Survey of Methods for Selective DC Fault Detection in MTDC Grids

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Abstract

Recent demand of renewable energy generation has placed new requirements on the flexibility of transmission systems. These requirements together with technical advancements of high-voltage direct-current (HVDC) technology have resulted in the ambition to build large-scale multi-terminal DC grids (MTDC). These large-scale MTDC grids are expected to require fast DC breakers which allow for selective fault clearing. Selective fault clearing strategies avoid decreased availability during faults because only the faulted part can be isolated whereas the healthy part continues operation. For successful operation of a MTDC grid with multiple breakers, a protection system with selective fault detection is thus required such that the DC breakers achieve correct fault isolation in the event of a fault. Selective fault detection in MTDC grids is however not trivial because of low impedance characteristics and short required isolation times. This paper summarizes previously suggested selective fault detection methods for protection of a MTDC transmission system using DC breakers.

1 Introduction

HVDC technology has been established as a valuable complement to existing AC (alternating current) transmission systems. The inherent properties associated with DC allow for long cables without capacitive leakage currents. The development of voltage source converters (VSC) for HVDC has solved especially one limitation associated with line-commutated converters (LCC): In VSC converters semiconductor devices are used that are capable of both turn-on and turn-off which adds controllability. This has made the VSC-HVDC a popular technology for connecting islanded systems such as large scale wind farms because VSC-HVDC allows providing wind farms with a constant voltage, frequency, and phase angle [1].

Since the generation provided by wind farms depends on wind conditions, the existing point-to-point HVDC connections are only fully utilized during short time periods. If a wind farm were to be connected to multiple AC systems by multiple HVDC links, these HVDC links could enable electricity trading during periods when the wind farm does not operate at full power [1].

The concept of connecting multiple converter stations on the DC side, forming a MTDC grid, was subject of research in the 1980s, but only a few projects with more than two terminals were ever built [2].

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At the moment however, the recent demand of renewable power generation in Europe has resulted in a planned capacity of over 100 GW [1] in the North Sea. Since many of the planned projects are located in the geographical vicinity of each other, the potential benefits of connecting them have been acknowledged by academia, industry, and authorities.

Technically, an MTDC grid with VSC technology could be operated without DC breakers. However, in case of contingencies, e.g. faults, the entire MTDC grid would have to be shut down to clear the fault. This is not considered to be practical in a large scale MTDC grid [3]. To avoid shut-down of the entire MTDC grid, DC breakers are required that allow for disconnection of only the faulted part of the grid. DC breakers are therefore one of the key technologies required for building a DC grid [2], [3]. They have to be able to break large fault currents that are associated with VSC-DC transmission systems. Also, DC breakers have to be fast to limit the fault propagation into the healthy MTDC grid parts.

This paper is structured as follows: After presenting the relevant background for MTDC grid protection, different fault detection methods are described. These methods are discussed and compared. The results are summarized and conclusions for an MTDC protection system are drawn.

2 Background

DC fault detection methods are part of an overall MTDC system protection. The overall MTDC protection has to meet general protection requirements (section A below). This implies use of proper fault clearing strategies (section B below). Fault clearing strategies, however, include fault detection which is the main focus in the remainder of this paper. Selectivity during fault detection can e.g. be accomplished by exploiting the electrical distance that is introduced when using a current limiting reactor (section C below). Another advantage of the reactor is to limit the current rise rate (*di/dt*) in the DC breakers.

A. General Protection Requirements

There are several properties associated with any system protection, AC or DC:

- Reliability: The protection system is required to be both dependable (operate when required) and secure (do not operate during other disturbances).
- Speed: Detection and isolation of faults must be fast enough to minimize the system disturbance, minimize stresses on equipment and occur before the fault current exceeds the breaking capability of the DC breaker.
- Selectivity: The protection system should only act during faults within its designated protection zone.

A typical protection system consists of many individual protection functions where each contributes to operating the system in a safe and satisfactory manner. This implies that a MTDC grid protection will consist of many different protection functions, each designed to fulfil a specific purpose. The protection requirements can however also be applied to individual protective functions. Note that the properties listed above are difficult to measure without access to statistical data regarding the protection. In the protection development stage, these properties should however be analysed with regard to a particular protection principle to predict any possible misoperation and to introduce measures to avoid that.

B. DC Grid Fault Clearing

One of the main advantages of an MTDC grid is the low impedance and low transmission losses. This however entails that short-circuits result in high currents and propagate very quickly throughout the entire grid. During a fault, all energy available in the MTDC grid will eventually discharge into the fault, making power transmission impossible until the fault has been cleared. In smaller schemes with limited transmission capacity, e.g. three-terminal schemes, it might be acceptable for the entire power flow to be interrupted if a DC fault occurs. However, for large-scale high-power MTDC grids, complete shut-down is most likely not acceptable.

Different fault clearing strategies were classified in [4] for the HVDC test grid defined in [5]. The classification was done regarding fault clearing time as well as communication and breaker requirements. The investigated fault clearing strategies included e.g. methods relying purely on DC breakers, purely on the VSC-HVDC capabilities (full-bridge converter blocking) or a mixture of both. Another scenario was simulated in [6] where a hybrid DC breaker is used to divide the 11-terminal system into two different zones in case of a DC fault in either of the two zones.

In order to achieve the same availability as AC transmission systems with regard to faults, the DC fault clearing time has to be in the range of milliseconds which requires employment of fast DC breakers [3]. The number of breakers and corresponding protection zones must be similar to those in an AC grid. If only line faults are considered, the maximum performance is achieved if each line can be isolated by operating a DC breaker at each end. A line fault can then be cleared by only disconnecting the faulted line which is the least unfavorable consequence to the remaining DC grid. An example of such a DC grid is shown in Fig. 1.

The purpose of the present paper is however not to compare MTDC grid fault clearing strategies, but to focus on fault detection methods. An MTDC grid with fast dynamic isolation of faults is assumed within the remainder of this paper since it provides the most difficult task for detection.

C. Current Limiting Reactor for Selective Fault Detection

Due to the low impedance inherent to MTDC grids, the fault current flowing through a DC breaker will typically have a high steady-state value and increase at a high rate (*di/dt*). The fault current behavior depends on several aspects which will be summarized below.

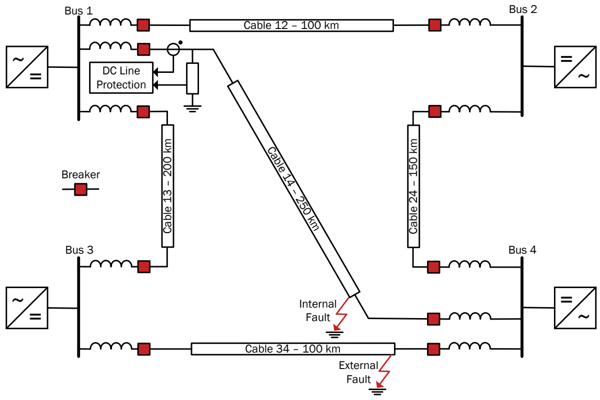

Fig. 1: Schematic of a DC grid where each line is equipped with a DC breaker and a current limiting reactor at each end [5]

The impact of grounding and grid configuration on the transient and steady-state fault behavior was simulated for point-to-point HVDC links and discussed for MTDC grids in [7]. Simulations of the fault current contributions from converter and adjacent cables were presented in [8] for the transient and steady state phase after fault occurrence. In the study, a bipolar two-level HVDC link with VSC topology and concentrated midpoint-grounding of the capacitors was assumed. It was concluded that the fault current during the first couple of milliseconds is mainly dominated by the discharge of pole capacitor and cables.

The peak magnitude of the instantaneous discharge current (surge current) from a cable is determined by the surge impedance. The ±320 kV DC cable in [9] has a surge impedance of approximately $Z_c = 19\ \Omega$, which results in an instantaneous surge cable current in the range of $I_{sur} = 17$ kA for solid ground fault and in case that there are no current limiting reactors in the path of the fault current. After an instantaneous peak, the surge current will decrease with time as the surge impedances of cables are typically frequency dependent. Note, that a surge current is also present in the case of overhead transmission lines. However, the surge impedance of overhead lines is typically much larger which implies that they will contribute with a smaller peak current compared to cables, although still instantaneous. The total current flowing through the breaker (I_{BRK}) is the sum of all contributors, which implies that the more cables connected to the DC busbar, the higher the current.

The steady state fault current cannot be limited by a current limiting reactor, however introduction of a reactor does two things: First, an initial sharp current rise is avoided, also suggested in [8]. Second, the electrical distance between two line ends is increased which can be used for coordination of line protection. Limiting the current rise is beneficial because it gives the protection system more time to detect and clear a fault. The currents are kept below allowed limits e.g. in the semiconductors and DC circuit breakers. However, the energy the breaker has to dissipate is also increased, which might have an adverse effect on performance [10].

If the applied protection scheme at one of the ends relies solely on local measurements, the reactor at the opposite line end can be used for limiting the reach of the protection zone, in which the line protection should operate during faults. By increased electrical distance, the fault detection is enabled to differentiate between internal and external faults.

The concept of selectivity is illustrated in Fig. 1. An internal line fault in cable 14 should be detected by the DC line protection at the end connected to converter 1 which then operates the corresponding DC breaker. Naturally, the breaker at the opposite end of cable 14 also has to open. The external fault in cable 34 should however be cleared by the breakers in cable 34. The protection in cable 14 should not operate during this external fault. The only electrical difference influencing internal and external fault behavior is a DC reactor.

In fact, the concept of using a DC reactor to define the DC line protection zone is not new and it is commonly used in conventional point-to-point LCC schemes [11]. The main purpose in that application is however not to differentiate between internal and external faults, but for the line protection (at the rectifier) not to act during commutation failures in the inverter because they are known to collapse the DC voltage [12], [13]. Using a DC reactor to differentiate between protection zones in order to achieve selectivity in a VSC-MTDC is also suggested in [14], [15]. The impact of using DC reactors in a radial three-terminal grid was simulated in [16] for different single-ended fault detection methods, i.e. methods that rely on local measurements only. The results indicate that introduction of a DC reactor enables selective single-ended fault detection. The impact of DC reactor size and grid topology on protection settings is also discussed in [17]. Furthermore, a way to determine the open protection zones is shown for the suggested scheme.

3 Fault Detection Methods for DC Lines

DC line fault detection methods can be divided into two different types, single-ended and double-ended. Single-ended detection methods rely exclusively on local measurements for selective detection whereas double-ended methods rely on information from measurements at both line ends. Double-ended detection therefore requires a communication channel between the line ends. Different fault detection methods are described in the following. In practice, an implementation might combine multiple methods that complement each other. All measurements are assumed at the positive pole with positive current flowing from the busbar to the line.

3.1 Single-Ended Fault Detection

1) Voltage Derivative

Fault detection by voltage derivative is one of the most commonly referenced methods for main DC line protection in LCC transmission [11], [18], [19]. The concept works with

$$\Delta v \leq \Delta v_{ref} \quad (1)$$

where Δv is the incremental change of DC line voltage and Δv_{ref} is the setting threshold, such that the protection operates during line faults and not during other disturbances [18].

This fault detection method is fast, because it relies on the rapid collapse of voltage, however, it is affected by damping of the wave-front. Damping is typically more pronounced in cables and long overhead transmission lines.

2) Current Derivative

Fault detection by current derivative is based on the incremental change of the line current. Using the current to differentiate between fault locations is investigated in [14], [15], [20]. The fault detection works with

$$\Delta i \geq \Delta i_{ref} \quad (2)$$

where Δi is the incremental change of DC line current and Δi_{ref} is the positive tripping threshold. Note, that the formulation in [14] is expressed as the voltage drop over the DC reactor. Since this voltage drop is proportional to the derivative of current, the principle can be considered a current derivative measurement.

Similarly as with the voltage derivative, also the current derivative depends to the wave-front. Based on the source impedance of the bus where the current is measured, either voltage or current derivative might be preferable. As an example, if the node is mainly capacitive, the reflection results in a large current increase. If the node is mainly inductive, the reflection results instead in a voltage collapse.

In [21] both current and voltage derivative detection are used at the same time to increase the protection margin. Notably, the DC breaker reactance was found sufficient to achieve selectivity in this study. No extra current limiting reactor was used.

3) Transient Based

Another way to combine voltage and current derivative for fault detection is by transient based fault protection (TBFP), as done in [21]. Again, TBFP achieves selectivity in the forward direction by use of DC reactors. The fault detection works with

$$\Delta v \cdot \Delta i \leq -p_{ref} \quad (3)$$

where the protection operates if the product of incremental changes in line voltage and current reaches below the setting threshold $-p_{ref}$.

During line faults in the forward direction, the product is negative because the line voltage collapse results in a negative change. The polarity of current change is positive. During faults in the backward direction, the sign of Δi will be negative, resulting in a positive product.

The protection can achieve selectivity in the forward direction by adjusting the setting so that it does not operate during faults beyond the reactor at the other line end. The main advantage of this formulation is that it uses changes in both voltage and current. Since each of them has the possibility to differentiate between internal and external faults in the forward direction, multiplying them has an amplifying effect on the protection margin.

The same principle, using the product of voltage and current variations is also suggested in [19] but is only considered as a starting element and not considered a main protection which provides selective detection.

4) Traveling Wave

If the surge impedance of the line is known, the incident voltage wave at the relaying point is calculated with

$$u^{m-} = Z_c \cdot i^m - u^m \quad (4)$$

where u^{m-} is the backward traveling voltage wave whereas i^m and u^m are the modal domain line current and voltage respectively [22], [23]. The formulation in (4) makes the detection inherently directional by comparing the calculated the wave-front slope with a setting to differentiate between internal and external faults in the forward direction [18].

One major advantage of the principle is elimination of the reflected wave. This makes the fault detection independent of the source impedance and thus operating conditions, e.g. the number of connected cables.

Fault detection using the incident current wave and considering the distributed line parameters was done in [24]. The presented method was furthermore compared with other single-ended detection methods regarding protection margin. This was done in an MTDC grid model based on [5].

5) Undervoltage

Line faults are typically characterized by a low voltage so that undervoltage detection has been used for backup line protection in LCC schemes [11], [18]. The measured line voltage is compared to a setting threshold v_{ref}, and operates if

$$v \leq v_{ref} \tag{5}$$

is fulfilled during a predetermined time.

Undervoltage detection is very predictable, easy to implement and robust. Selectivity is, however, difficult to achieve because a DC reactor typically only influences the transients following a fault and not the steady state fault voltages. Furthermore, directional protection can typically not be achieved by exclusively using undervoltage detection.

Undervoltage detection might however serve as a complement to other algorithms by confirming the fault under a predetermined period of time [21]. Another fault detection method would then be responsible for selective detection. This is done in [17] where undervoltage, voltage derivative and current derivative criteria are combined.

6) Overcurrent

The fault current behavior depends on grounding and MTDC grid configuration [25]. The bipolar 3-terminal grid in [8] uses concentrated midpoint-grounded DC capacitors at each terminal. The used half-bridge VSC technology lacks fault blocking capability. A pole-to-ground fault in this configuration will typically result in large fault currents flowing from the AC side through the freewheeling diodes of the converters. This current can be used for magnitude-based overcurrent detection with

$$i \geq i_{ref} \tag{6}$$

where the protection operates if the measured DC line current i exceeds the threshold i_{ref} during a predetermined time. Owing to the constant polarity of DC voltage in VSC technology, directional detection can easily be achieved by monitoring the current polarity.

Similarly to the undervoltage detection, limiting the forward reach by the means of a DC reactor is difficult since a fault on either side (i.e. internal and external) will not result in decreased magnitude of the steady state fault current.

Even though an overcurrent protection might not fulfil the requirements for a selective main protection, it can, however, serve as a robust backup protection.

7) Refinements by Signal Processing

Fault detection methods based on transients can be further refined by signal processing. Such methods still rely on the measured voltages and currents, but apply for example Fourier analysis or similar concepts [3]. Some improvements on DC line protection using wavelet transforms are suggested in [13], [26], [27]. In [28], local current measurements at the bus are processed in so called classifiers which identify a faulted line. The classifiers are trained with a set of fault currents corresponding to different fault locations. Notably, [28] also discusses the impact of noise and quantization on fault identification.

3.2 Double-Ended Fault Detection

Double-ended protection schemes are also called pilot protection schemes. A communication link is needed to compare electrical conditions at each end of the line as shown in Fig. 2. The communication link can be referred to as pilot or pilot channel [29]. The naming “pilot” originates from a patent for current differential protection in 1904 [30]. Two possible concepts for double-ended fault detection in MTDC are described in the following.

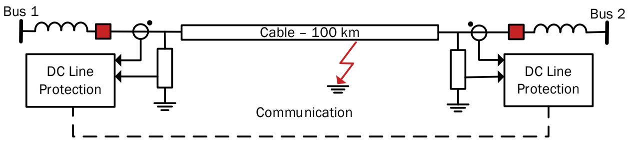

Fig. 2: Double-ended fault detection for one line

1) Directional Comparison

There are two ways to use communication for directional comparison in fault detection: the tripping scheme and the blocking scheme [32]. The tripping scheme relies on directional detection at each end of the line. If a relay detects a fault in its forward direction, it transmits the information to the other end. If the relay at the other end has also detected a fault in its respective forward direction it will operate the breaker upon arrival of the fault message from the first end.

Since the protection scheme only operates if both relays detect a fault, limiting the forward reach is not as important as with single-ended detection. This allows for the detection setting at each end to overreach the line and eliminates the need for extensive simulations. This implies that no DC reactors are required for protection coordination purposes.

For faults close to bus 1, an asymmetry in detection speed is present: Once information from bus 1 is received at bus 2, the breaker at bus 2 can instantaneously be operated. The total detection time of the protection at bus 2 (the time it is exposed to the fault) is the communication delay subtracted by the wave propagation time at the line. This delay might very well be acceptable within a MTDC system. The breaker located at bus 1 can, however, not be operated until the telecom message from bus 2 arrives. When this message arrives, bus 1 has been exposed to the fault for a time corresponding to the communication delay plus the wave propagation time. As this is the most critical line fault at bus 1, this time will most likely be too long. The detection delay increases with line length.

Since the detection performance (delay) is asymmetrical, i.e. depending on the fault location, directional comparison is most likely not suitable as main line protection. It might, however, serve as a complement to the main protection.

In comparison to the tripping scheme, a relay in a directional blocking scheme detects a fault in its forward direction and triggers if no blocking signal is received from the other line end after a certain time delay. The blocking signal is activated in case a relay detects a fault in backward direction. The maximum detection time corresponds to the communication delay subtracted by the wave propagation time through the line [32]. Again, the protection zone is clearly defined so that the detection settings are allowed to overreach the line. Again, this implies that no DC reactors are required for protection coordination purposes.

A directional double-ended fault detection scheme based on incremental change in the current was investigated in [31]. It is concluded that it is unlikely to use the concept as main protection due to the slow detection time for certain faults.

2) Longitudinal DC Line Current Differential

Line differential fault detection is typically used in LCC schemes to provide backup for less critical faults which are not detected by any of the other protections, e.g. high impedance faults [11], [18], [33]-[35].

The concept relies on comparison of the line current at each end, where samples are communicated between the ends by the means of a telecom link and the criterion

$$\left| i_1 + i_2 \right| \geq i_{d,ref} \tag{7}$$

is used, with i_1 and i_2 being the line currents measured at bus 1 and 2, respectively, and $i_{d,ref}$ being the threshold.

Due to the typical geographical distance between terminals and the corresponding communication delay, samples have to be buffered in order to calculate the summation in (7). Buffering is necessary for synchronized comparison, meaning that the data received from the remote station is compared with buffered local data.

Similar to the directional comparison, the relay at bus 1 detects a fault close to bus 1 instantaneously. The differential current can, however, not be calculated until the corresponding sample has been received from the relay at bus 2. The time is equal to the communication delay. This corresponds to the worst case with the longest detection delay. However, fault detection by line current differential is still faster than by directional comparison because bus 2 does not need to see the fault for the detection to trigger. The most favorable case is the same for directional comparison and line current differential. Again, the performance of the line current differential technique depends on the line length.

However, due to the distributed parameters associated with transmission lines, particularly for long line lengths in HVDC, the relation in (7) results in false differential current during external disturbances. In order to avoid misoperation of the protection, pick-up time delays in the range of 500 ms are typically used [11], [33], [35]. Line faults in a VSC MTDC scheme must be detected much faster than that.

In [36]-[39], the differential principle in (7) is used as a main protection for a cable MTDC grid. The pick-up delay is fairly short and in the range of 30 µs. In order for the protection not to operate during the transients following an external disturbance, the protection is blocked if the initial transient in the differential current is of opposite polarity to what would be expected during an internal fault. This is possible because the polarity of fault current during internal faults is typically known since it depends on the voltage polarity. The protection blocking must remain until the DC system has reached its post-fault operating point, which in the studies is chosen in the range of 20–30 ms.

In [40], a differential fault detection method was presented, that accounts for the distributed parameters of the line. Rather than using only the current at both line ends, current as well as voltage are being measured. From these, the traveling waves are calculated by applying the propagation characteristics of the line. The wave which enters the transmission line at one end is compared to the wave which arrives at the other end. A non-zero traveling wave differential current signifies a fault inside the protection zone. The formulation is inherently insensitive to external disturbances. As the formulation includes the wave propagation time, pick-up delays are superfluous and performance is gained regarding the communication delay.

4 Discussion

Fault detection methods for an MTDC grid have to be in context with the grid design, i.e. for example grid and converter topology as well as grounding method. Also, the operating point can change in MTDC grids. Models have to be reasonably close to reality and especially require detailed line models. If these are not detailed enough, particularly fault detection methods based on travelling waves will not depict real behavior with sufficient accuracy. Measurement noise and sampling frequency influence fault detection performance which is why they should be included in simulations.

4.1 Single-Ended Fault Detection

Single-ended schemes rely solely on locally measured voltages and currents to achieve selective fault detection. DC reactors increase the electrical distance and thus allow differentiating between internal line faults and external faults. For the selective operation of a single-ended protection scheme, correct settings are crucial. They are typically tested in simulations to ensure that the protection zone is covered.

The most important fault cases are the remote internal fault and external forward direction fault, i.e. faults at both sides of the DC reactor at the opposite end. The interval, in which a selective setting might be chosen, specifies the protection margin. The protection margin can be interpreted as an indication whether a protection is likely to operate reliably in practice or not. A small protection margin will therefore require a sensitive setting which then is very likely to

misoperate in practice because the simulations can never be in complete agreement with reality. Regardless of the principle chosen, all single-ended fault detection methods inherently require that the primary DC voltage and/or current differ between internal and external faults. Therefore, the reactor value is of great importance for the sake of protection coordination where a larger inductance is generally preferably in terms of protection margin. As with other main circuit equipment, the DC reactor size will have to be optimised with the target to minimize the total cost and to limit the energy that has to be dissipated in the corresponding DC breaker.
The damping of the wave-front as it propagates along the line, particularly in cables, will also reduce the protection margin. Since the propagation is directly related to the line length, selective operation will be more difficult in longer lines. However, a line with high damping will also limit the rate of rise of the particular fault, making the detection time less critical compared to a near fault.

4.2 Double-Ended Fault Detection

Double-ended schemes rely on information from both sides of the transmission line to detect faults. The protection zone covers the line between the relays at each side. Double-ended fault detection does not rely on main circuit equipment for selectivity coordination and does not need carefully tuned protection settings to cover the protection zone. Since the double-ended schemes rely on a communication channel, the performance is limited by the communication delay. If a tripping scheme is used, asymmetric delays occur depending on the fault location. These aspects can make double-ended fault detection unsuitable as the only main protection, particularly in long lines where the performance is severely degraded by the communication delay.

However, the double-ended methods seem to perform best (minimum communication delay) during faults at the remote line end as communication and wave propagation move in the same direction. This fault is, as mentioned, the most difficult to detect by the single-ended methods where small protection margins might require the protection zone to underreach the line length in order not to operate during external faults.
Table I summarizes the comparison of the above mentioned fault detection schemes.

5 Conclusion

The extreme fault clearing requirements in a VSC-based MTDC grid requires a reliable and fast protection system. In order to achieve fast fault clearing, fast fault detection based on transients might be required for some faults.
DC reactors provide single-ended fault detection with a possibility of distinguishing between internal and external faults in the forward direction. The reactor will however be subject to optimization where decreasing its size will be preferable from a cost perspective but also result in higher speed requirements of the DC breaker and less protection margin. Furthermore, the damping associated with the line might further reduce the margin. The full line length might not be covered by the protection zone.
Faults located at the far end of the line, particularly in long lines or cables, might however not be as critical in terms of detection time. These faults could therefore be detected by a double-ended scheme while such a scheme also provides a backup for critical faults.
A complete line protection scheme in an MTDC system is therefore not likely to consist of a single protection principle since it is difficult to detect all possible faults. A more likely solution is that several different principles are included where they can complement each other to achieve a safe and robust transmission system.

Table I: Summary of fault detection schemes

<table>
<tr><td rowspan="2"></td><td colspan="7">Single-Ended Fault Detection</td><td colspan="2">Double-Ended Fault Detection</td></tr>
<tr><td>dv/dt</td><td>di/dt</td><td>Transient Based</td><td>Traveling Wave</td><td>Under-voltage</td><td>Over-current</td><td>Signal-Processing</td><td>Directional Comparison</td><td>Longitudinal DC Line Current Differential</td></tr>
<tr><td>Sources</td><td>[11] [18] [19]</td><td>[14] [15] [20] [21]</td><td>[19][21]</td><td>[18][22] [23][24]</td><td>[11][18] [21]</td><td>[8]</td><td>[3][26]-[28]</td><td>[29][31]</td><td>[11][18][33]-[40]</td></tr>
<tr><td>Communication required</td><td colspan="7" rowspan="3">no</td><td colspan="2">yes</td></tr>
<tr><td rowspan="2">Maximum communication delays</td><td>tripping: ($T_{wave} + T_{com}$) asymmetrical</td><td rowspan="2">($T_{wave} - T_{com}$), asymmetrical, faster than directional comparison for faults close to relay</td></tr>
<tr><td>blocking: ($T_{wave} - T_{com}$)</td></tr>
<tr><td>Protection zone reach / behavior for faults at remote line end</td><td colspan="7">- DC reactor provides electrical difference between internal and external fault
- worst performance for faults at the opposite line end (esp. for long lines and waveform damping)
- need carefully tuned protection settings to cover protection zone</td><td colspan="2">- well-defined protection zone (line)
- therefore less effortful tuning of protection settings
- best performance for faults at opposite line end</td></tr>
<tr><td>DC reactor</td><td colspan="7">needed</td><td colspan="2">not needed</td></tr>
<tr><td>Suitability for main / backup protection</td><td>main</td><td>main</td><td>main</td><td>main</td><td>complement in main protection</td><td>backup, complement for derivative-based</td><td>main</td><td>probably not main</td><td>main</td></tr>
<tr><td>Improve protection settings by means of</td><td></td><td></td><td></td><td>line and node impedance</td><td></td><td></td><td>wavelets, trained fault classifiers</td><td></td><td>distributed line parameters</td></tr>
</table>

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