

# Selective Wave-Front Based Protection Algorithm for MTDC Systems

*N Johannesson\**, *S Norrga\**, *C Wikström †*

*\*KTH Royal Institute of Technology, Sweden, [njohanne@kth.se](mailto:njohanne@kth.se), [norrga@kth.se](mailto:norrga@kth.se)*

*†ABB HVDC, Sweden, [christian.wikstrom@se.abb.com](mailto:christian.wikstrom@se.abb.com)*

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## Abstract

Protection algorithms which can differentiate between different faults is a necessity for the reliable operation of multi-terminal HVDC systems with multiple DC breakers. For selective detection by single-ended line protection algorithms, the current limiting reactors installed in series with the breaker at the opposite side of the line can be used for limiting the reach in the forward direction. In this paper, a further development on the idea of basing the detection on the incident traveling wave is presented. The extraction of the incident wave is achieved by representing the frequency dependent characteristic admittance with a rational approximation. The main advantage over other single-ended protection methods is that the incident wave is independent of the boundary conditions at the terminal of the line. This is illustrated by the simulation of internal and external faults during two different operation scenarios where the result is compared to other methods.

## 1 Introduction

The ongoing migration towards renewable energy generation is challenging the structure and operation of existing power transmission systems. Therefore, an increasing share of HVDC transmission is expected in the future. For optimization of investment cost and minimization of transmission losses, multiple HVDC converters might be connected together on the DC side, thus forming a multi-terminal HVDC system (MTDC). Recent developments of DC breakers, capable of clearing DC faults within a few milliseconds since their application allow for selective disconnection of DC faults.

For maximum reliability of MTDC systems, the protection zones should be as small as possible, ideally containing a single object such as a busbar or a DC cable. This type of configuration is similar to those being used in AC transmission systems and allow for disconnection of the only faulted object and allowing the healthy parts of the system to continue its operation.

The protection system in such configurations with multiple DC breakers must be able to differentiate between different faults such that the correct DC breakers operate and selective fault clearing is achieved. Achieving selective detection of cable faults is, however, not straightforward since the low impedance

characteristics of the DC network provides a very small electrical distance at the boundary of the protection zone in the forward direction. The presence of current limiting reactors installed in series with DC breakers increase the electrical distance between protection zones and does therefore enable single-ended protection schemes to differentiate between faults at either side of this inductance where one is internal and one is external.

The principle of differentiating between remote internal faults and external faults by using a DC reactor is not new and has been used for many years in LCC HVDC schemes. However, the critical external faults in these systems are typically commutation failures, during which the DC line protection at the rectifier should not operate [1]–[3].

The principle of using reactors for selective detection of faults has recently received further attention for applications in MTDC systems. Previously published methods for single-ended algorithms typically rely on measured voltage, current, their derivatives or combinations thereof [4]–[9]. The drawback of single-ended methods is that the selective operation heavily rely on the protection setting. This setting has to be determined by extensive time-domain simulations where all imaginable operation scenarios are studied.

In this paper, a detection method based the principle of using the incident wave is described. This idea has previously been presented for application in both AC [10] and HVDC [11] applications. The further development from previous work consist of adapting the technique for cables, in which the characteristic impedance is strongly frequency-dependent and can therefore not be accurately approximated by a constant. In the proposed method, this is achieved by using rational approximations, the same approach which is commonly used in time-domain simulation programs. The main advantage of basing the detection on the incident wave is that the incident wave is independent of the boundary conditions at the terminal where the protection is located.

After presenting the relevant theory and explanation of the principle, the performance of the proposed method is benchmarked against other methods in PACAD/EMTDC simulations of a four-terminal MTDC model provided by the authors of [12]. The remote internal and external faults are simulated during two different operation scenarios, with and without one converter connected. The incident wave protection is shown to give identical results which is in agreement with the theoretical discussion.



where  $\tau_A$  is the propagation time of the cable length  $\ell_A$ . The voltage wave is therefore initially equal to the voltage in the fault location.

Since the voltage and current waves in each direction are accompanied by each other, the application of the fault simultaneously initiate a current wave  $\mathbf{I}^+$ ,

$$\mathbf{I}^+ = -\mathbf{Y}_c \mathbf{V}_f, \quad 0 \leq t < 2\tau_A \quad (9)$$

Similarly as for the voltage, the current wave will initially be equal to the current contribution from the cable into the fault. Due to the polarity convention, the discharge current ( $\mathbf{I}_f$ ) illustrated in Figure 2 is of opposite direction to the current wave.

The waves which originated at the fault location arrive at the end of the cable ( $x = \ell_A$ ) at  $\tau_A$  later and appear with an altered shape, determined by the propagation function ( $\mathbf{H}_A$ ). Once the waves arrive, they encounter the equivalent source impedance ( $\mathbf{Z}_{eq}$ ) which is a combination of all equipment connected at that point (e.g. inductance, converter, neighbouring cables AC network etc). Since the voltage and current at the relaying point must fulfil the circuit laws according to  $\mathbf{Z}_{eq}$  and the incident waves are determined at the fault location, some of the incident waves are in the general case reflected backwards in the negative direction. This implies that the voltage ( $\mathbf{V}_\ell$ ) and current ( $\mathbf{I}_\ell$ ) to be used for detection are depending on the boundary condition of the line. Since the source impedance is a combination of all equipment at that point, it is very likely that this will change during operation in a MTDC systems. For instance, if a DC busbar has multiple cables connected, the operators could switch any of the cables in or out of service at any time. This will change the source impedance which results in a different behaviour of voltage and currents, thus influencing protections based on them.

### 2.3 External disturbances

For the DC line protection to be able to differentiate between remote internal faults and external disturbances in the forward direction, the two most crucial cases are faults on each of the sides of the reactor at the remote end. One of which is internal and should be detected whereas the other one is external during which the line protection should not operate.

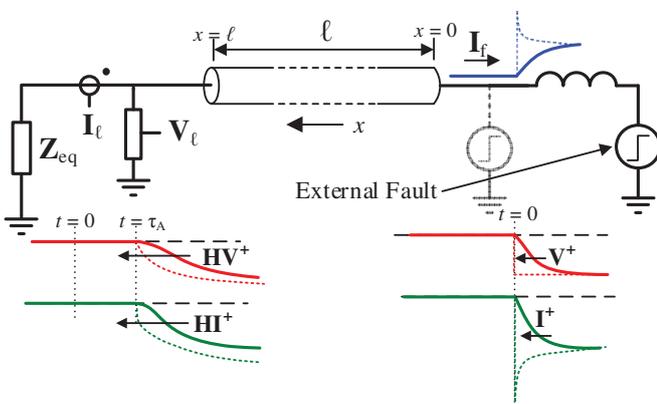


Figure 3 Waves which enter and arrive at the protection during internal (dotted) and external faults (solid).

During a fault beyond the reactor, as illustrated in Figure 3, the voltage and current at the line side of the reactor does not change instantaneously as during the internal case. Instead, they depend on relation between the characteristic impedance of the line and the inductance of the reactor. The result is that the waves which are initiated in the positive direction have a limited slope of the wave-front. This is illustrated by the waves which enter the cable at the right side in the figure. The dashed lines in the figure are provided for comparison with the wave-shapes during the internal case which was discussed in the previous subsection.

As the waves propagate along the line, they are influenced by attenuation and distortion before they finally arrive at the terminal shown on the left side of the figure. As indicated by the difference between the wave-shapes of internal and external fault, the line protection can be designed to differentiate between these two cases. Even though the waves which enter the line are clearly different, the waves which eventually arrive at the protection are much more difficult to distinguish between due to the low-pass characteristics of the propagation function ( $\mathbf{H}$ ). As the propagation function is dependent on the length of the line, at a certain length of cable the difference between the waves which arrive at the protection will not be significant enough for differentiating between them. In such cases, single-ended protection schemes might not be able to reliably cover the entire line length.

### 2.4 DC line protection setting

As single-ended DC line protection methods are not inherently selective, they require the setting to be coordinated such that its forward direction reach is limited and the protection can operate with selectivity. In principle, the setting needs to be determined from extensive numerical simulations where all possible operation scenarios and events are covered. The setting can then be chosen by identifying the “worst” internal and external case and they choosing a setting which makes the protection to only operate when required. The process is illustrated in Figure 4 where the protection algorithm output during internal and external faults are compared.

As illustrated in the figure, the protection setting could in principle be chosen anywhere within the interval between the two cases and thus only operate during the internal faults and not during the external fault. However, the result of simulations can not be assumed to be one hundred percent accurate and some deviation is always to be expected if the protection is to be applied in practice. Therefore, the margins are very important as they provide some indication on whether a protection scheme will be reliable or not. As illustrated in the figure, applying a reduced setting will result in a more dependable protection since it will be more sensitive. On the other hand, the probability that the protection might falsely operate during an external fault or other disturbance is increased. Similarly, increasing the setting will make the protection less sensitive, but then risk that the protection does not operate during actual internal faults. Essentially, obtaining a proper setting is a trade-off.

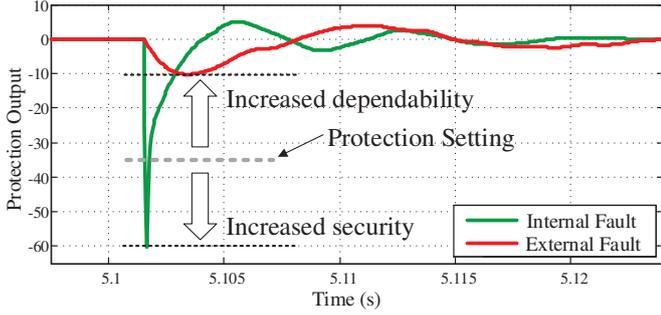


Figure 4 Principle of achieving selective detection by coordination of protection setting.

Even though the actual setting of a protection is a trade-off, the width of the interval in which a setting can be chosen is a good indicator of how suitable different protection principles are for a given main circuit. Alternatively, the protection margin can be considered as the ratio between the protection output during internal and external faults as

$$m = \frac{\text{Algorithm output, Internal}}{\text{Algorithm output, External}} \quad (10)$$

where the numerator is the most difficult internal fault to detect and the denominator is the external disturbance during which the protection shall not operate. The resulting margin ( $m$ ) is in per-unit and a larger margin is better whereas 1.0 would signify that the protection is not able to differentiate between internal and external faults. Calculating the protection margin from the example in Figure 4 results in  $m = -60/-10 = 6.0$  pu.

### 3 Incident traveling wave protection

#### 3.1 Protection algorithm

As previously described, the sudden breakdown of voltage at the location of a fault on a transmission line initiate voltage waves where the wave-front is a step function. Since external faults in the forward direction results in a limited slope of the wave-front, detection of faults might be based on the slope of the incident wave.

The voltage wave is accompanied by a current wave which is related to the voltage wave by the characteristic impedance of the line. For cables, the characteristic impedance is typically frequency-dependent and the current wave does therefore have a different shape than the voltage wave. The shape of the current wave is more suitable for detection since it results in larger margins with regard to internal/external faults.

Even though the wave on a transmission line can not be measured directly, they can be calculated. For detection of the incident current wave, the protection at the end of the cable calculate the incident wave according to

$$\mathbf{i}_{TW}(t) = 0.5(\mathbf{i}_\ell(t) + \mathbf{y}_c * \mathbf{v}_\ell(t)) \quad (11)$$

where  $*$  denotes the time-domain convolution,  $\mathbf{y}_c$  is the matrix with impulse responses of the characteristic admittance and  $\mathbf{i}_\ell$  and  $\mathbf{v}_\ell$  are column-vectors of the measured currents and voltages at the end of the line, respectively.

For detection of the wave-front, the slope can then be determined as the difference over a pre-determined period of time ( $T$ ),

$$\Delta \mathbf{i}_{TW}(t) = \mathbf{i}_{TW}(t) - \mathbf{i}_{TW}(t-T). \quad (12)$$

The calculated slope for each element in the vector  $\Delta \mathbf{i}_{TW}$  conductor is then separately compared with setting threshold. A block diagram for illustrating the algorithm is shown in Figure 5.

The protection algorithm is in principle directional since it only operate during wave when travel down the line from the forward direction. For application in practice, it might however be beneficial to interlock the operation with low voltage and/or high current. In such a combination, the incident wave protection provides the selective detection and the presence of additional criterions will ensure that a fault is actually present.

#### 3.2 Characteristic admittance

As stated in the description of the algorithm in (11), the convolution between characteristic admittance and voltage is required for extracting the incident current wave. Since it is frequency-dependent, numerical time-domain simulation tools often rely on frequency-domain approximations in a form which can easily be transformed into the time-domain and implemented with a high computational efficiency. One of the commonly used forms is a series of rational approximations,

$$f(s) = \sum_{i=1}^N \frac{c_i}{s - a_i} + d \quad (13)$$

where the approximation is of the N-th order,  $d$  is a constant,  $c_i$  and  $a_i$  are residues and poles, respectively.

For the calculation of the incident wave, each element in the characteristic admittance matrix ( $\mathbf{Y}_c$ ) is then fitted into the form given in (13). In general, all elements of the matrix should be represented but in some cases the off-diagonal elements might be neglected if they are close to zero, i.e. if the coupling between conductors is very low. This is typically the case for cables which are surrounded by their separate shields.

For some special cases, when there exist a particular symmetry in the configuration of the transmission line, it is convenient to perform the calculations of the waves in the modal domain rather than the phase-domain since the characteristic admittance matrix becomes diagonal in the modal domain, thus allowing for each mode to be considered as independent single-phase conductors. This is however typically only possible in some situations where the transformation matrices are real and constant whereas the phase-domain approach is more general.

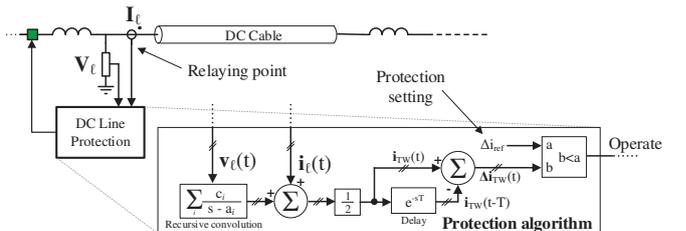


Figure 5 Block diagram which illustrate the method of the incident traveling wave protection.

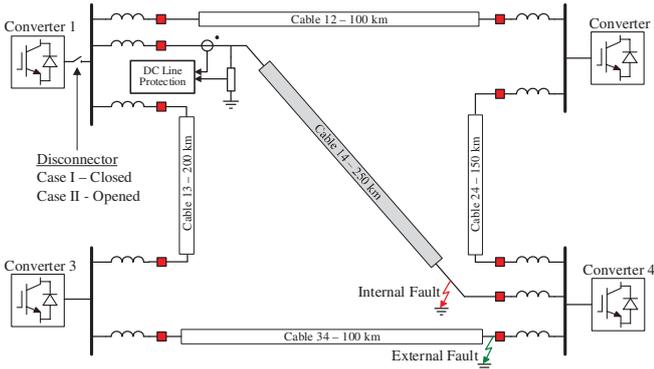


Figure 7 Meshed MTDC systems with four terminals.

#### 4 Time-domain simulations

For illustrating the performance of the incident and traveling wave protection, time-domain simulations have been performed in PSCAD/EMTDC of the four-terminal as developed in [12]. The system is based on symmetrical monopoles with a rated voltage of  $\pm 320$  kV. The four converters are connected by DC cables with varying lengths according to the illustration in Figure 6. Each cable has a DC breaker at both ends and the inductance of the current limiting reactors is 50 mH.

The original cable model in [12] is based on a 1200 mm<sup>2</sup> copper cable which has a comparatively low distortion for the lengths given in the original model. This makes the differentiating between internal and external faults comparatively easy with large protection margins. Therefore, the protected cable (Cable 14) was replaced by a model of a 250 km long aluminium cable which has larger distortion and thus makes the protection design a bit more challenging.

For illustrating the influence of the source impedance on protection performance, both internal and external faults were simulated during two different operation scenarios, denoted as Case I and Case II. The difference being that in the latter, the converter 1 is isolated by a disconnector. Consequently, the converter does not contribute with any fault during in Case II, thus reducing the current through the measurement used by the protections.

Since the cable configuration is symmetrical (2 cables which are buried at the same depth with the same internal geometry), the modal domain approach is used for the implementation of the incident traveling wave protection. The two modal domain

characteristic admittances (ground and pole mode) are realized as 5<sup>th</sup> order rational approximations.

#### 5 Results

The resulting voltages and currents of the four simulations are shown in the two left subfigures of Figure 7. The right subfigure show the incident current wave. The solid lines show the results during Case I, i.e. with converter 1 connected to the DC network. The figure reveal that the voltage is quite similar during the first couple of hundred microseconds whereas the current almost instantaneously deviate between Case I and Case II due to the absence of the pole capacitor which is disconnected together with converter 1.

As expected, the incident current wave is not noticeable influenced by the changed impedance encountered by the wave at the protection location. This is in agreement with the previously discussed theory. The incident wave at the protection will in fact not differ until the reflected wave returns to the fault location and is reflected back, i.e. until after  $3\tau_A$  which for the 250 km long cable in these simulations correspond to approximately 4.4 ms since the fault is located at the very remote end of the cable.

The differences in primary voltage and current due to the changed boundary conditions obviously has an impact on the DC line protections which use them for detection. The result of a few different protection methods are shown in Figure 8. As previously discussed, the protection margin is a valuable performance indicator since it provides a sense of how much deviations are allowed with regard to modelling errors and therefore also the probability of successful operation in practice. Assuming that the protection settings are not to be

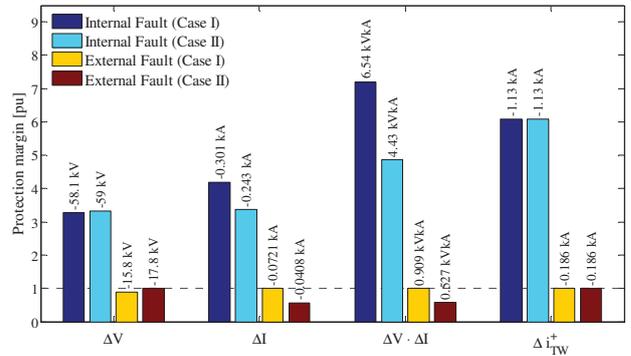


Figure 6 Simulation results for each protection.

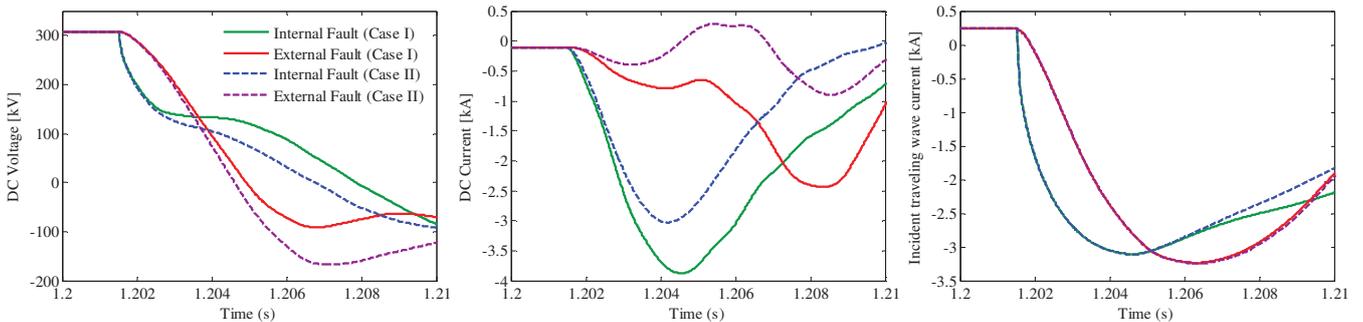


Figure 8 Simulation results during internal and external faults when Converter 1 is connected/disconnected.

changed for different operation scenarios, which would increase the complexity, the settings must be chosen with regard to all possible scenarios in which the protection should, respectively should not operate. The y-axis in Figure 8 is therefore normalized with regard to the external fault which is the more severe of the two which yields that the protection margin of each protection is the height of the lowest internal fault in the figure.

As already expected from the primary voltages and currents, the protections based on currents ( $\Delta I$  and  $\Delta V \cdot \Delta I$ ) show the largest deviations due to the disconnection of converter 1. This can be further illustrated by one extreme case where only a single cable is connected to the bus such that there are no contributors of fault current at all. Since the fault current will be zero, so will also the derivative and the protection based on current will fail to recognize the fault. This is perhaps a non-critical case since no equipment will be feeding the fault, but it is still illustrative of the dependence to boundary conditions.

## 6 Discussion

Since the voltage and current at the terminal of a line is subject to the circuit laws at that point, incident waves originating from a fault will generally be reflected back onto the cable and travel back towards the fault. Basing the detection solely on voltage or current derivatives is therefore not actually a detection of the traveling wave caused by the fault but is actually the detection of both incident and reflected wave where the reflected wave is a function of source impedance encountered by the wave at the protection location. Particularly in MTDC systems, the operation conditions might change, thus changing the equivalent impedance.

## 7 Conclusion

Single-ended protection algorithms are not inherently selective and does therefore rely on a proper setting in order to operate reliably. For MTDC system studies where single-ended protection principles are used and the forward direction is limited by the presence of a current limiting inductance, there will always be a slight difference between two of the most critical faults, remote internal and external fault. This slight difference will always make it possible to design a protection algorithm to differentiate between the two. However, for application in practice, there will always be deviations from the model used in the study, e.g. noise, unforeseen contingencies, uncertainty in parameters etc. It is therefore important to consider the margins of a protection before application in practice since it will indicate how robust a protection principle is and thereby also the probability that it will succeed.

Basing the detection on the incident wave by combining the current with voltage and characteristic admittance of the cable makes the detection principle independent of the boundary condition at the terminal of the line. This has been demonstrated in this paper by considering two different operation scenarios, with and without one of the converter connected to the DC bus. If the protection is required to have the same setting, without changing settings depending on the

configuration, the incident traveling wave has the largest protection margin of the compared protection principles.

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