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A Review of the Protection Algorithms for Multi-Terminal VSC-HVDC Grids

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***Abstract*— With the rapid development of renewable energy generation and consequently modern DC transmission technology, more complex HVDC installations are planned for power systems worldwide. Upgrading point to point (P2P) VSC-HVDC transmission lines to multi-terminal DC (VSC-MTDC) networks takes the DC transmission technology to the next level, but meets major technical difficulties in various aspects like control and protection of the grid equipment. This paper reviews the latest researches on the development of novel protection strategies for multi-terminal VSC (MTDC) transmission grids, as well as a brief categorization of converter modeling techniques. Many proposed strategies exist for the protection of HVDC systems based on traveling waves, transient based, voltage and current derivatives, advance signal processing methods, namely wavelet and Fourier transforms, artificial intelligence methods, etc. However, most of them are designed for P2P HVDC Grids and not applicable to MTDC systems.**

Keywords*— *MTDC, Protection, Review, HVDC, VSC

I. Introduction

High voltage direct current (HVDC) transmission is an established technology that has attracted a lot of attention in bulk power transmission and has been improved significantly in recent years. The developments in semi-conductors and controlling methods have made voltage source converter (VSC) based HVDC available and this technology will likely be widely used in future transmission networks, as a new economical way to transmit power from remote offshore wind farms, transmit power over long distances or, interconnect asynchronous ac regions with better performance and higher benefits compared to classics line commutated (LCC) HVDC transmission. LCC-HVDC systems cannot be connected to weak AC systems, because they rely on AC voltage in order to turn off the thyristors, something that it is not a concern in VSC-HVDC systems. Multiple wind farms can be connected to the grids by means of multi-terminal VSC-HVDC (MTDC), enabling high power transmission. A single MTDC transmission system is preferred over multiple point-to-point HVDC transmission systems, as it has economic and technical benefits, because of fewer converter stations. Additionally, MTDC topology reduces the transmission loss significantly and has less visual impact and lower electromagnetic fields[1]. Like LCC-HVDC, there are also weak points in VSC based transmission like the vulnerability of VSC terminal modules to DC faults, particularly when using MMCs, which makes protection more complex. Protection of DC grids is not as straightforward as AC line protection, because of the low resistance and zero reactance of DC lines, which limits the application of traditional impedance based protection methods. Most of HVDC proposed protection methods are applicable to point-to-point HVDC systems, which cannot be extended to MTDC transmission systems, and the design of MTDC protection systems are considered to be work in progress. Although some of the converter topologies like full-bridge MMC have DC fault current blocking capabilities and several vector control and direct control based strategies have been proposed for VSC converters, which also contribute to the fault blocking process, a proper protection algorithm is essential to detect the faults in the first milliseconds of the occurrence and also discriminate and separate the faulted section from the healthy parts of the gird. Voltage and current derivative, traveling waves and signal processing based methods like wavelet and fast Fourier techniques are the most common methods used to design protection algorithm for MTDC systems. This paper tries to discuss the latest researches concentrating on the protection of VSC-MTDC girds, where most of the proposed methods for P2P DC grids are not applicable on, which is laid out as follows: section 2, 3 and 4 discuss various converter topologies, switching equipment and modeling strategies in HVDC. Section 5 reviews the latest proposed methods in VSC-MTDC protection and finally, section 6 concludes the discussion and suggests further possible works in the topic.

II. Modeling Techniques

There are a number of modeling strategies, which each is used for specific types of analysis based on parameters like time frame. A summary of the most common methods are described as follows [2]:

1. Full-physics based models: This is the most complex method which uses differential equations for the elements.

2. Full-detailed models: switches are modeled as nonlinear resistors.
3. Models based on simplified switchable resistances: Switches are modeled as two-value resistors.
4. Detailed equivalent circuit models: A brief version of number 3 with a reduced number of nodes but still including the accurate impact of various capacitor voltages.
5. Average models: This method uses controlled voltage and current sources with harmonic for modeling AC and DC characteristic.
6. Simplified average models: Similar to the previous method, but without considering switching harmonics.
7. Load flow models: This method only considers steady-state converter outputs without any transient modeling.

Among the mentioned methods, only the first one cannot be implemented in EMT tools and method 7 is only used in steady-state power flow analysis programs. Methods 2, 3 and 4 offer detailed studies of faults in submodules and are mostly used to validate the simplified models. Method 5 is proper for DC and AC transient studies and consists of a high-level control system and harmonic studies and method 6 is valid for remote DC and AC transient studies. Method 5 is the one usually used for protection studies in EMT analysis. Other than considering different modeling strategies, the difference between the converter topologies should also be considered. Figure 1 depicts common converter configurations, which is not discussed in this paper for page limitations.

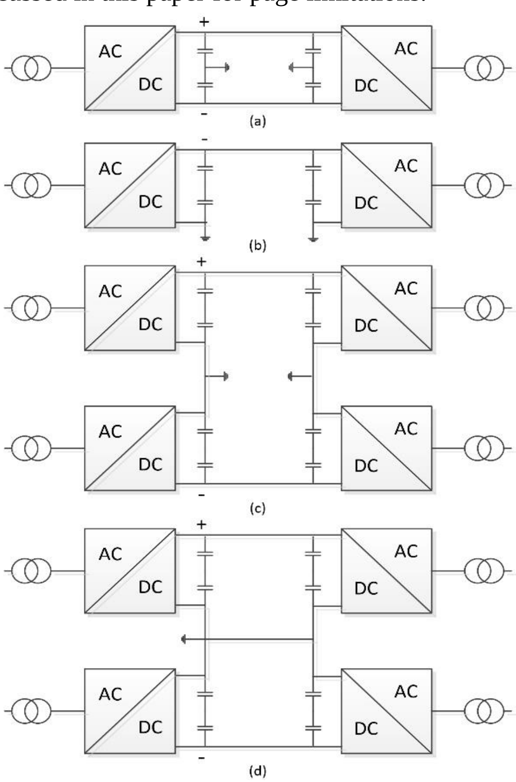

Fig. 1: Common converter configurations: (a) Symmetric monopole (b) Asymmetric monopole (c) Symmetric bipolar (d) Asymmetric bipolar

III. Switching Devices in DC Protection

The breaker switches play an important role in DC protection. Currently, the DC breakers are not commercially available and the only option is to use the traditional AC breakers to deal with faults. Combining AC breakers with slow mechanical DC switches is possible for selective fault discrimination[3].

A. *Handshaking Approach with AC Breakers*

Currently, using the AC breakers is considered as the only available method in DC fault dissipation. Handshaking method firstly introduced in [4], is based on blocking VSC switches just after fault detection and opening all AC breakers, which are on the AC side of VSCs and can separate the DC part consisting the faulted line, opening the DC switches of the faulted line, which do not have arc quenching capability to clear the fault independently and finally connecting back the healthy DC part to the main grid via closing AC breakers and unblocking VSC switches. This method is used for different types of DC faults and doesn't need a communication channel, using only local measurements. Although using handshaking method may solve the need for fast DC breakers, which are not currently available, it suffers from a considerable outage time of the whole DC system, which brings up major reliability issues and a huge loss of infeed. Additionally, no further developments of the method have been published recently.

B. *Future DC Breakers*

Currently, there are many challenges in DC breaker development such as the low inductance of DC system and lack of zero crossing current which leads to the need of break down a big energy value [5]. Considering the half-bridge MMCs as one of the most promising technologies in HVDC grids, their submodules enable the ability to clear DC faults, but that leads to high power loss and converter blocking. The other option is using hybrid breakers which have been investigated in [6] together with a control strategy. The assembly breaker introduced in this work is consisted of an active short circuit breaker, a mechanical disconnector, a primary breaker and a discharging switch. The method is suitable for meshed MTDC networks and further work for developing the proposed method can be performed to improve the fault-ride through capability of the system. There is a comprehensive review about HVDC breakers in [7] and more discussion about various breaker topologies like solid-state or hybrid breakers is out of the scope of this paper.

IV. VSC-MTDC Protection Methods

There are known methods and techniques in HVDC protection that can be developed for MTDC grids. Although there are many proposed works in HVDC protection and control, this chapter tries to discuss the latest publications concentrating on the protection of VSC-MTDC transmission, which is categorized as follows:

A. *Differential Protection*

Currently, the use of differential with backup overcurrent protection is the most feasible option to protect VSC-DC lines[8]. Considering the need for a fast communication link between the ends of the lines, differential protection is able to detect the high resistance faults, which is difficult for other methods. While many of differential-based methods use traveling wave theory, which is covered in section 5.4, there are updated publications trying to develop this method for MTDC grids. In [9], a fast differential based fault location method for VSC-MTDC grids is proposed using multipoint optical current sensing, which removes the need for communication link in differential protection and the originating communication delay. A series of differential currents are calculated based on the measurements of two consecutive sensors, which are close to zero for external faults and high for internal faults. A hybrid breaker design is used which is introduced by ABB [10] and the suitability of using the optical sensor technology for DC protection is clearly shown. The simulations are compared with the laboratory testing which had minimum errors. Although the investigation of multiple sensors is challenging similar to communication links, the proposed method is one of the latest proposed differential based protection methods, which is also applicable on VSC-MTDC grids.

B. Overcurrent/Overvoltage Protection

Among common traditional protection methods, overcurrent protection uses direct measuring of current values and it is commonly defined as a function of current with respect to time. While the low accuracy in selectivity makes overcurrent protection useless for main protection in MTDC grids, it gives tolerable results as a backup protection. It is also used to prevent damage to the thyristor valve caused by overheating[11]. In [12], and inverse time overcurrent scheme is proposed for the protection of MTDC grids along by adding inductors near protection relays, which reduces the severity of fault current and current derivatives. Similar to overcurrent protection, overvoltage protection is another direct measurement based strategy, which is applied to each pole in HVDC system. This function cannot be used as a stand-alone strategy to protect the DC grids and it mainly protects the cable and surge arresters in HVDC systems.

C. Transient/Derivative Based Methods

The rate of change of voltage or current signals, namely *dv/dt* and *di/dt* are useful criteria for designing DC fault analysis methods. As to mention the latest researches using derivatives, a fault detection method based on identifying suited fault detection variables or markers, i.e. DC current and voltages derivatives and local measured magnitudes is proposed in [13]. Selecting the suited markers for various situations is carried out by common criteria such as dependability, speed, security, and selectivity, showing that using derivative values give the fastest results. The paper considered the impact of fault current limiters (FCLs), claiming the DC current derivative markers suit best using limiters while the voltage derivatives give better results for the system without FCL. However, a 10 mH FCL is used but a sensitivity analysis is needed for the FCL size. In the other hand, the resistance to the ground of the considered faults is too low, which makes the fault detection easier than considering higher impedance faults. The method is applied on a radial multi-terminal DC network and it should be applied on meshed MTDC grids in order to show its robustness. In [14], a communication-less protection system is presented based on a threshold limit on the DC current derivatives and using dc breakers applied on the same three terminal radial HVDC with bipolar configuration used in [13]. Although the simulations show that the fault currents develop very fast and have really high derivatives, which needs to very fast protection system and DC switches, the DC breakers are not commercially available yet, which makes the practical implementation of the propose method infeasible. In [15], a new protection scheme consisting of the main algorithm and a pilot backup protection is proposed. The method calculates the ratio of transient voltages (ROTV) as the ratio between the transient voltages of the two sides of each supplemental inductors placed at both ends of DC line for discrimination between internal and external faults. A three terminal radial MTDC system based on half-bridge MMC is built in RTDS for real-time simulation results, but the validity of the method for meshed MTDC grids is not studied. Although the rate of change in voltage can be considered as a useful criteria in DC protection, in higher resistance DC line faults the *dv/dt* value becomes too small and unusable for fast and accurate DC protection. Other than that it depends on system topology and parameters like resistance and capacitance, resulting in larger rate of change in healthy lines than faulted lines and tripping malfunctions. The proposed method just concentrated on fault on DC cables and faults on converters and AC sides have not been considered to be dealt in the algorithm.

D. Traveling Wave Based Methods

Traveling wave-based methods are widely used in HVDC protection. Fault current and voltages generate impulses, which travel from generating point to the line ends. This phenomenon is used for fault detection, based on estimating first and second reflections at one terminal, which solved the need for communication link in some of the proposed methods [5]. They can also detect lower impedance faults, which is difficult to handle in other methods. Other than being used as a standalone DC protection method [16], it is also being implemented in other protection and fault locating methods, like differential and frequency based strategies. Authors in [17], presented a new differential protection technique, introducing a ratio between operating and restraining signal indices for discriminating between internal and external faults based on double ends traveling wave technique. Different configurations of DC sections such as cables and overhead lines have been considered. Although the method is reliable in fault detection and classification, the two end data acquisition needs high-end communication links between terminals, which economically is considered as a drawback in MTDC protection studies. Other than that the dependency of the traveling wave-based methods to detect the initial wavefront for gathering the fault data, makes them hardly practical.

E. Frequency Based Methods

In [18], a novel algorithm for MTDC fault location is presented using natural frequency using only current measurement and frequency spectrum identification for each terminal using Fourier transform and calculating dominant frequency component. Authors in [19], presented a natural frequency based single-ended protection method from the pure reflection of traveling waves, which is because of large shunt capacitors in-line terminals. It is based on the fact that natural frequency magnitude is proportional to the fault resistance and subsequently the fault distance and uses fast Fourier transform (FFT) and Prony algorithm for accurate extraction of the natural frequencies. Although the proposed natural frequency-based methods do not have to use wave head to extract the natural frequency and can use any post-fault data, pure frequency-based methods are not suitable for time-varying faults and transients, and using hybrid methods such as a combination of frequency based and wavelet algorithm gives significantly better results.

F. Wavelet Based Methods

Wavelet transform is a powerful signal processing method for detecting signal changes like power system transients and faults with time scaled windows using a wavelet analysis function named mother wavelet. Authors in [20], proposed a protection method which uses one side current measurement data and the discrete version of wavelet transform (DWT) for signal processing. It uses shunt capacitors to absorb high frequency transients caused by external faults without affecting internal fault-generated transients, resulting in better and faster zonal protection. It introduces indices based on the spectral energy of different frequency bands in the measured signals to discriminate between internal and external faults. However, there are fails in discriminating the faulty lines in some specific bus-bar arrangements and the optimal capacity of shunt capacitors need to be determined as accurately as possible. Using voltage and current wavelet analysis and voltage derivative and magnitude, as three independent fault criteria, a new protection method is proposed for VSC-MTDC protection in [21]. It gives high selectivity without using communication link, introducing redundant TMR technique. Although the detection time is less than 1 ms, which is essential in MTDC protection particularly when using DC breakers, it is proper only for low resistance faults. In [22], a Wavelet-based DC cable fault analysis approach for MTDC systems is proposed, utilizing hybrid DC breakers to break the DC current. The results give very fast detection results with a detection time about 1 ms for current change in DC cables during faults, which is compared to a time of 3.5 ms as the result of the latest proposed methods. The proposed DWT uses the lowest number of coefficients, but because of the high sampling frequency of wavelets, the output time is shifted.

G. Artificial Intelligence Based Methods

Modern artificial intelligence based methods such as ANN, fuzzy logic and genetic algorithms have gained much attention for line and converter fault protection and control for both AC and DC networks. With the capability to extract information in time-dependent and non-linear systems ANN methods give better results than methods such as frequency or modal analysis, which confront major difficulties in such situations [23]. Comparing the use of PI controllers with fixed gains and constant parameters, fuzzy logic, and ANN methods give more flexible parameter tunings resulting improvements in HVDC operation. Various AI-based approaches have been presented for fault identification of classical point to point LCC-HVDC systems as well as new researches on VSC DC grids. The authors in [24], proposed a comprehensive protection method based on three separate ANN methods for detection, classification, and location of faults, using only high-frequency components from one end current data and needless to any communication link. The proposed method can be fast enough for being used with future DC breakers and based on the results it is robust to high resistance faults and noise. Only 2-level converters have been considered in the modified CIGRE B4 DC model which, as further works, can be upgraded with more complicated topologies like the half-bridge or Full-bridge MMC converters.

H. Other Studies

Other than the aforementioned methods, which are categorized in common Protection methods, there are more publications, introducing strategies to deal with protection challenges in MTDC systems. One of the methods that has recently received attention in MTDC protection, is using reactors to detect the faults as selective as possible. In [25], this principle is investigated for the protection of MTDC cables using incident waves which are non-dependent of boundary conditions in the protection terminals. In [26], a protection method based on unidirectional hybrid circuit breakers (UHCB) using DC bus logic is presented for MTDC grids. The proposed method consists of two different unidirectional strategies based on local communication based and remote overcurrent fault detection, and the impacts of using UHCB and the proposed methods on converters, DCCB, surge arrester energy ratings and CB current ratings are investigated. The results show technical and economic benefits of UHCBs over typical hybrid circuit breakers. In [27], a protection strategy for large MTDC networks is introduced, using MMC based DC-DC converters as firewalls to keep the remaining parts of MTDC operating in islanded zones during DC faults. Considering higher availability level of the healthy DC part, the proposed strategy is accurate but it is not fast enough for MTDC protection and a more detailed algorithm in the switching sequence of breakers and switches is needed. Authors in [3], presented a DC grid topology using fault-tolerant LCC-VSCs and mechanical DC CBs, showing that slow protection schemes and resulting longer fault clearing times based on slower mechanical DC CBs have no impact on grid security during the fault. Three separate protection systems are employed as cable differential traveling wave based protection, bus bar and a backup protection which lead to a total fault clearing time of 60 milliseconds and high-cost fault limiting reactors and fast communication links as are needed. Authors in [9], proposed a single-ended protection strategy using distributed optical sensors, which basically works on the differential current between each two sensors to detect and locate the fault. The key advantages of the proposed method are the enhanced reliability, meaning that the algorithm still works in case of one or more sensor failures. Other than that, the method limits the protected element between each two sensors, which eliminates the cable capacitance effect producing a short burst of differential current and making problems for conventional differential based protection methods. The paper also proposed experimental results using Fiber Bragg Grating (FBG) sensors, in order to show the feasibility of the algorithm. However, there are also drawbacks in using the proposed methods like the cost of sensors and their installation and maintenance. Based on the first carrier frequency harmonic (FCFH) current in VSC-MTDC, a protection method is presented in [28]. The method studies the response of FCFH currents at the two ends of the DC cable under external and internal faults. The main idea is that the circular current for external faults will be between the converter and the DC link capacitor, which cannot be detected by the protection. On the other hand, for internal faults, the direction of the currents will be in such a way that the first carrier frequency protection relays from both sides can detect the fault. The discrete Fourier transform is used to determine the harmonic content of the current signals. Although the method works well in discriminating between internal and external faults, but the determination of the faulty pole on DC cable faults and the AC faulted phase has not been clearly described. Other than that the simple 2 level converters are used, which have higher harmonic domains and the fault determination process is not a big challenge for the algorithm, while using MMC leads to lower harmonic domains, which puts the harmonic based protection in real challenge. Authors in [29], presented a protection method based on improved electromagnetic time-reversal (ETMR) technique. Comparing to traveling wave-based methods, it does not need the high sampling frequency and the exact fault located time and works precisely on higher resistance fault situations in comparison to transient-based methods, But it is only considered the lose less transmission. It uses high frequency 0/1-mode current and takes frequency dependent parameters of the transmission line. The results show that 0-mode and 1-mode currents eliminate current harmonics for monopolar and bipolar faults respectively. The impact of measurement errors and reduction in measurement points has also been considered in the study.

V. Discussion and Perspectives

As discussed earlier, speeding up the detecting and tripping performance of the protection algorithms while keeping the accuracy does matter a lot in VSC-MTDC protection, which is hardly achievable practically until the availability of commercial DC breakers. Using handshaking method as the only practical way, which is significantly slower and does not meet the reliability standards. Voltage/current derivative-based methods give acceptable results for faults with low resistance while meeting accuracy problems facing higher resistance faults which is important in DC protection. Signal processing-based techniques as stand-alone methods to protect the grid independently may not give acceptable results and are mostly used in combination with other techniques like traveling wave-based methods. Artificial intelligence-based methods may give relatively acceptable results in research-based EMT simulations, but getting them practically applicable will not give reliable results for practical MTDC investigations. The traveling wave-based differential protection methods give more acceptable results than other methods in literature, while they need communication link between the measuring points, facing the algorithm with sudden communication delays particularly in long transmission distances. For one-sided methods, the remote faults face major problems, while using reactors are needed to discriminate between internal and external faults. Table 1 briefly describes the advantages and disadvantages of the reviewed methods. Further developments in MTDC protection can consist of designing protection algorithms using wide area measurement systems (WAMS) for VSC-MTDC networks particularly for developing traveling wave-based methods using traveling wave recorder (TWR)s installed on optimal places in the grid. Developing the protection methods for ultra-high voltage direct current (UHVDC) transmission grids, which have structure that is more complex, particularly in multi-terminal design.

TABLE I. PROTECTION METHODS SUMMARY

Method	Advantages	Disadvantages	Reference
Handshaking method	Practically applicable	Long down time of whole DC grid	[3], [4]
Overvoltage/Overcurrent	Good as backup protection	Low accuracy and selectivity as main protection	[11], [12]
Transient/Derivative	High selectivity and identification of DC line faults from external side faults.	Depending on system topology and parameters (capacitance and resistance), Low accuracy for high resistance faults	[13], [14], [15]
Traveling Wave-based	Giving high speed protection algorithm	Accurate timing of the wave front needed- sensitive to noise and current capacitive distributions in differential protection	[16], [17]
Frequency-based	Can use any post-fault data	Algorithms are not stable and fast enough compared to other methods.	[18], [19]
Wavelet-based	Consisting filter banks and no need for designing band pass filters	Not suitable as a stand-alone protection method	[20], [21], [22]
Artificial intelligence-based	Give fast accurate results in simulations	Not robust enough to implement practically	[23], [24]
Harmonic-based	No need to install series reactors, Fast discrimination between internal and external faults	Hard to detect on MMC but useful for 2,3 level, Not robust detection of faulty pole	[28]

VI. Conclusion

VSC-HVDC protection is one of the most promising technologies for the development if DC grids worldwide, but there are also many technical control and protection problems in VSC based DC grids such as the vulnerability to the DC faults due to the conduction of antiparallel diodes, needing very fast isolating DC switches to overcome this problem which are not commercially available yet. In the other hand MTDC grids are predictable with the growing installation of P2P HVDC lines worldwide. MTDC has many benefits over point to point links such as bulk power transmission from multiple generation busses to several loads and asynchronous connection between multiple AC grids. Considering the future plans for developing VSC based DC grids to multi-terminal systems, the control structure, and protection strategies gets even more complex. This paper reviewed the latest protection studies and methods introduced which concentrate on the protection of VSC based MTDC transmission systems. Although there are several proposed protection methods based on traveling waves, artificial intelligence, frequency analysis etc. and taking the advantage of different techniques such as wavelet and Fourier transforms, this topic is not mature yet and more researches should be investigated to gain more robust protection strategies to have a more stable future DC grid.

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