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MMC Based MTDC Grids: A Detailed Review on Issues and Challenges for Operation, Control and Protection Schemes

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ABSTRACT For decades high voltage alternating current (HVAC) was considered as most economical solution to transmit and deliver electric power. With the recent developments in power electronic devices, high voltage direct current (HVDC) system becomes most prominent technology. Multi-terminal direct current (MTDC) based system as a promising technology for future power system is the major focus area for researchers and industries these days. A number of MTDC systems have been implemented physically. The major motivation to construct such MTDC systems is the integration of large-scale offshore power sources such as wind turbines and solar systems. This article discusses the most critical challenges and issues related to operation, control and protection schemes for integration of modular multi-level converter (MMC) based MTDC systems. At first detailed literature survey has been presented to show the challenges for MMC based MTDC systems, then an analysis related to those challenges for operation, control and protection schemes for existing MMC based MTDC systems has been provided. Finally, a road map to tackle such challenges has been suggested.

INDEX TERMS High voltage direct current (HVDC), modular multi-level converter (MMC), multi terminal direct current (MTDC), power system control, power system protection, power system stability.

I. INTRODUCTION

Due to increased demand of electric power, the power sector industry is moving towards generation of electric power through renewable energy sources. This requires synchronous and asynchronous interconnections. With the recent developments in power electronic devices such as IGBTs and thyristors, HVDC systems become most prominent solution for such interconnections [1]. The development in control methods for VSC and MMC based HVDC systems have brought numerous advantages such as: transmission of electric power over long distance, interconnection of offshore wind power plants and interconnection of asynchronous AC systems with better performance than line commutated (LCC) HVDC systems. Multiple power sources can be interconnected by means of VSC MTDC and MMC based MTDC systems. MTDC provides meshed interconnections between onshore and offshore

power sources. With such interconnections the reliability and flexibility of AC and DC systems can be improved [2]. The MMC has been recognized as most prominent technology for high power transmission as compared to two level VSCs and other converter topologies. Some salient features of MMC include: high efficiency, reduced dv/dt stress on switches, modularity & scalability to meet high voltage requirements, improved THD, reduced voltages, fault tolerance and fault blocking capacity. With such features MMC has become the basic building block for MTDC systems and grids these days [12], [13]. A schematic diagram of MMC is shown in Figure 1.

Over the past years there has been a wide concern for addressing the technical issues and challenges for operation, control and protection of MTDC grids. Multiple solutions have been proposed by researchers which show that as compared to LCC and two level VSCs, MMC is more suitable for MTDC systems [6], [7]. However, still some technical issues and challenges relevant to integration of MMC based

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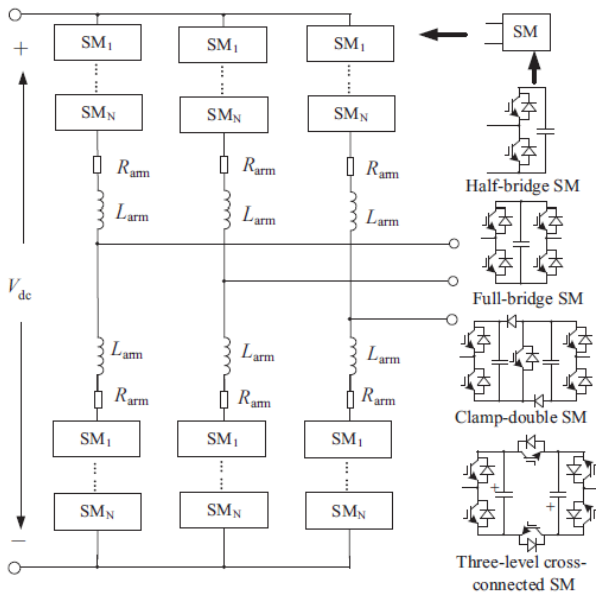


FIGURE 1. Schematic diagram of MMC.

MTDC grids exist [5]–[8]. The main contribution of this article is to provide a comprehensive review on those issues and challenges for operation, control and protection of MMC based MTDC grids. First of all, a detailed history of MTDC systems has been provided. After that some general challenges pertaining to MTDC systems have been discussed in brief. Later on as per title of paper, an in-depth analysis on issues and challenges for operation, control and protection systems of MTDC systems has been provided. Finally, some future recommendations based on critical analysis have been provided.

The rest of paper is organized as follows: Section II presents an in-depth overview of existing MTDC installations based on classical LCC technology to the latest deployment in form of VSC and MMC based MTDC networks. Section III gives a brief overview of challenges for MMC based MTDC grids. Section IV presents an overview for existing operation and control methods for MMC based MTDC grids and discusses various challenges related to them. In section V, the existing protection schemes for MMC based MTDC grids and their issues have been discussed. Section VI gives a future map to tackle the issues discussed in section III. Section VII concludes the paper.

II. DEVELOPMENT OF MTDC SYSTEMS

DC technology has entered into a new era after invention of power electronic devices. In early 19th century, AC system became dominant due to cost effective power transmission provided by AC transformers. DC systems started rebooting with the implementation of high voltage DC link between Gotland and Swedish Mainland. This project was accomplished by ABB [13]. Nowadays more than 180 HVDC projects are in operation, out of which most are two terminals. At present, the question is not about the choice of AC or

DC but it is about best integration of both systems. This can be done with implementation of MTDC systems. The successful implementation of point-to-point HVDC suggests the concept of Super grid which is most likely to be achieved via MTDC lines. It provides the most cost effective and efficient solution for interconnecting multiple converter stations through DC network. The MTDC systems are classified into three categories: radial MTDC system, meshed MTDC system and series connected MTDC system [14]. The future of meshed MTDC grids relies on VSCs which are two, three or multi-level converters (MMCs). Multi-level converters possess many advantages over two level or three level converters. It can be predicted that future of MTDC grid relies on this technology [2].

A. LCC BASED MTDC SYSTEMS

LCC based HVDC systems dominates long distance and bulk power transmission but with limited reactive power control. A lot of projects using this technology have been commissioned while some are under construction. The need of fast communication, complexity of control system and inability to change the direction of current have posed limitations on this technology for future projects [15]. The Italy-Corsica-Sardinia (SACO) HVDC project is the first three terminal HVDC project having a total capacity of 300 MW [16]. The Qu’ebec-New England LCC-HVDC system is the first five-terminal HVDC transmission system in the world with a power rating of 2000 MW and a DC voltage rating of ± 450 kV. The north Agra East UHVDC project is the first 5 terminal transmission link project based on LCC having a capacity of 6 GW [13].

B. VSC AND MMC BASED MTDC SYSTEMS

VSC technology have been effectively utilized in point to point HVDC transmission since late nineties. Nowadays two and three level VSCs have been effectively deployed in various MTDC systems, however MMCs are becoming more popular due to their flexibility for processing high power levels without any filter link at AC side [3]. VSC and MMC technology can address other conventional grid issues, such as asynchronous ties, back to back AC connection, system voltage and frequency support. They are also suitable for integration of offshore wind power plants. Due to their late development their portion in deployment of MTDC grids is very small as compared to LCC [2], [3]. MMC technology is applied to upgrade Nan’o 3 terminal VSC based HVDC system which is world’s first 5 terminal HVDC system. The five converters rated at ± 200 kV in the Zhoushan DC grid are connected via modular multi-level voltage source converter (MMC-VSC) HVDC links to form a 5-terminal DC grid [17]. Zhoushan multi-terminal HVDC project commissioned in 2014 in China is the first high voltage project interconnecting five terminals using VSC HVDC. Though its capacity is only 400 megawatt (MW), much less than the conventional LCC based HVDC, but the flexibility and control outweigh this aspect [17]. Zhang-Bei a project designed

to supply power to Beijing from clean energy sources such as wind, solar and hydroelectric power, is a four terminal MMC based MTDC grid which includes 3 sending terminals (1500MW/±500kV each) and one receiving terminal (3000MW/±500kV). In future addition of two more terminals in existing grid are planned, which will make it 6 terminal MTDC system [19]. The Atlantic Wind Connection (AWC) Project is the first offshore MTDC project based on MMC. The project would enable transfer of 7000 MW power from wind turbines into regional grid upon completion having 12 converter station and a rated DC voltage of ±320 kV. The project is expected to be completed in 2021 [18]. A layout for MMC based Zhangbei project is shown in Figure 2 [32].

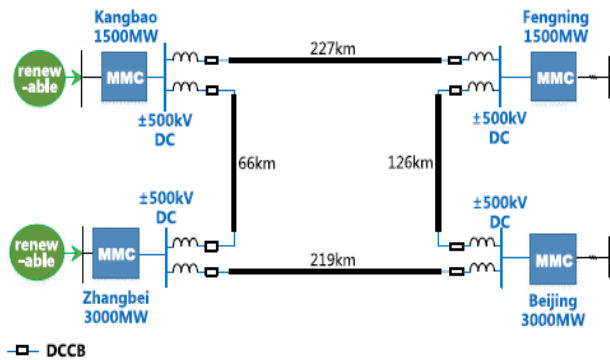


FIGURE 2. MMC based 4 terminal Zhangbei HVDC Grid [32].

C. FUTURE PROSPECTS OF MTDC SYSTEMS

Several HVDC projects are being installed in Europe that serve the purpose of transmitting clean renewable energy across the grids. Germany has several HVDC projects (in operation and planned) which connect offshore wind power with its transmission grid. With the increasing maturity in this technology, now the regional connections are also possible. For example, there are some Euro-African HVDC projects under consideration which can potentially bring the benefits of massive solar potential in North Africa to the European grid. In terms of HVDC topologies, US has installed few VSC based HVDC projects whereas Europe and China have several VSC HVDC projects. Upcoming HVDC projects like the Plains and Eastern clean line could be a positive start to a bigger goal of a North American Super grid (NAS or Super grid) which proposes a 52-node HVDC connection throughout the lower 48 states [20], [21]. Over the last century, china has emerged as global leader of HVDC market in R&D as well as in commissioned projects [20]. China has implemented unique HVDC topologies such as multi-terminal VSC projects, paralleled LCC and VSC, and even a hybrid LCC and VSC project is in the pipeline. Under the ‘Belt and Road Initiative’ there are currently discussions around building multi-terminal HVDC connections between China and Europe, including several other Asian countries [20]. With multiple R&D institutes and HVDC labs operating under SGCC, it can safely be predicted that China will continue to introduce new technologies in this field,

maintaining its position as a global HVDC market leader for the next decade [20], [21].

III. CHALLENGES FOR MMC BASED MTDC SYSTEMS

The challenges for operation and control of MTDC grids are similar to those which were faced in the development period of HVAC systems. Hence the most economical approach would be to learn from those problems which were faced in that era. Applying any of those solutions to DC system would shorten the way towards the development of DC systems. In this section some general challenges regarding to implementation of MMC based MTDC grids are discussed.

A. MODELLING

Due to numerous advantages over LCC and VSC, MMC has become an integral part of future MTDC grids. The half bridge (HB) sub modules (SM) is the dominant topology of MMC due to its reduced cost and low losses. However, for faults occurring on DC side HB sub modules are unable to block fault currents on AC side. Various submodules have been proposed to improve fault blocking capability of MMC such as full bridge (FB), unipolar full bridge (UFB) and clamped double circuits (CDC). The main challenge related to modelling is availability of accurate and efficient MMC models [24], [25]. significant research has been conducted to deal with challenges of its modelling and simulation. The detailed switch modelling (DSM) of MMC is infeasible for large scale MTDC systems due to huge time consumption in simulations. Average modelling of MMC is not capable to investigate DC side transients. Detailed equivalent circuit models (ECM) are able to calculate capacitor voltage for HB MMC. However, they are not applicable for full bridge (FB) sub modules. ECM with fault blocking capability are considered for MMCs with self-blocking capability. For large-scale power systems, more efficient models are required to be developed with fast simulation speed. However, for dynamic behaviors, these models are required to be accurately simulated with more state variables and smaller step time, which leads to a high computational load. Therefore, there is a tradeoff between accuracy and efficiency.

B. SYSTEM INTEGRATION

MTDC systems are evolving from simple structures to complex structures. The structures of MTDC are well defined. However, there is need to enhance its operating procedures specially for integration of AC and DC systems. One of the major challenge for integration of AC and DC systems in an MTDC system is stability requirements for AC and DC grids at different operating conditions. Integration of MTDC grid with an existing AC grid generates new operational and control issues. This is due to difference in behavior of conventional devices used at AC side and high speed switching devices at DC side [22]. Several control strategies have been proposed in literature which are mainly focused on modifications in droop control. Some researchers have presented power flow solutions without considering MTDC control.

Some research work is focused on detailed modeling for combined AC and DC systems in an MTDC network [22], [23]. However, control configurations are not taken into account. For a proper system integration in an MTDC network there is need of complete operational strategy including primary, secondary and tertiary control systems. The targets required for an optimal control in an MTDC network are: identification of power balancing and coordination requirements, identification of generic control configurations, development of combined AC and DC system models with a generic control and identification of power optimization requirements and safe economic dispatch.

C. PROTECTION

The essential requirements for a good protection system for MTDC system are: sensitivity, selectivity, reliability, speed of operation and robustness [26]. In an MTDC system it is essential that a fault on one AC system must not propagate to another AC system. Secondly fault on the DC side must not contribute to fault current on AC side. During a DC fault, generally the fault current propagates to all interconnected converters thereby reducing their output DC voltage, which can cause stoppage of power flow. A fault inside the converter station may lead towards loss of generation or load. Hence the development of proper protection strategies for MTDC system is a challenging issue. For an MTDC system, the half bridge MMC and two level VSC possess similar DC fault characteristics. Due to current flowing from freewheeling diodes they are unable to block fault current during a DC side fault [25]. Hence a proper protection scheme is required for HB MMC based MTDC systems. A fault blocking capability can be added to MMCs by employing fault blocking sub modules to block the fault currents. Another solution may be design of DC circuit breaker [25]. In this regard ABB has launched world's first hybrid HVDC circuit breaker (CB) that combines an ultrafast mechanical actuator with IGBT valves for protection of MTDC grids. A single line diagram of hybrid DC circuit breaker launched by ABB is shown in Figure 3 [31]. However, both solutions increase cost as well as loss of power. Hence it is still a challenge to design a cost-efficient protection scheme for MMC based MTDC systems with proper coordination of converters, circuit breakers and other protection devices.

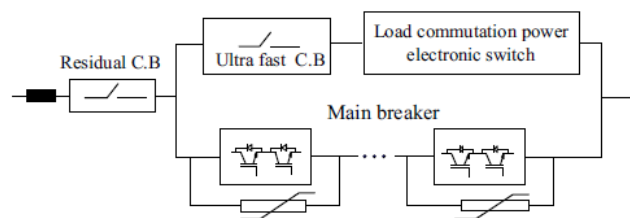


FIGURE 3. ABB's hybrid DC CB [31].

D. POWER FLOW CONTROL

In AC grids flexible alternating current transmission system (FACTS) are used to control active and reactive power.

However, in DC grids bus voltages are only characterized by their magnitude and impedance of bus doesn't contain any imaginary part. Hence for an MTDC control only magnitudes are used to control active and reactive powers [23]. In point to point HVDC system one terminal controls active power while other controls dc voltage. Such control algorithms can be extended for MTDC grids but it is not an optimal solution for the complex MTDC systems. The commonly power flow control architecture for VSC based MTDC system contains inner and outer loops. Similar architecture can be applied for MMC based MTDC systems.

E. DYNAMIC BEHAVIOR

In comparison to synchronous generators, power converters possess time response that can be much faster. Due to lack of mechanical inertia in power converters, a precise modelling of power converters and their controllers is required to control the dynamic behavior of an MTDC grid. Because of increased switching operation of power converters they are characterized by discontinuous dynamic equations which are difficult to analyze [23]. To improve the system stability, [110] proposes an active damping method to suppress power damping and resonance in VSC based MTDC systems. Such type of system is applicable to MTDC systems at a risk of transients on converter side. In [111], a unified reference controller has been proposed to share inertia for operation and control of MTDC grids. With such controller VSC stations can operate in different operating modes. However, such type of controller can interfere low inertia grids. In order to enhance security of MTDC grids in fault condition, [112] proposed a sensitivity based method for optimal location and setting of multi type power flow control (PFC). The results are verified for two four and eight terminal MTDC systems. Such type of system can effectively handle single line contingencies only. To simplify these issues, averaged dynamic models of converters are proposed by different researchers. The averaged models allow simplified analysis but with some limited analysis of power converters dynamics. Hence efficient control strategies are required to be developed to elaborate the complete dynamics of power converters in MTDC systems.

F. STABILITY

Stability analysis for an MTDC grid relies on DC voltage magnitude. It has to be approached in different manner as compared to HVAC system. For this, it requires detailed state-space models of converters, controllers, AC and DC grids. A proper systematic analysis is required to get the proper gains for controllers in order to ensure dynamic and transient stability of system. In an MMC, the sub modules possess energy storage capability which can be used to damp oscillations of power [27], [28]. However, internal dynamics of MMC poses serious challenges to stability of MTDC system. If such internal dynamics are not controlled MMC may cause large second harmonics currents. To eliminate such harmonics a circulating current suppression controller (CCSC) is employed in MMC based MTDC systems. However, these

CCSC may cause poorly damped oscillations on DC side of converter. Consequently, MMC provides enhanced stability for an MTDC grid with proper design of internal dynamics of MMC and its controllers. Further developments should consider the dynamic analysis of a more advanced energy management in MMCs, where the energy sum and difference are explicitly controlled to obtain optimal stability requirements for MTDC system.

IV. OPERATION AND CONTROL OF MMC BASED MTDC SYSTEMS

In recent years some of challenges related to operation and control of MTDCs are identified by researchers and industrialists. The major areas of focus are: improving performance of converters, developing control systems, optimized and flexible operation of MTDCs. The effective control of an MTDC can be achieved by employing proper DC voltage control and AC side auxiliary control [77]. However, the enhanced features of VSC and MMC enables fast response and power decoupling that provide auxiliary support to AC system and improves its stability. The existing control strategies that are implemented using outer control loops and inner control loops for VSC based MTDC systems are also applicable to MMC based MTDC systems [26].

A. DC VOLTAGE CONTROL

In an MTDC system, the DC voltage control is provided by outer control loop. The variation in DC voltage is due to power flow that is controlled by difference in bus voltage and grid voltage [77]. Primarily there are three methods employed for DC voltage control: master-slave control, voltage margin control and voltage droop control [77]. In a master-slave control, one converter station is selected as master controller which is responsible for controlling voltage while others control power. A voltage margin control is an improved control scheme where some converters are reserved for DC voltage regulation when power reaches to its saturation limits [78]. However, a voltage droop control is different from above mentioned techniques, because it possesses centralized control and master-slave and voltage margin possess decentralized control. In a voltage droop control, DC voltage is controlled by multiple converters in order to maintain voltage stability and power control.

A master slave control method is employed in Nan'o Five terminal MTDC system. A master-slave control faces instability issues in case of failure of master converter station. Additionally, it requires strong AC grid ties in order to achieve stability of DC grid in minimum time with zero negative effects on AC grid. Reference [79] proposed a précised voltage margin control for MMC based MTDC systems using d-q coordinate. It switches control mode to another converter station during power flow disturbances. An improved DC voltage margin control has been proposed in [80], which effectively controls steady-state power flow and possess good transient voltage response. In [81] an adaptive droop control strategy based on voltage margin control is proposed which

effectively reduces power fluctuations in DC grid. A lot of methods have been proposed based on voltage margin control in literature. However, the voltage margin control faces same issue of instability because only one converter regulates DC voltage at a time. A possible solution to shift the master control to another station may lead toward collapse of DC grid. Additionally, it is not good enough for dynamic stability of MTDC grid. The voltage droop control covers the deficiencies of both methods. Despite the popularity of voltage droop method, it also suffers from some draw backs. It cannot perform fixed power control or fixed direct voltage control in some operation modes. To overcome the limitations of these three control methods, some modified and improved control strategies which provide robust DC voltage control are proposed by various academicians and industrialists. The improved methods are focused on design and optimization of coefficients of voltage droop such as adaptive droop control strategies [82], integration of renewable power sources in MTDC system and optimal power flow control [77], [83], [86]. In [87] an improved droop control strategy has been proposed using droop coefficients to maintain voltage stability and power balance in an MMC based MTDC system. An adaptive droop control strategy for hybrid MTDCs has been proposed in [88] which minimize the deviation of DC voltage. Some modified methods based on combination of these three control methods have also been proposed. An auxiliary coordinated control strategy based on combination of voltage margin and voltage droop method has been proposed in [78] for integration of offshore wind power plants. In [89] a combination of droop control method and optimal power flow controller has been proposed which performs effectively during power sharing between multiple converters. In [78] a coordinated control strategy based on voltage margin and voltage droop control has been proposed to maintain the and transient stability of MTDC system and adequate power flow. In [113] a droop coefficient design method has been proposed that can ensure arbitrary power sharing between all converter stations in MTDC system. Such method doesn't require any communication medium. Hence accuracy is assured. However, DC line resistance varies which causes thermal variation. To conduct a deep frequency domain analysis, [114] has proposed a linear method for small signal stability analysis. The proposed method has been verified using test set of CIGREE DCS3. The proposed method is valid for dynamic stability analysis only. An optimal power sharing method using DC optimal power flow control (OPF) has been proposed in [115]. With such method operating point of MTDC grid is calculated and optimum operation of system is performed with minimum losses. Such method is applicable for dynamic and steady-state conditions only.

B. OPTIMAL POWER FLOW CONTROL (OPF)

The optimal operation of AC and MTDC grids requires OPF calculations at highest level of grid control structure. In this regard an MTDC system can be effectively controlled under voltage droop control strategy for any variations on

generation side or power consumption side [90]. Reference [90] proposed an effective DC voltage and power flow control method which is based on OPF calculations and voltage droop control method. In [91] an analytical expression to estimate the distribution of power under voltage droop control is proposed. Reference [89] presented scenarios of droop controlled MTDC to minimize DC transmission losses. It is supported with an average value modelling and optimization techniques. An improved droop control with an adjustable coefficient method for MMC based MTDC system has been proposed in [92]. The proposed methodology is focused on optimization of coordinate control method based on the analysis of DC voltage, power deviation and droop coefficient. In [116], a series-parallel DC power flow controller along with its complete control strategy has been implemented. The proposed controller effectively enhances the flexibility of MTDC system. However, solutions for the grid efficiency and grid congestion are not proposed. A power injection model (PIM) has been proposed in [117] for power flow control for in MTDC system. The proposed control method has been effectively verified using Newton Raphson DC power flow solver. Dynamic simulations are also performed to validate the results. However, there is no hardware implementation of controllers. To limit the fault current and manage flow in HVDC transmission line, a high temperature superconductive (HTS) power flow controller and fault current limiter have been proposed in [118]. The operation modes for proposed controllers have been analyzed using mathematical modeling and performance has been verified using experimental and simulation analysis. The proposed controller effectively controls the power flow between upstream and micro grid within a specified band. In [93], an interline current flow controller (CFC) with its average model has been proposed to calculate parameters for optimal power flow for hybrid AC/MTDC grids. The proposed CFC reduces the operational costs of hybrid system. Reference [94] presents a power shift based optimal corrective control method to improve the operational security of MTDC system utilizing maximum intake of power from renewable energy sources available. The characteristics for power sharing in an MTDC are shown in Figure 4 [26].

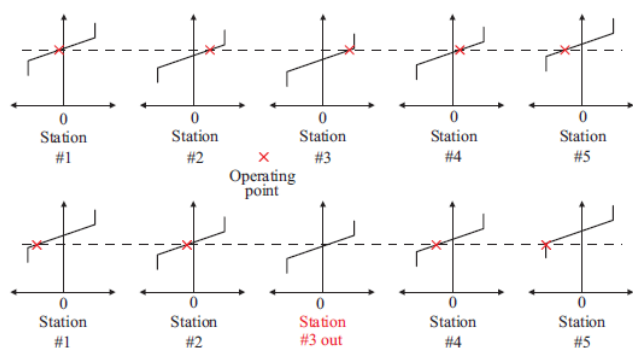


FIGURE 4. Characteristics of power sharing in an MTDC network [26].

C. DAMPING OF POWER OSCILLATIONS

The additional features of MTDC system w.r.t to its control system include: power oscillation damping, transient stability, fault recovery and enhanced damping [101], [102]. The power oscillation control can be integrated into DC power control of MTDC system. The basic concept is to compensate the oscillations of AC system by modifying the DC power reference value.

In [103] an inter-area oscillation damping solution for two machine MTDC system is proposed using active power modulation. In [104] a coordinated control strategy is proposed for damping oscillations of a VSC based MTDC system connected with wind power plants. An oscillation damping controller to provide electrical damping for inter converter oscillations in an MMC based HVDC system is proposed by [105]. A detailed analysis for low frequency oscillations for an offshore wind farm connected to MMC based MTDC grid have been provided by [106]. The characteristics of power oscillations and their impact for wind farm integration with MMC based HVDC system have been presented in detail in [107]. A flexible model to analyze small signal stability of VSC based hybrid AC/MTDC system is presented in [108] to damp inter area power oscillations. In [109] power oscillations are effectively damped with the support from virtual capacitance of MMCs. The power oscillations are reduced with the help of energy stored in SM of MMC. The methods applied for VSC based MTDC systems are also applicable to MMC based MTDC systems. But still there is lack of research work to be carried out to identify the internal dynamics of MMCs. MMC need more complicated control structure to effectively control the internal dynamics. The improved stability of AC as well AC system can be obtained through effective utilization of internal dynamics of MMCs.

In a hierarchical control of MTDC grid, those control schemes which are implemented with the inspiration from AC grids allow converters to operate independently. Hence an MTDC grid operating in analogous manner to AC grid allows implementation of converters from different manufactures with different power ratings [95]. In [96] a detailed two level control structure for MTDC system that is analogous to AC system is proposed. The proposed structure achieves system stability in an effective manner. Moreover, the concept of AC/DC super grid allows the addition of renewable energy sources in existing MTDC systems in an efficient way, maintaining overall system's stability. The concept of super grid and its related challenges are discussed in detail in [97]–[100].

V. PROTECTION SCHEMES FOR MMC BASED MTDC SYSTEMS

HB MMC cannot block DC fault currents, this behaviour is similar to two level VSCs. Hence the protection schemes which are applicable for two level VSC systems can be applied to HB MMC system. The DC system fault handling is similar to AC system fault handling which include locating & detecting fault and fault interruption. The fault

propagation speed in DC system is much faster than AC system. So protection system for DC system is required to operate in a time span of milli seconds [32]. As discussed earlier, the conventional HB MMC doesn't possess fault blocking capability. So in recent years MMCs with fault blocking capabilities such as full bridge (FB), clamped double sub module, three level modules and others have been proposed.

A. FAULT DETECTION AND LOCATION METHODS

Various methods for fault detection and location have been proposed in literature. Travelling wave, over current and under voltage possess fast fault detection time, but they are unable to detect high impedance faults. For high impedance faults differential protection is employed. Such protection scheme requires a communication medium such as optical fiber which increases fault detection time w.r.t length of line [34]. Another issue with the travelling wave base method is its practical implementation, due to high sampling method it is difficult to implement in hardware [33]. The frequency spectrum of voltage and current can be utilized to design an effective protection scheme. However, they are not fast enough as compared to other methods. The wavelet transform is an effective tool to extract information from voltage and current thereby reducing noise. Artificial intelligence (AI) is a promising approach for fault detection and location due to its superior pattern recognition capabilities, but at a cost of huge computational algorithms [33]. The research work conducted in TWENTIES project [35] suggests that best scenario of protection can be created using current differential protection as main protection scheme and overcurrent as backup protection.

The DC current direction method can be effectively used to identify the faulty line in an MTDC network [36]. However, with such method faulty lines can only be identified in process of clearing faults. Several fault detection and location methods are proposed in [37]–[40] based on transient voltages and currents, but they are not sensitive to high resistance faults. Wavelet and travelling wave based methods have been proposed in [41]–[45] which accurately identify type of fault and its location. In [46], [47] several ANN and support vector machine (SVM) based methods have been proposed. Several researchers have proposed hybrid protection schemes which are combination of existing protection schemes. In [44] a combined wave front detection and graph theory is implemented to detect fault location in MTDC network. In [48] a combined coordinated protection strategy is proposed for offshore MTDC networks using local measurements of voltage and currents and their derivate. In [49] wavelet transform is used to process the DC voltage signal and AI is applied to detected the fault in MTDC system.

A transient simplified model with high frequency components is proposed by [50] for fault detection in MTDC systems. The major work is focused to design a non-unit DC fault detection method, utilizing average transient value of current with low complexity and high sensitivity. A real

TABLE 1. Summary of fault detection and location methods.

Protection Scheme	Advantages	Limitations
Overcurrent / overvoltage	Provides robust protection as backup protection.	Can't be applied as main protection scheme due to low accuracy.
Transient Derivative	Suitable for detection of external faults due to high selectivity.	Not applicable for high resistance faults.
Frequency based	Good for post fault data.	Fault detection time is not good as compared to other methods.
Wavelet based	Robust fault classification method. It consist of filter banks so need of band pass filters can be omitted.	Not applicable for standalone systems.
AI based	Give fast and accurate results due to parallel processing and training.	Hardware implementation is not economical.
Travelling wave based	Gives high speed protection.	Sensitive to noise and other capacitive disturbances.

time boundary wavelet transform method for fault detection in MTDC is proposed by [51]. Reference [52] has examined the dependency of short circuit current on fault location in MTDC systems. The work presented is focused on evaluation of characteristics of current curve through fault location steep. Reference [53] proposes an effective fault location technique that is based on estimated RL representation of transmission line. With this method, the data for voltage and current at both ends for faulty line is gathered and an accurate fault location is estimated using proposed formulae. In [54], a high-frequency (HF) equivalent model of MMC-based MTDC grid that is utilized for initial dc fault current calculation is proposed. Reference [55] proposes a hybrid approach that consists an ANN based technique for fault detection and the discrete wavelet transform (DWT) to extract the information from ANN for MMC based MTDC grids. A wavelet package energy entropy based backup protection method is proposed by [56]. The proposed method is efficient for of fault resistance, fault distance and different operating conditions. In [57], extreme learning machine (ELM) method has been proposed to locate faults in MTDC systems. In this work s-transform and wavelet transform techniques are used as extraction methods for ELM. A summary of fault detection and location methods is given in TABLE 1.

B. FAULT INTERRUPTION METHODS

The coordination of AC side circuit breakers to interrupt DC fault may lead towards slow fault interruption operation. However, the fault clearing time required for DC system should be much faster than AC system. In this regard, the possible solutions to interrupt faults in an MMC based MTDC system may include employment of DC circuit breakers, integration of MMCs with fault blocking capabilities and coordination of MMCs with CBs and other protection devices.

1) EMPLOYMENT OF DC CBS

In literature, three types of DC CBs are proposed for MTDC grids which include mechanical DC CBs, solid state DC CBs and hybrid DC CBs. A mechanical DC CB includes a normal current path, a commutation path and energy dissipation mechanism. A solid state DC CB include various combination of solid state devices and ancillary circuits that enables ultra-fast operating speed [58]. Hybrid DC CB is a combination of controllable solid state switch with fast mechanical breaker.

A lot of research work has been carried out to design effective DC CBs for MTDC systems. The major focus is to design hybrid DC CBs due to its numerous advantages over other types. In [59] an ultrafast and modular hybrid DC CB is proposed for MTDC grids. A fault property identification (FPI) based with hybrid DC CB is proposed in [60] for half bridge MMC based MTDC system. Such method can distinguish between instantaneous and permanent faults. Reference [61] examined voltage and current characteristics of DC CBs. With this approach, the factors affecting fault interruption of DC CBs analyzed in detail. In [62], a detailed overview of hybrid DC CBs is provided to evaluate the performance of different technical designs. In [63], a sequential tripping method is employed to improve the interruption performance of hybrid DC CB by sending command to main breaker in a proper sequence. With this method, the fault interruption time is minimized and maximum overcurrent is reduced. In [64], a hybrid DC CB based on forced zero current is proposed for MTDC grid. The proposed breaker possesses very less interruption time with reduced ancillary circuitry and power loss. In [65], a detailed analysis of hybrid DC CBs is provided focusing topology and operating principals. Upon isolation, mechanical DC CBs withstand the system voltage and possess low conduction losses. However, their interruption time is long which ranges from 10 to 100 ms. The solid state DC CBs possess very high switching speed, which is less than 1 ms but at a cost of increased power loss [58]. The hybrid DC CBs possess high switching speed with a very low power loss as compared to mechanical and solid state DC CBs but their overall cost is very high. Hence such systems are still ambiguous w.r.t economical design of MTDC grids.

2) MMCS WITH FAULT BLOCKING FEATURES

HB MMC is considered as most effective topology for building HVDC networks. However, during a DC side fault, the fault current can flow from AC side through

freewheeling diodes. To tackle this issue, it is required to design an MMC with self-blocking capability. Such MMCs are proposed by [24], [25], which includes FB, UB and 3 & 5 level LCC. In such configurations, the fault current which flows through freewheeling diodes is blocked by sub module capacitor voltages. The capacitor of SMs generate reverse voltage to block the fault currents flowing from AC side to DC side.

In [72], a HB submodule with double direction control switch is designed to reduce the power loss in an MTDC network. Such sub module topology is known as hybrid double direction blocking (HDDDB) sub module. A novel double reverse blocking (NDRB) sub module has been proposed in [73]. This type of MMC possesses fewer power devices with same output voltage. In order to block the short circuit current flowing through diode, an addition of inverse series IGBTs and diodes to existing double thyristor MMC is proposed in [74]. With this design, a DC side protection scheme based on self-fault clearing is designed. In [75], a modified MMC sub module topology with DC fault clearing capability has been proposed. An addition of a directional switch and two diodes to existing HB sub module has been provided to quickly block DC fault current without changing original control strategy. Reference [76] has proposed a full bridge director switch based MMC that effectively blocks DC side faults in a more compact way. A suitable control strategy is also proposed in order to minimize the error of sub module voltages and AC current. Currently, a number of MMC designs with fault blocking capabilities have been proposed. The proposed designs effectively block the fault current. However, the increased number of semiconductor switches and other control circuitry leads to huge power loss as compared to half bridge MMCs.

3) COORDINATION OF MMCS AND DC CBS

Due to higher cost and higher losses, MMC with fault blocking features is not considered as a cost effective solution for MTDCs [25]. However, fault interruption with only DC CBs is also not a cost effective solution because a number of DC CBs are required to in meshed MTDCs [67]. Hence coordination of MMCs with DC CBs seems a good choice which gives low losses as well reduce the overall cost of protection system for MTDCs.

Reference [66] proposed a protection scheme that coordinates the system parameters with DC CBs in order to ensure their operation before triggering of MMCs. In [67], an assembly of DC CBs and coordinated control strategy is proposed for MTDC grids. In [68], a coordinated control strategy between FB MMCs and mechanical DC CBs is proposed for MTDC systems. A dc grid protection strategy based on temporary blocking of MMC in coordination with DC CBs is proposed in [69]. This system is implemented on a three terminal MTDC grid with a low protection cost. In [71], a protection scheme for MTDC system consisting FB MMCs and mechanical DC CBs is proposed. In this method, differential protection is employed because of its robustness

over wide range of impedances and low cost. A coordinated control strategy between HB MMC and hybrid DC CB is proposed in [70]. Such scheme suppresses DC fault currents and prevent overcurrent through arms of MMC. Future work requires to design backup protection schemes with the help of proposed coordination schemes where the effective solutions for failure of MMC and DC CBs are required.

VI. FUTURE RECOMMENDATIONS

In future, MMC based MTDC system as an emerging technology would lead towards building of super grids. With this, the issues related to control and protection of MMC based MTDC systems would be more challenging. More efficient models of MMCs with reduced simulation time and burden would be required for their effective operation. For a proper system integration, the enhanced hierarchal control architectures would also be required. A very few researchers have explored internal dynamics of MMC. In future, the internal dynamics of an MMC would be required to be explored in detail order to effectively reduce power oscillations in MTDC systems. The protection system purely based on DC CBs is not a cost effective solution. The future protection system would require coordination of DC CBs with MMCs. The protection coordination strategies presented in literature are still ambiguous due to increased switching losses and overall cost. Hence cost effective protection coordination methods would be required to be explored for future MTDC systems. Further developments would also require the dynamic analysis of a more advanced energy management system in MMCs in order to obtain optimal stability requirements.

VII. CONCLUSION

This article is intended to provide a wide overview for existing MTDC systems. The prospects for emerging control and protection strategies for MMC based MTDC systems are discussed and summarized in this article. The major issues and challenges for MMC based MTDC systems are discussed in detail and possible solutions are highlighted.

It can be concluded that in present era of DC power system, MMC has been recognized as a basic building block of MTDC systems. The MMC based MTDC systems ensure a reliable and efficient performance of power system. The effective control strategies of MMC make it suitable for synchronous and asynchronous ties between different power sources. Such systems provide robust control for integration of off-shore wind power plants. However, there are still several challenges that are required to be addressed for a reliable and robust future power system design.

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