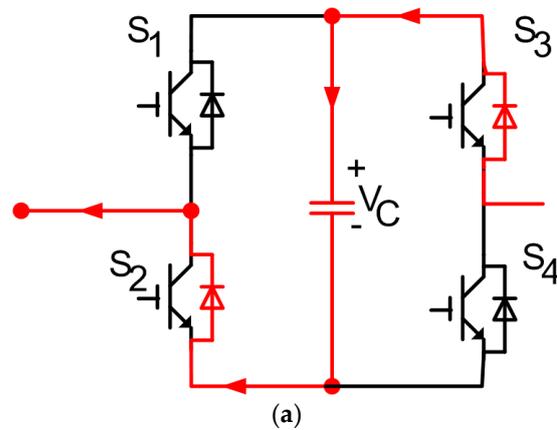

(**a**)
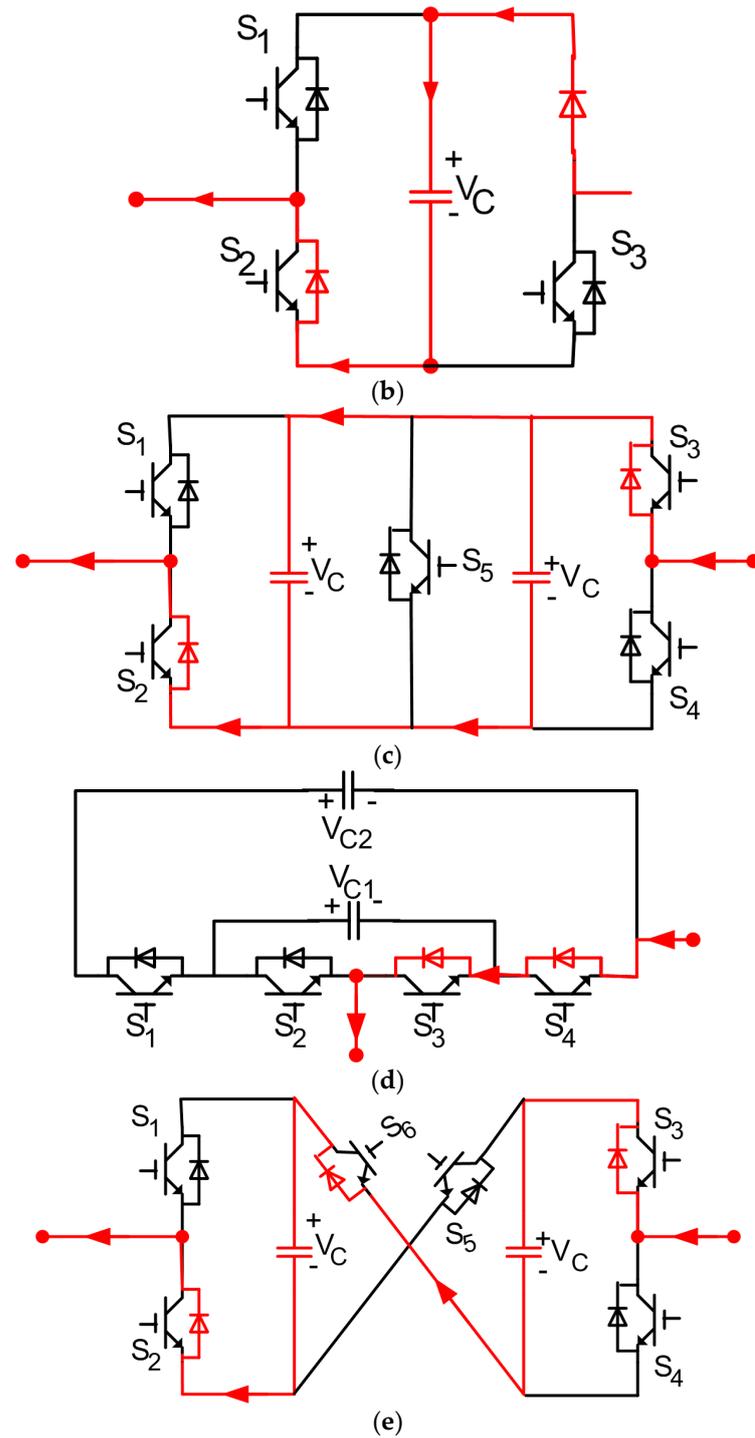
Figure 6. *Cont.*

Figure 6. Schematic diagram of different SM topologies, where the red line shows the fault current discharge path: (**a**) FB SM, (**b**) UFB SM, (**c**) CD SM, (**d**) 3LCC SM, (**e**) 5LCC SM.
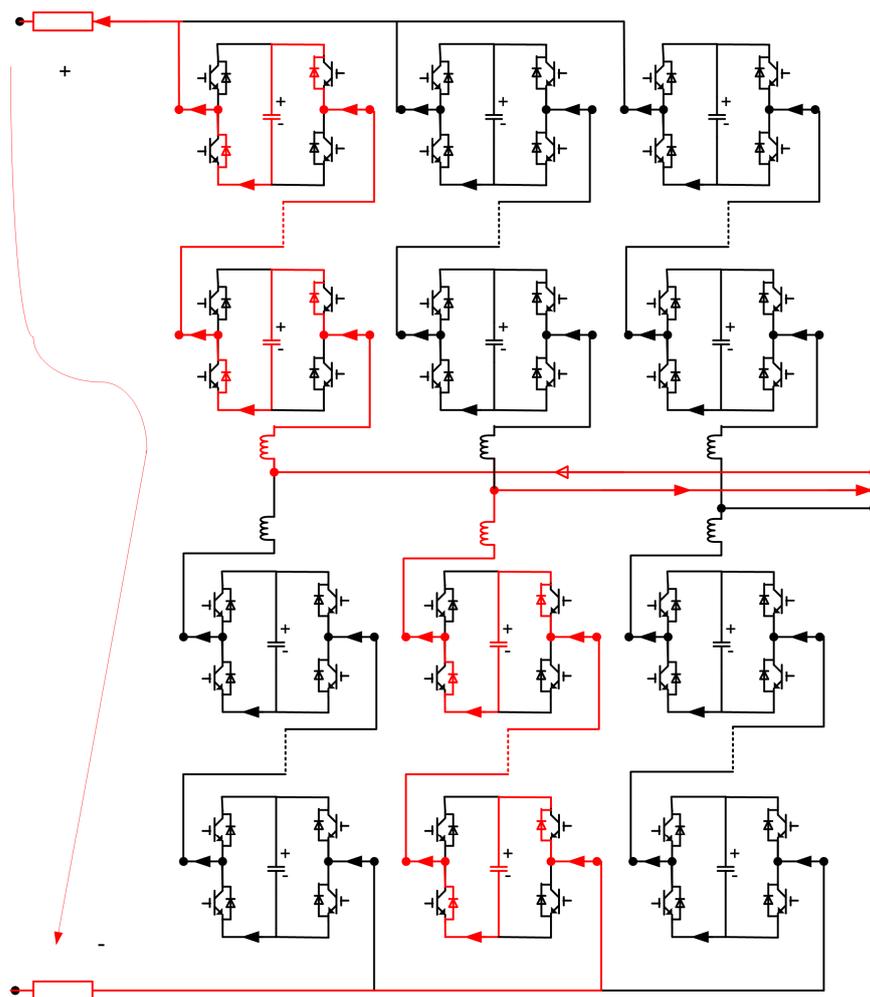
Figure 7. Fault current path during a DC-side fault having MMC with FB SM.

However, such sub-modules with DC-fault-blocking capability need extra semiconductor devices in the current path in the course of normal operative conditions, which yields more power losses and increased capital expenditure [9]. Even though the traditional MMC with HB SMs cannot block DC faults significantly, it can hold the lowest possible loss and capital expenditure in comparison to other MMC designs. Little research has also discussed the active and passive DC fault ride-through (FRT) strategies with improved MMC topologies [32]. In the case of a large MT-HVDC system, during DC faults, it becomes essential that the converters coupled with the healthy DC cables continue operating without disruption, while the faulty branches are quickly isolated. This raises the requirement for fast fault detection and faulty-line identification [33].

4.2. DC Circuit Breaker

While few converter topologies (as explained in the previous sub-section) are able to block the fault current significantly, these are only useful to protect the converters from over-currents. Thus, to provide complete protection, an isolation circuit is desirable to detach the healthy parts of the HVDC system [9]. In contrast to DC fast switches, DC-CBs are developed to interrupt the fault current significantly and quickly (within a few tens of μ-seconds to 10 ms). The basic principle of DC-CBs is to establish a zero-current switching to break the fault currents and a complete dissipation of stored energy. Detailed and comprehensive literature studies of different DC-CBs on the design aspect are presented in [34–36]. Fundamentally, the DC-CBs are classified as (i) electromechanical, (ii) solid state, and (iii) hybrid. A schematic representation of all these DC-CBs is presented in Figure 8.
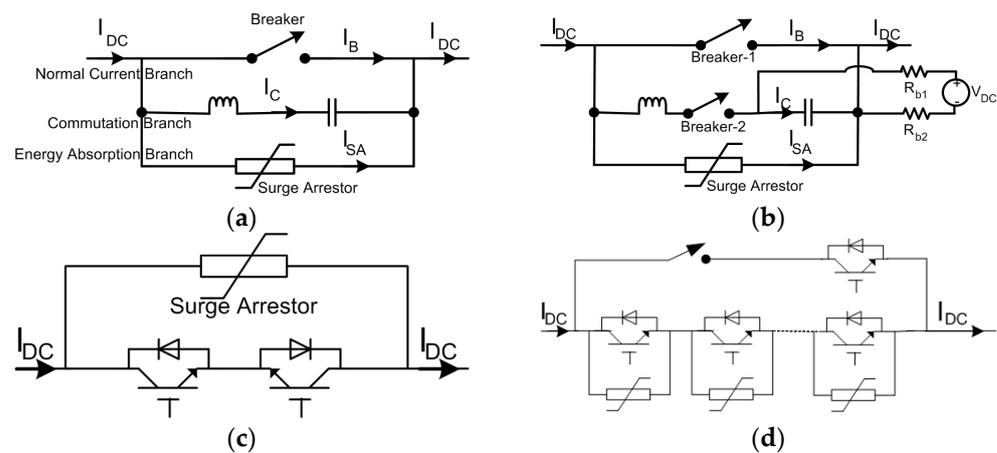
Figure 8. DC-CBs general architecture: (**a**) passive, (**b**) active, (**c**) solid state, (**d**) hybrid.

4.2.1. Electromechanical DC-CBs

This type of DC-CB is comprised of the following key elements: a low-resistance mechanical interrupter/switch in the most important conduction branch, an LC resonant circuit in the commutation branch, and surge arrestors or varistors in the energy dissipation branch [37,38]. The initial status of the mechanical switch is normally closed (NC), and current is transmitted through it during normal operation (no-fault condition). However, as soon as the fault occurs, the switch is operated and becomes an 'open' condition. An arc voltage produced as a result of the mechanical breaker opening will instigate the current flow toward the communication branch, which can cause current oscillation. As soon as the arc is surpassed, the capacitor present in the LC resonant circuit is charged to the system voltage. In the meantime, the dielectric strength of the mechanical interrupter revives and is capable of holding the system's voltage. When the voltage exceeds the threshold limit of the varistor, the fault current communicates to the surge arrestors, and a counter voltage is developed. This leads to a reduction in the fault current to zero. Thus, the energy stored in the line inductance gets absorbed. The losses that occurred in these mechanical CBs are very low. The mechanical DC-CBs can be classified as active or passive types based on the resonant circuit (refer to Figure 8a,b). In the passive type, as explained earlier, the resonance is initiated by the arc voltage produced through the mechanical interrupter opening. The electromechanical passive resonance HVDC breaker has a very low response time. These CBs are bulky and larger. These CBs can also lose their stability under various adverse conditions. In the active type, the resonance is through a previously charged capacitor and a power semiconductor device.

4.2.2. Solid-State Circuit Breaker

A solid-state circuit breaker executes the current interruption task with the help of power semiconductor switches. The quick and ultra-rapid switching capacity for the semiconductor components selects this CB as a powerful contender for interrupting faults. If it is a purely doped semiconductor then it makes them the fastest of all the types. These types of CBs have two or more high-voltage (HV) semiconductor-based valves and are capable of DC fault current interruption [39–41]. These types of arrangements make it faster than the electro-mechanical type of CBs. Generally, these CBs are lighter and simpler in design [42]. The desired current breaking point can be reached by connecting the switches properly. Back-to-back HV valves are used for fault current interruption in both directions. The general arrangement of a solid-state CB is presented in Figure 8c. As shown in the figure, it consists of two branches. The main breaker with the IGBT stacks is connected parallel with surge arresters to prevent it from going over-voltage during fault current interruption. The number of valves is defined by the ratings of current and voltages. During the operation of CBS, the current flows inside the valves. As soon as the

fault is encountered the valves are closed, and this blocks the flow of current. The fast response and absorption of the heat that is generated during operation make this type of CBs more efficient and durable. These CBs are much more efficient than the previously discussed electromechanical circuit breakers. However, problems arise with its complexity of handling high voltage levels in IGBTs attached to the CB [43,44]. A very fast way of isolating fault currents is observed here, but the conduction losses are excessively more than the electromechanical type of circuit breakers [45,46]. These solid-state-valve-based CBs may face several challenges for practical application in the MT-HVDC system. Further research on semiconductor materials may help to minimize the losses. The minimization of high on-state losses will give rise to a new concept of hybridization of technologies. These valves can be reduced in size and the number of components can be reduced. By adopting new and advanced technologies in the design process, the performance of the CBs can be significantly improved.

4.2.3. Hybrid Circuit Breaker

The combination of CBs can explore a new perspective for reduced switching duration and quick arc-extinguishing properties. A hybrid DC-CB is a combination of both the solid-state valve types and the electromechanical breaker. This combination is undertaken for overcoming the disadvantages or loopholes of both types of CBs. The design of this hybrid CB makes it more costly and complex in architecture. The operation of hybrid DC CBs is based on using a low-impedance path for current in normal operation and redirecting it to a solid-state high-voltage valve in the event of a DC fault [47]. Figure 8d shows the typical topology of a hybrid DC-CB. Table 1 presents a comparative study of all these DC-CBs based on the design specifications, economics, and reliability.

Table 1. A comparative analysis of different DC-CBs [3,37,48].

Essential Details of DC-CBs	Electromechanical CBs	Solid-State CBs	Hybrid CBs
Main branch	Mechanical breaker	Semiconductor devices	Both mechanical switches and power electronics devices
Commutation branch	LC resonant circuit	Not available	Power electronics breaker or capacitor snubber circuit
Interruption time of DC fault Current	60 milliseconds	1–2 milliseconds	2 milliseconds
Commutation time for contact separation	20 milliseconds	0.1 milliseconds	0.2 milliseconds
Energy absorption time (milliseconds)	30 for active and 2 for passive	1 millisecond	1 millisecond
Maximum rated voltage	550 kV	800 kV	320 kV
Maximum current-breaking capability	8 kA for active and 4 kA for passive	~6–12 kA	~9–20 kA
Expected power losses in comparison to the VSC-HVDC system	≤0.001%	≤30%	≤1%.
Cost	Least expensive	Expensive	Highly expensive
Life span	Very large	Short	Large
Maintenance required	High	Low	High

4.3. Coordination between CBs, Converters, and Other Protective Devices

MMCs with fault-blocking capability may sometime be very costly and have higher conduction losses because of the involvement of a large number of semi-conductor devices. However, as mentioned earlier, DC-CBs are still required to achieve a reliable solution, but, for an interconnected DC grid, fault interruptions through DC-CBs are also faced the same economical issue because of the requirement for a large number of breakers. Therefore, coordination between MMCs and hybrid DC-CBs can be a promising solution to

DC faults [8]. Several research works have been proposed and have reported recently on the coordination strategy of MMCs with hybrid DC-CBs [49–54].

4.4. Fault-Clearing Strategies

When a fault occurs in HVDC transmission lines, the faulty part must be detected and isolated to minimize the adverse effects. For minimizing the hypercritical effects of faults, the isolated portion of the grid should be shortened as much as possible. The length of the isolated portion should be kept minimum to save the healthy portion of the grid from further damage. This additionally ensures protection for all the devices of the grids. In case a larger portion is isolated from the grid, it leads to stability issues. It directly affects the AC portion of the transmission system. For avoiding such impacts of faults on the HVDC grids, various fault recovery methods are taken into account. The clearing strategies of faults are divided into non-selective, full-selective, and practically selective methods [3,55]. If these were adopted, then it will result in an easy clearing of faults. The details of the categorized methods are included in Table 2.

Table 2. Brief discussion of different fault-clearing strategies [3,55].

Non-selective strategy	Principles	Soon after the fault detection, the whole transmission network is shut down with the help of AC circuit breakers. Then, the faulty part is isolated using the DC switches located at both ends of the HVDC line, followed by reactivating the grid through the AC switches. In this fault-clearing method, AC circuit breakers and fault-tolerant converters play a very crucial role in the clearance of faults.
	Fault Clearing Devices	AC-CBs and DC switches
	Fault-clearing time	60 milliseconds (approx.)
Full-selective strategy	Principles	The grid is separated into several portions so that only the malfunctioning region can be disconnected. Each protective region has two HVDC-CBs connected at the end terminals. Each protection zone has its own protection elements (HVDC-CBs). As a result, the effect of the fault conditions is reduced, while the healthy components of the grid continue to function.
	Fault Clearing Devices	HVDC-CBs
	Fault-clearing time	10 milliseconds (approx.)
Partially-selective strategy	Principles	This approach is a combination of both the preceding strategies. The transmission grid is divided into several protective regions that are linked together via DC links. After a fault has been detected, the faulty region is isolated from the healthy regions using HVDC-CBs or DC/DC converters placed at interconnected DC links. After being isolated from the entire grid, AC-CBs turn off the defective protection zone. Then, the safe sections of the grids are re-energized, while the faulted section inside the protective region is disconnected by fast DC switches. There is no HVDC-CB inside the protection zones.
	Fault Clearing Devices	HVDC-CBs or DC/DC converters at the DC interconnected links for faulted protection zone separation. AC-CBs/DC switches are used for fault isolation.
	Fault-clearing time	Less than 10 milliseconds for protection zone separation and approximately 60 milliseconds for fault isolation.

5. HVDC Fault Detection and Location Methods

Fault detection and location (F-D&L) algorithms embedded in the protective relaying systems are among the most essential parts of a VSC-HVDC network. Just like HVAC systems, the protection algorithms for HVDC systems can be categorized as, either, (i) single-end/multi-end measurement-based methods, or (ii) unit/non-unit-based methods, or (iii) communication/non-communication-based methods. The taxonomy of the HVDC protection methods is pictorially presented in Figure 9. The terms "unit and non-unit", "single-end and both-end information", and "communication and non-communication" refer to different characteristics or features of protection schemes used in power systems. These characteristics are not necessarily interdependent, but they may be used in combination to

achieve the desired level of protection for the power system. The protection algorithms are generally based on the information extracted from voltage and/or current signals at single or multiple ends of MT-HVDC systems. The single-end information-based methods are less costly, as well as less selective, as compared to multi-end information-based methods. The protection scheme based on multiple-ends measuring generally requires an advanced communication infrastructure and relay technology. The communication-based approaches are inherently selective [56]. However, the time delay imposed by the communication channel makes it unsuitable for an application demanding fast relaying speed [57]. The range of protective relays is also an important aspect of the protection system. In this regard, the protection system can be classified into the unit- and non-unit-based methods. The unit protection method is designed to protect a particular zone with a fixed boundary. Here, the measurement of voltage or current signals is carried out at each end of the protected zone. Likewise, the non-unit schemes are intended for the protection of a specific area but have no fixed boundaries. Although these are used to protect their own designated areas, the protective zones can overlap with other zones. The non-unit schemes are inherently capable of providing backup protection whenever a neighboring protection system fails to operate.
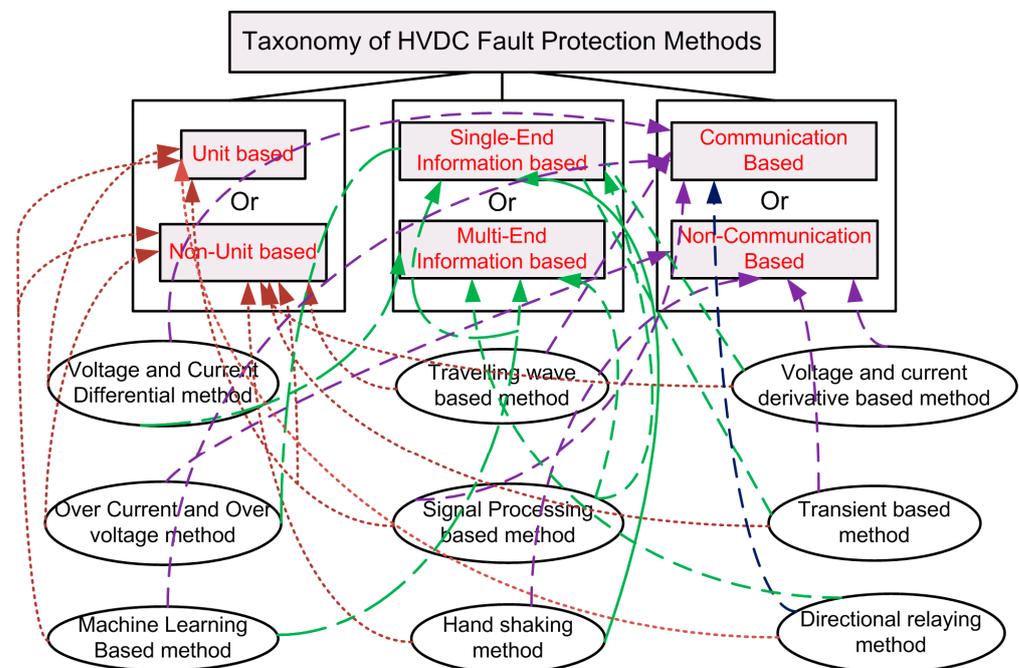
Figure 9. Taxonomy of HVDC fault protection methods.

Although there are several well-known protection algorithms/approaches already reported and implemented for HVDC protection systems, continuous research and development is being undertaken to achieve improvements in the following aspects: speed, accuracy, reliability, sensitivity, selectivity, robustness, and design complexity [4,57,58]. Despite that several state-of-the-art protection algorithms have been proposed for VSC and CSC-based HVDC systems, this paper is truly focused on the latest publications (within the last decade). The advantage and disadvantages of different fault analysis methods are mentioned in Table 3. Brief literature studies on each protection architecture, as mentioned in Figure 9, are presented in the subsequent sub-sections.

Table 3. Advantages and disadvantages of different fault analysis methods.

Fault Analysis Methods	Advantages	Disadvantages
Voltage and current differential	Good selectivity, good directionality, extremely robust, can be used for both main and backup protection.	It may face communication delays. It becomes costly owing to the need for synchronized measurement units and communication channels.
Over-current/Over-voltage	The scheme is very simple and useful for backup protection.	It may face selectivity and limited speed issues. It has low accuracy and selectivity as compared to the main protection.
Derivative Based	High-speed protection can be possible by the use of a first incident wave.	It is highly susceptible to a noisy environment. Moreover, the selectivity is limited owing to the low cable impedance.
Transient Based	High selectivity, better reliability, and good accuracy during DC-line fault detection from external side faults.	The performance is highly dependent on the HVDC network topology and system parameters (such as capacitance and resistance). It has low accuracy for high-resistance faults.
Directional	High sensitivity, good reliability, better directionality.	It may face communication delays. It has low accuracy for high-resistance faults.
Traveling Wave based	High-speed protection can be possible by the use of a first incident wave.	Accuracy can be hampered in very long lines.
Handshaking Methods	It is based on local measurements deprived of any communication frameworks, making it more economical, uncomplicated, and practically feasible.	It can temporarily de-energize the whole grid following unwarranted outages. Long downtime of the whole DC grid. Unsuitable for LVDC grid.
Signal Processing based	Very fast, highly reliable, and extremely robust; can be used for both main and backup protection.	Extensive simulations or analyses are needed to set the thresholds. Providing proper thresholding is quite difficult. Not suitable as a stand-alone protective solution.
Distance Protection	It is more useful through utilizing the signal processing technique.	A small value of cable impedance makes its application impractical in a DC system.
Machine Learning based	It has a fast execution period, good sensitivity, and better reliability.	Practical implementation is difficult as it needs an extensive input dataset for training the machine learning algorithm for achieving good accuracy.

5.1. Voltage and Current Differential Techniques

Fault detection approaches based on voltage or current differential use the signals extracted from both ends of HVDC networks. When the differential value exceeds a predefined threshold limit, the fault is said to be detected [56]. It is considered a unit protection scheme and can be used to protect the busbar, converter stations, and DC lines. These techniques are extremely robust and provide inherent directionality. However, as the method is highly dependent on the time-stamped data from both ends, communication failure will definitely harm a lot. The current differential protection methods can reliably protect the high-resistance faults and, hence, are deployed to provide backup protection for DC transmission lines in the LCC-HVDC system. On the other hand, owing to the influence of the large-line distributed capacitor on the fault current, the differential current-based approach may fail to differentiate the internal and external faults, which yields protection mal-operation [10]. This can be avoided by introducing a large time delay (hundreds of

milliseconds) for the backup relaying scheme [59]. As a result, the operating time of current differential protection has been increased to a higher value (a few hundred milliseconds), which makes it unsuitable for application in the VSC-HVDC system. In contrast to this, the Bergeron-model-based current differential protection can be applied, as it can avoid the impact of distributed capacitors significantly [60]. Tzelepis et al. [61] proposed a fast differential current-based fast fault-location method for the MT-VSC-HVDC system using multi-point optical current sensors. Here, a series of differential currents is calculated through two consecutive sensors. The value of the differential currents is found to be a null value for external fault and very high for internal fault. Elalien et al. [62] presented a differential scheme using discrete wavelet transform (DWT) to differentiate the external and internal faults. The ratio of two signals such as the operating and restraining signals (which are calculated from the wavelet coefficients of the current signal at both ends) is compared with a predefined threshold for decision-making. This approach is much more suitable for both bolted and high-resistance faults. Zheng et al. [63] proposed a new differential scheme based on the compensation of the distributed capacitive current (DCC). Initially, the voltage and current signal at both ends of the distribution feeder is processed through the same low-pass filter having a low cut-off frequency to discover the linear-distributed voltage and current. The DCC has been computed by integrating the linear voltage distribution in real time. Afterward, this DCC is used to compensate for the original differential current. Through this process, a novel differential criterion has been developed and implemented.

The author in [64] has proposed a novel differential protection scheme for fault detection and faulty pole identification in an HVDC system. The stated approach is based on the distributed-parameter line model and compensated current ($I_{Compensated}$). The suggested approach has high reliability and sensitivity during fault events as it is uninfluenced by the DCC.

Lan et al. [65] proposed an improved Bergeron-model-based current differential protection with parameter error tolerability. The impact of the parametric error on the compensated current has also been explored in the paper. The parameter error is typified by the characteristic impedance and velocity of TW. The error in TW velocity has a major impact, $I_{Compensated}$. The proposed scheme was intended to mitigate the impact of parameter error by utilizing the wavelet transform modulus maxima. The scheme was found to be highly useful for backup protection in the HVDC line by avoiding the chance of maloperation during internal faults. A proper balance between speed and sensitivity is a major factor for effective HVDC protection. The usual tripping time of the current differential scheme ranges from 10 milliseconds to 1.1 s, which is considered to be too high for a VSC-HVDC system. To solve this issue, an ultra-fast current differential protection scheme based on the Bergeron model is presented in [66]. Elgamasy et al. [67] proposed an enhanced differential protection method for a VSC-HVDC system through a comparative analysis of relative conditions of the TWs beside the DC underground cable (or overhead line) at its ends.

5.2. Over-Current/Over-Voltage Protection

The over-current (OC) or over-voltage (OV)-based approaches are classified as non-unit protection schemes and are regarded as traditional protection methods. This kind of protection scheme uses the direct measurement of signals (voltage or current) at a single end and is based on a time-graded characteristic. Low accuracy and minimal directional selectively make this kind of relaying scheme useless for primary protection in MT-HVDC systems, but it can be useful for backup protection [68,69]. It is popularly used to protect the semiconductor valve from overheating [70]. In the OC protection scheme, an accurate setting for the time characteristic is very essential to ensure selectivity. This requires detailed and precise modeling of the different power system dynamics that are responsible for the fault current contributions in each fault scenario in a specific MT-HVDC grid, which is not an easy task [71].

5.3. Derivative-Based Methods

Derivative-based methods are based on the rate of rise of voltage (dv/dt) or current (di/dt) measurement at a single end of the HVDC grid. These are classified as non-unit protection schemes and can be considered as one form of traveling wave-based protection. The (dv/dt)-based protection method is more advantageous than the OC and current differential schemes in terms of speed of fault detection [72], but the accuracy is influenced by the feeder length, and the selectivity is reduced with less line impedance. Similar to the voltage derivative, the (di/dt) scheme uses an initial rate of rise of current for fault decision-making. The principle is quite similar to OC protection, but the amplitude of the current transient is used instead. This method is vulnerable to a noisy environment and could mal-operate owing to the possibility of inappropriate data sample collection [11].

Marvik et al. [73] studied different variables (or markers), such as magnitude and derivative of DC voltage and current, for identifying the fault events in an MT-HVDC system. The performances of these variables are measured individually through common criteria such as dependability, speed, security, and selectivity, where it is found that the derivative-based variable outperforms and gives the quickest results. Moreover, this work has studied the impact of FCLs embedded with these markers. The result shows that the current derivative marker suits better using FCLs, while the voltage derivative performs better without FCL. The same group of authors [74] presented a non-communication-based protection scheme where DC breakers with proper thresholding of DC-current derivatives are used on the same three-terminal bipolar radial HVDC system [73]. Although the simulation results indicate that the fault currents amplify quickly and have a surely high amplitude of (di/dt), which necessities a very fast protection system and DC switches, the DC breakers are not commercially available yet, which makes the practical implementation of the proposed method infeasible. In [75], the authors have presented a one-end (dv/dt)- and (di/dt)-measurement-based protection scheme for the MT-HVDC system. Similarly, Sneath and Rajapakse [76] have used the rate of change of voltage (ROCOV) as a detection index for an earthed HVDC grid. Li et al. [33] presented a protection scheme for the MT-HVDC system using a second derivative of the DC fault current with a predefined threshold limit. The stated approach does not require any communication channel and is robust to any change in fault resistances. However, the effective selection of threshold limit is a challenging task for differentiating the different fault zones or fault segments and high-resistance faults [32,75,76].

Leterme et al. [77] proposed a non-unit protection scheme for the MT-HVDC system, where the inductive termination decides the zone of protection. Here, the under-voltage criterion is applied to detect the fault with a pre-set threshold value of 85% of the rated DC voltage. As soon as the fault is identified, the (dv/dt) and (di/dt) measurements are carried out to discriminate the first and second zone faults. Owing to the fact that the (dv/dt) is susceptible to close faults and noise, a directional criterion of (di/dt) is used to discriminate the frontward and backward faults. However, the scheme may mal-operate during the zone 2 solid faults as it shows very similar characteristics in the case of zone 1 high-resistance faults. Moreover, with the fault-resistance variation, the scheme may fail to discriminate the faults properly. Eladl et al. [78] presented a three-level protection scheme for the MT-HVDC system. In the initial level, the (di/dt)-based over-current method is used to provide the primary protection, whereas the second level is based on (dv/dt), the under-voltage method intended for back-protection against the failure of the primary relaying scheme. If both primary and backup relaying fail to trip the circuit, the third-level protection scheme comes into the picture, which is over-current protection by AC-CB in the AC-side grid after a coordinated time.

5.4. Transient-Based Methods

These kinds of relaying schemes generally use the high-frequency components of the voltage/current signals for the recognition of DC line faults, which makes them more capable and robust against high transition resistance. Liu et al. [79] presented a protection

scheme for the MT-VSC-HVDC system that is able to provide both primary and backup protection. The principles for both primary and backup relaying schemes are based on the supplementary inductor employed at each terminal of the DC line. Fault recognition has been accomplished using the ratio of the transient voltages (ROTV) computed at both sides of the inductor. The primary scheme is non-communication based, whereas the backup relaying is a pilot scheme based on the ROTVs at both ends of the DC line segment. Ikhide et al. [80] presented a time-domain transient-based protection scheme for a four-terminal MCC-HVDC grid utilizing the TW power. Proper thresholding is provided to the TW power to differentiate the internal and external faults. The direction selectivity analysis has been carried out by calculating the ratio of forward and backward TW power. Toward improving the sensitivity of the proposed method for long-distance remote internal fault, an additional element applying the concavity of the forward TW power is also recommended. The authors in [81] have proposed a transient-based boundary protection scheme using high-frequency energy criteria to detect the fault in the MT-HVDC system. Cheng et al. [82] proposed a fault location scheme for MT-HVDC systems using the non-characteristic frequency signal extracted with the help of a complex wavelet transform from the current signal. As per the fault criterion presented in the paper, an internal fault is detected when the characteristic frequency is more than the non-characteristic frequency, otherwise perceived as an external fault.

The sheath of the cable is grounded at each converter substation. The measured voltage at these ends is referred to as sheath voltage. Niaki et al. [83] proposed a fault location scheme for an MT-HVDC grid using the sheath voltage of the DC cable. During no-fault conditions, the transient sheath voltage measures a null value; as a result, no current flows through it. However, during the fault, the transient sheath voltage has attained a certain magnitude leading to the flow of current. Therefore, a fault criterion has been established in this work using the transient sheath voltage magnitude and directions to detect the faults and discriminate it from capacitor unbalancing issues. Abu-Elanien et al. [62,84] extracted the high- and low-frequency transient current signal (FTCS) using wavelet transform to formulate the detection criterion for the internal and external faults. In [62], the difference of energy index was calculated from high-FTCS assessed at each end of the faulted DC segment to identify the fault in the MT-HVDC grids. In contrast to [84], the author has proposed a non-communication-based transient scheme, where the ratio of the energy index corresponding to high- and low-FTCS at a particular end is used to identify the fault events. Fault detection using high-FTCS extracted using wavelet transform is also reported in [85]. Dong et al. [86] proposed a transient harmonic current (THC)-based scheme to detect and classify the internal and external faults in the MT-HVDC grid. It has been reported that the THC is found to be low for external faults owing to the presence of a DC filter and smoothing rector, whereas it has a high value for internal faults. Therefore, the difference between the THC at both ends is applied to discriminate the internal and external faults. Variations in fault resistance and fault distance may impact the reliability of the scheme and the cost factor because of the requirement for communication infrastructure, which are a few major drawbacks of this scheme.

5.5. Directional Pilot Protection

Directional pilot protection schemes are communication based and useful to detect a fault upstream or downstream (of a specified direction) of its location. During the fault occurrences, each relay of one end communicates the information (phase displacement or direction of current) to the other end. As soon as a fault is detected by the protective relays in their respective forward direction, a trip signal is generated to isolate the healthy section. The directional protection schemes are considered more robust and reliable compared to the current differential schemes [87]. However, similar to the current differential, it also suffered from a similar limitation of communication-time delay. In reference [10], the directional pilot protection for an HVDC system has been studied through different

directional criteria based on (i) the change in current (Δi) or current derivative (di/dt), (ii) the boundary characteristic, and (iii) the traveling wave concept.

In the DC system, the conventional directional protection is generally based on Δi or di/dt. The method based on the change in DC current is able to detect a fault in the forward direction when a DC fault current exceeds a predefined positive threshold limit [88]. Special care is very much essential for the setting of the threshold value, and it should not be too small to avoid the confusion and impact of system disturbances, for example, system oscillation. However, for the high-impedance forward fault, where the DC fault is found to be extremely low, the directional criterion may fail to identify the fault as a forward fault. Similar to Δi-based directional criterion, the di/dt-based directional criterion detects the fault as forward when the rate of rise of fault current exceeds a positive threshold limit [77]. However, owing to the distributed capacitance of the line, the di/dt value swings between positive and negative values [86] for both forward and backward fault cases. This leads to mal-operation of the directional relay as a forward fault may falsely be detected as backward or vice versa.

Reminiscent of the single-end measurement-based protection, the boundary characteristics can be applied to recognize the fault direction. The high-frequency transient voltage (HFTV) at the line side of the DC reactor is greater than the bus side and vice versa during the forward and backward fault conditions, respectively [89]. Additionally, the frequency of the extracted components is directly proportional to the above characteristic. Contrary to the conventional direction criterion, the characteristic utilized in the stated criterion by Li et al. [89] considers the line-distributed parameter characteristics. It has been analyzed that the suggested principle more reliably detects the fault direction. Furthermore, the extracted HFTV components used for the criterion have better ability compared to high transition resistance for effective fault recognition. However, in some MT-HVDC grids (such as the Wudongde HVDC system), DC reactors are absent on the DC line sides. For such a type of condition, the boundary characteristic is not present, and therefore, the criterion that is not based on the boundary should be explored. In this situation, the traveling-wave-based direction criterion is found to be more beneficial [90]. A detailed study of the TW-based protection schemes is analyzed in the subsequent subsection.

5.6. Travelling Wave Based Protection

The basic fundamental of the traveling wave (TW) principle for fault detection and location in transmission lines is explicitly described in [91,92]. In contrast to the AC transmission system, the DC transmission system can encounter the presence of transient travelling waves as a result of the fault inception at any point. Thus, the application of the TW concept is highly suitable for the protection of an HVDC system. As soon as a fault occurs in the transmission line, the fault current and voltages give rise to impulses that then travel from the point of fault occurrence to the line terminals. Through estimating the reflections of this wave at one or both ends of the line, the fault location and detection task is generally executed. The phenomenon of fault current as travelling waves is illustrated in Figure 10 by the Bewley lattice diagram. The TW-based scheme based on single-end measurement avoids the communication requirement, whereas the TW-based pilot protection utilizing both ends' information needs communication infrastructure. Signal-processing methods are widely used in TW-based protection schemes as they can help to recognize the nature of waves that are reflected and encountered at the ends of the transmission lines. Using a one-end high-frequency transient signal, Liu et al. [85,93] presented hybrid schemes based on TW and boundary protection to discriminate between the internal and external faults. Initially, these approaches use stationary WT (SWT) as a pre-processing noise-removal technique to extract the useful TW signal. However, these methods require a very high sampling frequency of up to 50 kHz. Zhang et al. [18] proposed an integrated TW-based DC-line fault detection and faulty pole identification method using symmetrical component analysis. Initially, the initial value of voltage and current TW are calculated

and analyzed in detail. Afterward, a detection criterion is suggested based on zero-and positive-sequence backward TWs.
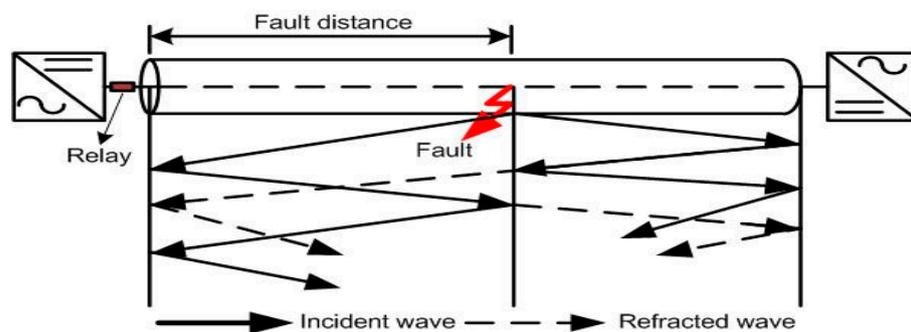

Figure 10. Bewley lattice diagram (Red arrow signifies the fault and its location point).

Nanayakkara et al. [94] proposed a robust TW-based fault location approach for the MT-HVDC system, where the surge arrival time used for the calculation of fault distance has been tracked by means of continuous wavelet transform (CWT) applied to the current signal extracted from the converter stations only.

Li and Jiang [95] presented a directional protection scheme for an MT-HVDC system with an inductive DC terminal. The suggested approach is used to detect the internal and external faults by comparing the transient energy polarities of TWs measured at both ends of the faulty segment of DC lines. The method is stated to be more reliable in comparison to conventional directional approaches for the MT-HVDC grid with inductive termination.

Hao et al. [96] proposed a protection algorithm for LCC-HVDC grids, where the difference in the process of TW propagation in the case of internal and external faults is used as a criterion to detect the fault incident in the DC line segments. The Teager energy operator (TEO) is additionally used to strengthen and quantify this difference for effective fault recognition. The main advantages of this approach include (i) easy calculations, (ii) faster detection speed, as it uses only a 2-millisecond sampling data window, (iii) it not needing to extract any harmonic or high-frequency components, and (iv) it being able to detect the high-impedance and long-distance faults.

The authors in reference [97] have proposed a protection scheme for MT-VSC-HVDC systems, where the amplitude and ratio of energy computed from the forward and backward TWs are used for the recognition of internal and external faults. Although this scheme is able to detect the fault efficiently, an improper threshold setting may affect the accuracy of the protection scheme. Elalien et al. [62] presented a pilot differential protection-scheme-based TW concept for differentiating external and internal faults.

5.7. Distance Protection

Distance relaying methods or impedance-based methods are basically used to estimate the length of the line from the relay location to the fault point using the measured short-circuit loop impedance. Although this method is very popular in the case of AC systems, a small value of cable impedance makes its application impractical in DC systems [98]. Furthermore, in the course of certain fault transients, power-frequency variation impedance (PFVI) can become capacitive in nature, which shrinks the zone of distance protection based on PFVI and can create system blackouts [99]. Moreover, unlike AC networks, symmetrical component analysis is applicable to a DC system to evade the impact of fault resistance [20,100].

However, some research that reported the implementation of the distance protection scheme for DC systems basically deals with the evaluation of active impedance. This method is accomplished by injecting an external perturbation of voltage or current signal with specific frequency spectra generated by probe units (a half-bridge or full-bridge inverter embedded with a large capacitor and connected to a power source) [99]. In this

type of active distance relaying scheme, the measured voltage and current signal are processed by improved SP techniques (for instance, FFT) and linear regression for the calculation of impedance and fault distance [101]. This scheme concentrates on the required zone of protection and avoids the obligation of a complete shutdown of the system, but the requirement of additional probe units makes it expensive. Suonan et al. [102] proposed frequency-dependent parameters (FDPs) based on distance protection of the HVDC grid. As per the transmission line equations, the FDP can be modeled in two parts: (i) distributed parameter model and (ii) a compensation matrix model with finite impulse response filters. Therefore, in this work, the voltage and current at the set point are computed precisely, and fault location has been carried out by solving the differential equations. This approach is found to be highly reliable for both close- and remote-end faults. In reference [101–104], the synchronized measurement of voltage and current at both ends of the line is used for designing the protection scheme. The unsynchronized two-end measurements can also influence the protection system. Therefore, Yuansheng et al. [105] considered the uncertainty inline parameters and unsynchronized measurement time difference to locate the faulty events in an HVDC system. Yang et al. [20] proposed a protection system with a relay coordination strategy for the VSC-HVDC transmission system. Simulation results look promising for small-scale applications and can be applied to offshore HVDC transmission systems on a higher scale. Yang et al. [21] proposed a fault location method using the voltage divider arrangement. The proposed approach is tested under different fault distances, resistances, and operating conditions. Zheng et al. [106] proposed a distance backup protection scheme for the MT-HVDC system based on a steady-state parameter model. Initially, this work has proved that the during the steady-state DC fault, the line model is equivalent to the lumped parameter model. Afterward, a directional relaying scheme based on transient currents is suggested to solve the dead-zone problem.

5.8. Handshaking Methods

The handshaking-based protection methods are used to identify and segregate various P2P and P2G faults in MT-HVDC systems. In this kind of method, if a fault (for instance, a positive P2G fault) occurs in a line of an MT-HVDC system, then the current direction of the faulted line will always be positive (from bus to fault instance) and regarded as a positive fault current, whereas in the case of a healthy line, the fault current is always negative and regarded as a negative fault current. This principle can be utilized as a handshaking method to detect the faulted and healthy line segments. Tang and Ooi [28] offered a handshaking method to detect the DC faults in MT-HVDC grids using AC-CB and DC switches. As soon as a fault occurs in a DC line, the AC-CB, followed by the DC switch, is operated to isolate the faulted line from the AC side and the remaining healthy DC network, respectively. This scheme is generally cheaper than DC-CBs and can be applied to point-to-point HVDC transmission networks, with few advantages noted [107]. On the other hand, for an MT-HVDC grid, all the MMCs ought to be shut down owing to the act of the AC-CB, which will interrupt the power flow in the whole network. As a result, capacitor discharge and FD operation stages occur very fast (in a few milliseconds) and possibly will damage the power electronics devices and other connected modules. The handshaking methods are able to detect and isolate the fault with high reliability in an MT-HVDC system. Furthermore, this kind of approach is based on local measurements deprived of any communication frameworks, making it more economical and uncomplicated. Conversely, this scheme can temporarily de-energize the whole grid following unwarranted outages, making it unsuitable for local distribution networks and LVDC microgrids, where a lot of energy resources and loads are coupled to the system [108–110].

5.9. Signal Processing Based Approach

Signal processing (SP) techniques are widely used mathematical tools for electrical power system (EPS) analysis. These SP techniques are effectively used to analyze the system signals measured and collected from various locations of the EPS, so as to address various

issues such as voltage control, power quality and reliability, power system and equipment fault diagnostics, power system control, protection, etc. Generally, the SP techniques are integrated with conventional protection schemes (such as differential protection, distance protection, and TW-based protection) to improve and refine the accuracy of fault detection. Although a wide range of SP tools is used for the analysis of AC transmission systems, the following are a few most commonly used for the HVDC protection approach: fast Fourier transform (FFT), WT, Stockwell transform (ST), Hilbert–Huang transform (HHT), etc. Guobing et al. [111] utilized the FFT, band-pass filters, and Prony algorithm to extract the natural frequency from the traveling wave current signal having a small window size and suggested a fault detection algorithm based on the natural frequency. In contrast to FFT, the WT has the advantage of improved time-frequency localization and offers both time and frequency information simultaneously. In the SP framework, WT is the most commonly used technique for HVDC protection [112–117]. The authors in [92,115] have integrated the WT principle with TW-based protection schemes for the detection of DC faults in the HVDC grid. Kerf et al. [118] implemented three fault-detection criteria, of which two are based on wavelet analysis on the locally measured voltage and current signals of an MT-HVDC system. The third criterion is based on voltage and current derivative-based time domain analysis. Here, triple modular redundancy (TMR) is additionally used to improve selectivity. Fault current rising time and oscillation pattern are captured through WT applied to a DC fault current signal and used for designing the decision-making algorithm for an HVDC protection system [119]. Internal fault location in an HVDC line is executed through a detection criterion utilizing the phase-frequency information extracted from the complex WT applied to a DC current signal [82]. The sheath voltage of positive and negative cables is processed through WT to extract the detail coefficients during several kinds of faults in a VSC-HVDC system [120]. Proper thresholding is provided for differentiating the AC and DC faults [121]. Abu-Elanien et al. [60,82] utilized wavelet analysis (specifically, discrete WT) in their protection algorithm for tracking high-frequency transient signals and used it for identifying the internal, as well as external, faults in the MT-HVDC system. In [62], the protection algorithm is communication based (differential protection), whereas Ref. [84] reported non-communication-based protection schemes. In WT-based protection schemes, the wavelet coefficients are predefined for specific fault detection. Moreover, in some literature, it is found that the varying fault inception angle, fault resistance value, and noisy environment have a negative impact on the performance of WT-based protection methods. Furthermore, sometime, it might not be appropriate as a stand-alone relaying scheme. In contrast to FT and WT, the ST is capable of extracting both the time and frequency information of a signal simultaneously. Some studies claim that this method is mostly immune to the noise environment. Although several studies related to ST application on HVDC line protections are reported in earlier literature [121–124], this work has highlighted a few recent findings, as follows. Zhao et al. [125] proposed a phase-mode transform method for a bipolar DC cable in a VSC-HVDC system to decouple the currents in the cables and analyze the transient DC current after fault events. Initially, ST is used to extract the frequency components from the mode currents. Afterward, a fault detection criterion is formulated through calculating the sudden change point of the high-frequency components. Internal and external faults are classified with the help of the fault current components' polarities. Xiaotong et al. [126] suggested the synchronous squeezed S-transform (SST)-based method for HVDC line fault detection and faulty phase identification. Initially, the line-mode components are obtained from the faulty current signals utilizing the extended Karenbauer phase mode transformation. The three transient energy ratios are calculated through applying the SST to the mode component of current travelling waves. These energy values are individually compared with specific pre-set values to determine the involvement of the ground during faults, type of faults, and faulted phase. The method is found to be an effective and fast phase-selection method and is protected from the communication failure issue. Zou et al. [127] proposed a non-unit protection method utilizing the ST-based energy ratio criterion for HVDC fault detection.

The suggested method is reported as a fast and reliable faulty pole identification method and is able to classify lightning disturbances and faults. Similar to ST, the Hilbert–Haung transform is also popularly used to extract the power frequency spectrum for different power system applications. Zhang et al. [81] suggested the use of HHT for the generation of a frequency spectrum of transient voltage signals and detection of internal faults.

5.10. Machine Learning Based Approach

In last two decades, the research on the development and application of artificial intelligence (AI) techniques in several power system design and protection systems has increased persistently [128–131]. In the framework of AI, the following are a few of the most widely used machine learning (ML) techniques for the power system protection problem, such as expert system, artificial neural network (ANN), fuzzy logic, support vector machine (SVM), etc.

Apart from many ML methods, the ANN method particularly has gained huge popularity for the application of HVDC protection. This method is less complex and less expensive as compared to other AI methods and has a fast execution period, which makes it suitable for real-time application [132–135]. Here, either the transient fault currents and/or voltage signals are (i) directly sampled and then fed to the neural network (NN) or (ii) processed by some additional techniques (for instance, SP methods) to obtain the distinctive features and then feed them to the NN [133–135]. The first approach (use of the sampled voltage and current signals) is found to be effective in fault recognition; however, it requires a prolonged training process and huge computation time and may possibly need appropriate and complex network architecture for correct fault prediction. Few of the works employing this kind of scheme are reported in references [136–139]. In the second approach, the SP-based time-frequency methods such as FFT and WT are generally used to extract the feature vector from the measured signals [140–144]. However, this kind of method may suffer from the presence of noise in the measured signal. Moreover, the ANN-based approaches need a large amount of data or features related to all possible fault situations and network topologies for the training process aimed at more accurate decisions. Currently, the design of accurate NN architecture is still a trial-and-error practice, and the design of the optimal network configuration includes a meticulous process.

In addition to NN, a few other ML techniques such as fuzzy logic [145], support vector machine [146–148], K nearest neighbor [149,150], etc. are also used for HVDC protection. A fuzzy-logic-based digital distance scheme is proposed in [145]. The fault identification task is executed through a fuzzy interference engine (FIE), where the magnitude of direct-quadrature (dq)-axis voltage and current are used as input variables. The FIE develops a fault detection index that is used to recognize the type of fault that occurred in the HVDC system. A one-end information-based fault recognition algorithm using SVM for the MMC-MT-HVDC system is proposed by Zhou et al. [146]. The symmetrical component analysis followed by the application of WT is carried out on the measured DC voltage signals to extract the input features for the SVM model. Johnson and Yadav [147] proposed an SVM-based method for HVDC fault recognition where the one-end DC voltage and current signals for a half cycle (before and after the occurrence of a fault) are used as input features. Muzzammel and Raza [148] have also suggested the SVM model for fault diagnosis in a VSC-MT-HVDC system, where the features extracted through principal component analysis (PCA) are used for the training and testing of SVM. Johnson and Yadav [149] have tested the applicability of the KNN network for fault-type recognition in a monopolar HVDC system. In the framework of KNN, the authors have tested several variations of networks such as fine KNN, medium KNN, coarse KNN, cosine KNN, cubic KNN, and weighted KNN. It has been observed that the detection delay is between 1 and 3 milliseconds of fault occurrence. Similarly, the authors in [150] have utilized the KNN model for both AC-side and DC-side fault recognition in a DFIG-integrated HVDC grid. Here, the DWT-based features extracted from the voltage and current signal of the relaying point are used as input to the KNN model.

Under the umbrella of ML, deep learning (DL) and its application is currently the most focused research topic in the power domain [151,152]. Recently, a few research works reported HVDC protection using DL techniques [153,154]. Yousaf et al. [153] proposed a transient-based HVDC protection scheme using a DL technique. In the framework of DL, a tuned long short-term memory (LSTM) algorithm is used here for DC transmission-line fault detection. Zhou et al. [154] used a deep belief network (DBN) for lightning-stroke transient identification for HVDC transmission lines. Here, the proposed DBN-based transient recognition model is trained and tested through the extracted features from the time domain signals utilizing the wavelet energy moment theory. The presented result shows that DBN has a better recognition accuracy compared to other superficial ML procedures in transient identification in HVDC systems. The drawback of the above-mentioned ML- and DL-based schemes is that their accuracy and selectivity can only be assured for the considered test systems with a large training dataset. The accuracy and selectivity can be calculated using the following Equations (1) and (2):

$$\text{Accuracy} = (\text{TP} + \text{TN})/(\text{TP} + \text{FP} + \text{TN} + \text{FN}) \tag{1}$$

$$\text{Selectivity} = \text{TP}/(\text{TP} + \text{FN}) \tag{2}$$

where TP represents the number of true positives (correctly classified positive samples), TN represents the number of true negatives (correctly classified negative samples), FP represents the number of false positives (incorrectly classified positive samples), and FN represents the number of false negatives (incorrectly classified negative samples).

In general, higher values of accuracy and selectivity indicate better performance of the machine-learning-based protection algorithm.

6. Converter Faults and Protection

The most common types of converter faults in HVDC systems as reported in [155,156] are (i) misfire, which is due to the failure of a switch to conduct on the programmed conduction period, (ii) backfire as a result of conduction in the opposite direction, (iii) fire-through, which is due to the conduction of the switch before the programmed instant of time, (iv) flashover, which is due to the occurrence of a short circuit in the non-conducting switch, followed by over-currents in the converter, (v) DC link capacitor failure, which is due to the occurrence of a short-circuit DC link capacitor, which can deteriorate the performance of an HVDC system, (vi) single communication failure, which is due to the malfunction of the valve and complete the commutation before commutating voltage reverses, and (vii) double successive communication failure, which is the failing of valve 3, for instance, to commutate 1, followed by 4 fails to commutate 2.

Lu et al. [157,158] reviewed several relaying schemes for converter internal faults (CIFs) such as open-circuit faults ($F_{open-circuit}$), short-circuit faults ($F_{short-circuit}$), and misfiring faults. Darwish et al. [159] reported a detailed analysis of the performance of differential and OC-relaying schemes toward the CIFs event and suggested that the placement of current transducers for OC and differential relays need to be changed. Abdou et al. [17] analyzed the impact of CIFs for both grid and rotor sides in the doubly fed induction-generator-based wind turbine generating system (WTGS). It has been studied that the $F_{open-circuit}$ on the DC link capacitor ($C_{DC-link}$) and misfire operation have a lesser amount of impact on the dynamic performance of the system than those of flashover and $F_{short-circuit}$ on the $C_{DC-link}$ and fire-through. It may also be required to pull the WTGS from the grid to evade a major breakdown in the converter controls, which may well influence the low-voltage ride-through (LVRT) ability of the network. Furthermore, the authors have proposed an approach to identify the CIFs using voltage and current measuring devices. Considering the measured voltage and current values, the active power is computed and then used to discriminate between a fault in the $C_{DC-link}$ and an IGBT-$F_{short-circuit}$ since the change in active power is higher in the case of a $F_{short-circuit}$ in the $C_{DC-link}$. Li et al. [160]

presented a relaying scheme for protecting the DC link faults (DCLF) in an MMC-based HVDC grid utilizing double thyristor switches (DTSs). Here, the DTSs help to decrease the DCLF current to null value as they eradicate the FDs' operational mode in the MMC during DCLFs. Venkatesh et al. [144] proposed a fast-acting CIF recognition technique using wavelet-based multi-resolution analysis and ANN. Here, the WT is used to extract the transients in the faults current, and ANN is employed to classify different CIFs events such as backfire, arc through, misfire, and commutation failures.

7. Perspectives

Considering the severity of DC faults, an effective relaying scheme for the HVDC system is highly essential, which is able to detect the faults within a few milliseconds. Detecting and isolating faults quickly is of utmost importance in VSC-HVDC systems, as highlighted in the literature. However, achieving this in practice is not straightforward without commercial DC-CBs being available. Since the MT-HVDC grid is designed for long-distance transmission, protection solutions based on communication are not very encouraging because of the communication delay, which contradicts the high-speed requirements of HVDC protection. In addition, the relaying schemes used in MT-HVDC grids must be selective to avoid disconnecting an active line or cable, which could have a significant impact on the system because DC cables are typically used to transmit a large amount of power. This can be achieved by using advanced hardware support and cutting-edge signal processing and AI methods to detect the transient presence in the signal measured at the relaying point within the first few milliseconds of the fault inception. Along with fault recognition, research regarding methods of limiting fault currents may perhaps help to decrease the harshness of DC faults. In this regard, a superconductor certainly comes into view as a capable solution [161–163].

7.1. Protection and Control Challenges Regarding Renewable Energy Integration with the HVDC Systems

There are many issues and challenges related to integrating renewable energy with the HVDC system. The substantial increase in renewables in the power grids requires a significant transformation from a control perspective to (1) handle the bidirectional flow of energy, (2) establish an efficient electricity demand and grid management mechanisms to regulate peak loads, grid flexibility, responsiveness, and security of supply with the uncertainty in generation and load, (3) enhance the interconnection of grids at different levels, such as at regional, national, and international levels, to control grid balancing capabilities, reliability, and stability, (4) initiate new technologies and procedures to ensure proper grid operation stability and control, (5) control the failures of synchronization with the AC grids with low inertia constant and SCR value signifying a weak system, (6) handle resonance conditions between the inverter DC-side capacitor and the AC system components, (7) control commutation failures in the HVDC converter, and (8) control many power quality and frequency control abnormal conditions [164,165].

With the synchronized wide-area communication infrastructure in the renewable-energy-integrated smart-grid environment, the real-time interaction and coordination between the wide-area protection and control, even with an HVDC-based power system, becomes a center of attraction as an innovative solution to the issues mentioned above and the challenges. However, the present protection and control system has difficulty handling real-time data recognition for this objective to be feasible and established. Many developments have been innovated in recent times in this field to look forward to fruitful development concerning the coordinated operation of protection and control systems related to HVDC. Though much research is demanded its successful implementation, certain developments are suggested, as follows [164,165]:

- A hierarchical approach and control framework can be formulated with integrated wide-area protection and control. Three levels starting from the local to the substation and wide area/regional level with integrated function at each level can be developed

to bring a coordination mechanism at each level that indirectly makes the smooth operation of the HVDC system overall.

- Many inherent abnormal conditions are focused on at the controller level, such as high dynamic overvoltage, voltage instability, harmonic resonance, and voltage flicker, to enhance the coordination with the protection strategy in the HVDC-based systems.
- Recently, the configurations of VSCs have been developed to incorporate renewable energy sources, such as modular multi-level converters (MMC), multi-terminal inverters, and hybrid structures. This helps to shut out and improve the coordination of control and protection in the HVDC system.
- The possible resonance conditions between the inverter DC side capacitor and the AC system components are considered to be handled by the robust and adaptive control strategy to avoid unstable conditions and false tripping.

From the specific control point of view, LCC-HVDC has many limitations that need to be focused on, not to affect the overall system's protection scenario, such as unreliable commutation failure associated with faults and operating point changes. This requires a proper control strategy with reactive power compensation and filters to reduce harmonics and enhance power quality. However, the LCC-HVDC is still preferred for bulk power transfer systems for a reliable, efficient, and secure option in the application. In the case of VSC-HVDC, the control structure substantially impacts not only the system stability but also the protection schemes because of its control rule and parameters. The primary controllers adopted, such as (1) voltage controller, (2) vector current controller, (3) advance vector current control, (4) power synchronization controller, (5) ABC frame controller, (6) voltage droop controller, (7) adaptive back-stepping controller, (8) flexible power control method, (9) proportional–integral (PI) decoupled method, and (10) fuzzy adaptive PI controller, are prominent and well-accepted techniques [166,167]. However, even though VSC has been more attractive than the LCC-type converter, many shortcomings need to be focused on for better upgradation to implement the wide-area control and protection concept with the communication technology. The complexity in angle and voltage stability regulation, limitations with maximum voltage and current, and improper selection of control parameters with communication-based approaches are the significant shortcomings of these control strategies for the VSC-HVDC systems.

Many significant issues and challenges must be focused on, enhancing the interaction between control strategy and protection schemes associated with the renewable-sources-integrated HVDC systems. First, the LCC-HVDC systems coupled to the weak grid force are unstable, particularly under communication failures. The system needs to be integrated with reactive power compensation for better operation and control. Similarly, even in the case of the VSC-HVDC system, it is found the frequent occurrence of the lack of synchronization particularly connected with weak systems. To handle this issue, advanced and adaptive control strategies must be adopted for overall performance with better control and protection. A similar scenario also very often occurs in the case of CSC-HVDC connected to a weak system and needs remedial measures by PMUs and PLL application. Overall, the communication-based protection scheme and control strategy as a wide-area operation perspective brings better coordination in the case of renewable-integrated smart-grid systems. However, secondary control and backup protection are needed for adequate security and reliability in system operation [168,169].

7.2. Recommendation for Future Research

As presented in the earlier sections, basically, the protection strategies that have been studied here include the fault current-interruption-based devices (changing the topology of MMC-SMs or CBs and its coordination) and different protection approaches based on measurement of current at one or both ends of HVDC system. In this regard, the following are a few recommendations for the improvement of protection strategies.

7.2.1. Fault-Current-Interruption-Based Devices

- The protection strategy for an HVDC system based on MMCs with DC-CBs is one of the potential solutions. To improve the overall switching or fault-current-interruption ability of the system during a DC fault, effective coordination of MMCs with hybrid CBs can be considered an alternative protective solution. Thus, prolonged research on the development of cost-effective coordination strategies becomes necessary.
- An extended study on the DC-CBs is required to (i) improve the current breaking capability and voltage rating, (ii) reduce the fault interruption time, commutation time, and energy absorption time, and (iii) make it more economical [91].
- More research on the optimization of FB-SMs' blocking action during a DC fault has become necessary.
- A single-end measurement-based protection method has less communication delay for long transmission lines compared to both-end measuring schemes. Here, the DC-CBs can be implemented with FCLs to limit the DC fault current. Therefore, special research attention has to be given to optimizing the FCLs in view of cost and size reduction. Further research on FCLs and their application with DC-CBs to control the rise of a fault current is required [169].

7.2.2. Fault Detection and Location Methods

- Advanced research on developing appropriate relaying schemes must be carried out to distinguish between momentary and permanent DC faults to avoid interruptions in DC grid operation.
- Because of the presence of a DC reactor on individual ends of the DC line, the TW-based single-ended strategy is still found to be suitable in the VSC-HVDC transmission stations, but its proficiency in contrast to varying fault resistances still needs to be enhanced.
- The foremost work of transient protection is to identify the internal, as well as external, faults with the help of high-frequency components extracted from voltage or current signals. This results in building stronger detection capabilities against high transition resistances. Furthermore, the working speed is extremely quick for the VSC-HVDC grids, allowing it to be the primary protection strategy.
- In the case of MT-VSC-integrated HVDC grids, directional pilot protection schemes and current differential protection schemes are generally recommended as backup protection for DC lines. In spite of this, improved schemes for a wide range of protection strategies are still needed to keep away from the obstructive impacts of transmission line parameters, as well as from reliant attributes.
- Usually, in an MT-VSC-HVDC system, the primary protection is provided by using single-ended measurement-based schemes, while the communication-assisted pilot protection schemes may serve as a backup. In contrast, when this primary protection strategy fails, the backup protection strategy (i.e., not based on boundary attributes) can be reflected as a primary protection scheme. However, DC-FCL should be developed with a strong limiting capability.
- For ensuring the robustness of the MT-VSC-HVDC transmission system, the protection strategies need to be examined with all possible AC- or DC-side short-circuit faults, converter station faults, rectification, and inversion-related faults with varying fault parameters.
- The major issues that emerged as a challenge for power engineers when going for higher-voltage-level DC operation are voltage drop, AC line overload, relay malfunction, system instability, and blackout. These factors need to be focused on during the design, planning, and establishment stage.
- Due to the lack of appropriate standards, additional research must concentrate on the protection of the DC system. New standards should be developed, or the modification of existing standards (such as IEC 60255, IEC 60834, IEC 61850, IEC 61869, etc.) can be carried out to provide a reliable protection to HVDC, as well as AC grids.

- A wide-area measurement system (WAMS)-based protection scheme for a multi-terminal HVDC network should be looked into deeper.
- Many factors should be taken into account while developing a protection strategy for the HVDC system. Detection of faults on converter stations, efficiency and smooth working of DC circuit breakers, proper coordination both at rectifier and inverter stations, and coordinated working with AC devices are the key factors that cannot be ignored.

8. Conclusions

MT-VSC-HVDC systems have become progressively more popular in current days. On the other hand, the development of a protective solution for MT-VSC-HVDC networks is more challenging, as it is vulnerable to DC faults on account of the smaller reactance and larger capacitance value of the DC lines. In this survey article, the characteristics of different types of DC faults in VSC-HVDC systems are comprehensively reported, in addition to several available fault-current-limiting methods. Effective protection of the MT-HVDC system is still challenging and requires more research. In this regard, this work has also reviewed several protection methods such as traditional differential current-based methods, over-current/over-voltage methods, voltage and current derivative methods, transient-based methods, and traveling-wave-based methods. In addition to this, the authors have analyzed the applicability of advanced signal processing algorithms and machine learning techniques in conventional protection schemes to provide better relaying support for the HVDC grid. The perspective of HVDC system applications and their protection challenges in the real-word scenario are also comprehensively studied in this work. To the end, this work has reported several future research scopes and possible solutions. The following are a few additional observations cited as concluding remarks.

- The power electronics converter-based strategies such as MMCs with fault-blocking capability and DC-CBs can be utilized to isolate DC faults in a few milliseconds, but the requirement for an increased number of switches makes them uneconomical and complex in nature.
- To improve the overall switching or fault current interruption ability of the system during a DC fault, effective coordination of MMCs with hybrid CBs can be considered an alternative protective solution. DC faults can induce high fault current, which is not tolerated by semiconductor-based devices such as in the VSC, CB, and other HVDC components. Therefore, fast fault detection and isolation methods are required to protect the MT-VSC-HVDC systems against DC faults.
- Among all the mentioned state-of-the-art protection strategies, which one performs better compared to the others is still in question, considering the protection measures such as speed, accuracy, reliability, sensitivity, selectivity, robustness, and design complexity. Thus, several research scopes are still available for further development to deal with the protection issues of VSC-HVDC grids
- The major issues that emerged as a challenge for power engineers when going for higher-voltage-level DC operation are voltage drop, AC line overload, relay malfunction, system instability, and blackout. These factors need to be focused on during the design, planning, and establishment stage.
- Before the establishment of the HVDC link, it is mandatory to do an extensive simulation study of the AC/DC hybrid system for system analysis and control. Traditional simulation tools such as PSS/EMTDC and MATLAB cannot deal with the complex dynamics of interaction between AC and DC exactly. The application is fairly good and restricted to simulating commutation failures in DC and resulting dynamics in AC networks. For small- and low-voltage scenarios, the result analysis is acceptable and fails to give better-simulated results for high-voltage-level scenarios as dynamics change very nonlinearly.
- The real industrial project should be focused on the development of the optimized multi-terminal and multi-vendor HVDC system and its protection challenges.

Nomenclature

AC	Alternating current
AC-CBs	Alternating current circuit breakers
ANN	Artificial neural network
CBs	Circuit breakers
CSC	Current source converter
CSC-HVDC	Current source converter–high-voltage direct current
CD	Clamped double
CIFs	Converter internal faults
CWT	Continuous wavelet transform
DC	Direct current
DC-CBs	Direct current circuit breakers
DWT	Discrete wavelet transform
DCC	Distributed capacitive current
DL	Deep learning
DBN	Deep belief network
DCLF	DC link faults
DTSs	Double thyristor switches
EPS	Electrical power system
EMTDC	Electromagnetic transients including direct current
FCL	Fault current limiter
FDs	Free-wheeling diodes
FB	Full-bridge
FB-MMC	Full-bridge modular multilevel converter
FRT	Fault ride-through
FTCS	Frequency transient current signal
FFT	Fast Fourier transform
FDPs	Frequency-dependent parameters
FIE	Fuzzy interference engine
HVDC	High-voltage direct current
HVAC	High-voltage alternating current
HVDC-CBs	High-voltage direct current circuit breakers
HVAC-CBs	High voltage alternating current circuit breakers
HB	Half bridge
HFTV	High-frequency transient voltage
HHT	Hilbert–Huang transform
ICFs	Internal converter faults
IGBT	Insulated-gate bipolar transistor
KNN	K-nearest neighbor
LCC	Level crossed connected
LVDC	Low-voltage direct current
LCC-HVDC	Line commuted converter–high-voltage direct current
LSTM	Long short-term memory

LVRT	Low-voltage ride-through
MMC	Modular multilevel converter
MT-HVDC	Multi-terminal high-voltage direct current
MT-VSC-HVDC	Multi-terminal voltage source converter high-voltage direct current
MMC-HVDC	Modular multilevel high-voltage direct current
ML	Machine learning
NC	Normally closed
NN	Neural network
OC	Over-current
OV	Over-voltage
PV	Photovoltaic
P2P	Pole-to-pole
P2G	Pole-to-ground
P-P2G	Pole-to-pole-to-ground
PFVI	Power-frequency variation impedance
PCA	Principle component analysis
ROCOV	Rate of change of voltage
ROTV	Ratio of the transient voltage
SVM	Support vector machine
SWT	Stationary traveling wave
SST	Synchronous sequenced S-transform
SP	Signal processing
SM	Sub-modules
TW	Traveling waves
TMR	Triple modular redundancy
TEO	Teager energy operator
THC	Transient harmonic current
UFB	Unipolar voltage full-bridge
VSC	Voltage source converter
VSC-HVDC	Voltage source converter high-voltage direct current
WTGS	Wind turbine generating system
WAMS	Wide-area measurement system

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