Fault Discrimination in HVDC Grids with Reduced Use of HVDC Circuit Breakers

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Abstract—HVDC grids are currently considered to accommodate the integration of renewable energy sources into the power system. Since HVDC circuit breakers might at present incur a large investment cost, fault clearing strategies with limited use of HVDC circuit breakers have been recently proposed. These strategies, here called partially selective, split the grid into a number of protection zones which encompass sub-grids of multiple converters, transmission lines or a combination of both. Although the application of such strategies within the HVDC grid has been studied recently, discrimination of faults between zones is not yet widely investigated. This paper analyzes the application of a communication-less protection algorithm introduced for fully selective protection in a partially selective protection strategy. A sensitivity analysis using a reduced model shows that the reach of these algorithms is determined by, on the one hand, the length of the cables and complexity of the grid within a protection zone and, on the other hand, the inductance of the series inductor associated with the breaker between the protection zones. A test case implemented in EMT-type software is used to demonstrate the fault clearing sequence in a partially selective strategy.

Index Terms—circuit breakers, HVDC transmission, power system faults, power system protection

I. INTRODUCTION

The increasing share of renewable energy sources such as wind power or photovoltaic sources requires an adaptation of the existing power system. First, power from sources such as offshore wind must be transported on submarine cables over increasing distances as new sites tend to be located farther from shore. Second, the variability of the power output of such sources requires more flexibility in power transmission compared with power generated by fossil-fueled power plants. Voltage source converter (VSC) high-voltage direct current (HVDC) multi-terminal systems or meshed grids can be used to provide both efficient power transfer over large distances and flexibility in power transmission. One of the challenges associated with VSC HVDC systems is protection against dc side faults [1].

Protection of a VSC HVDC grid using HVDC circuit breakers is challenging due to the nature of the fault currents to be interrupted [2]. Fault currents in HVDC systems do not exhibit natural zero crossings and exhibit, in the worst case, a high rate-of-rise. Therefore, HVDC circuit breakers must force the current to zero and absorb the energy stored in the system’s inductance on a millisecond time range [3]. Several prototypes have been reported in the recent literature, e.g., in [4], [5], [6], [7]. All presently proposed HVDC circuit breakers require the presence of one or more series inductors to limit the rate-of-rise of the dc fault current.

Several strategies for clearing dc faults using HVDC circuit breakers have been presented in the literature [8]. These strategies make use of HVDC circuit breakers at every line end, here called a fully selective strategy, between protection zones encompassing multiple lines, in a partially selective strategy, or placed in series with the converters. These strategies aim at finding a trade-off between investment cost due to HVDC circuit breakers and limiting the impact of a fault on the dc system and interconnected ac systems. Protection algorithms for fully selective protection have received a lot of attention in the recent literature, as shown in [9]. By contrast, protection algorithms for a partially selective strategy with limited use of HVDC circuit breakers are not yet widely studied.

This paper proposes a communication-less protection algorithm for fault discrimination for use in partially selective fault clearing strategies with a limited number of HVDC circuit breakers. As such, it contributes to the step to be taken between protecting a HVDC grid without any HVDC circuit breaker and with HVDC circuit breakers at each line end. The algorithm is based on the principles introduced for selective fault clearing strategies in [10], [11]. The selectivity and sensitivity of the algorithm is investigated for a wide range of parameters using a reduced model. Thereafter, these results are validated using a case study implemented in PSCAD.

II. PROPOSED PROTECTION ALGORITHM

In a VSC HVDC grid which is protected with a limited number of HVDC circuit breakers, also called a grid-splitting or partially selective protection strategy, protection algorithms are needed to operate the breakers at the end of each zone. In Fig. 1, an example HVDC grid is shown with three zones, L, M and N, which are separated using HVDC circuit breakers. To interrupt a fault current for a fault in Zone M, the HVDC circuit breakers $Br_3$ and $Br_2$, and the ac circuit breakers $Br_3$ and $Br_4$ are tripped. Thereafter, the faulted component is isolated using the switches placed at each line end and at each converter dc terminal. These switches do not have fault current interruption capability.
The functional requirements for the (combination of) protection algorithms associated with the HVDC circuit breakers in such a strategy can be stated as follows: (i) they must detect all internal faults (i.e., they must be dependable), (ii) they must not operate for external faults (i.e., they must be secure) and (iii) they must quickly act to avoid voltage collapse in neighbouring zones [12]. Due to the counteracting requirements of speed on the one hand and reliability, i.e., dependability and security, on the other hand, these functional requirements might not be achieved using a single principle. To achieve the required speed of operation, the protection algorithm under study in this paper is a communication-less principle which uses the inductive terminations of each zone to discriminate faults between zones. The inductive terminations of the protection zones bounded by the breakers are due to the series inductors required for all presently proposed HVDC circuit breaker prototypes. The inductors form a low-pass filter for the wavefronts of faults external to the protected zone. This can be used to discriminate external faults from internal faults, for which the traveling waves exhibit steep wavefronts. This principle was outlined in [10] and [11] for fully selective protection of VSC HVDC grids, i.e., employing circuit breakers at all cable ends. In [10], the possibility to use this principle in VSC HVDC grids with a limited number of HVDC circuit breakers was briefly mentioned.

The detection function used in this paper is based on the one introduced in [13]:

\[ S_1 = u'(t) - R_e i'(t), \]

where \( u'(t) \) and \( i'(t) \) are the superimposed components of the waveforms measured during a fault and \( R_e \) is an impedance to match the characteristic impedance of the cable at which the measurements are done. \( i'(t) \) takes positive values for currents flowing in the direction of the protected zone. The advantage of using this detection function is that, due to the almost ideal termination impedance, the network topology behind the relay does not need to be studied.

The possibility of using the detection function in a communication-less algorithm is investigated. To this end, the superimposed components \( u'(t) \) and \( i'(t) \) are obtained by taking the first derivative of the measured quantities and the resulting detection function is compared against a threshold:

\[ S_1 > S_1^{thr}. \]

### III. PROTECTION ALGORITHM SENSITIVITY ANALYSIS

#### A. Test case

The test system used to analyze the sensitivity of the traveling-wave based algorithms is based on the one shown in Fig. 1. Two of the transmission lines, i.e., those connected to zones L and N, are terminated by a breaker and associated series inductor. In the test system, the parameters for the transmission lines (submarine cables) and converters (Modular Multilevel Converters (MMCs)) are taken from [14] and recapitulated in Table I and III.

The analysis considers only the superimposed fault circuit by applying a step input in the voltage at the fault location (see also [15]). The Numerical Inverse Laplace Transform (NILT) described in [16] is used to obtain the waveforms of the superimposed components. To avoid non-linear effects, the converters are modeled according to the model given in [17].

In the sensitivity analysis, the performance of the algorithm associated with the breaker located at Bus A is considered for internal faults (Fig. 2a) and external faults (Fig. 2b). To analyze the performance, minimum and maximum values of the detection functions for internal and external faults were determined.

The minimum value of the detection function for internal faults was determined using the topology of Fig. 2a, since it results in the lowest transmission of waves originating from \( F_{int} \) to bus A. The transmission lines departing from bus B were assumed to be reflectionless. A voltage correction factor of 0.95 was applied to account for voltage variations during normal operation.

The maximum value of the detection function for external faults was obtained with the test system shown in Fig. 2b, since it results in maximum transmission of waves originating from bus C towards bus A. To incorporate worst case fault conditions taking into account voltage variations, a voltage correction factor of 1.05 was applied.

The sensitivity analysis was performed by adapting the line inductor value \( L_{br} \) and line length \( l_2 \), whereas \( l_1 \) was kept constant at 350 km. The line length \( l_2 \) was varied from 25 to 350 km with increments of 25 km, whereas the inductor value \( L_{br} \) was set to 10, 50 or 100 mH. The NILT was performed using 1000 samples in a time window of 10 ms.
The voltage and current signals were processed with a finite impulse response (FIR) filter of ten samples with coefficients \( b_0 ... b_9 = -1 \).

### B. Results

For internal faults, the maximum value of the \( S_I \) decreases with increasing cable length \( l_2 \) and number of cables attached to bus B \( n \) (Fig. 3). Increasing \( l_2 \) results in a higher attenuation and distortion of the wave, whereas increasing \( n \) results in a lower transmission of the wave towards the cable at which the relay is located.

Discrimination between remote internal faults and external faults requires either a low complexity of the grid topology in the protected zone, short transmission lines or high inductance of the series inductors between the protection zones. For instance, if a threshold of 50 is chosen (topology-wise) worst and best case for internal faults shows 350 km. For \( L_{br} = 100 \text{ mH} \), discrimination can in theory be achieved for \( l_2 \) within 200 to 225 km. For \( L_{br} = 100 \text{ mH} \), regardless of \( n \), discrimination can in theory be achieved for all \( l_2 \) up to or even exceeding 350 km.

The reach of the proposed algorithm with respect to the (topology-wise) worst and best case for internal faults shows a large variation. For instance, if a threshold of 50 is chosen for \( S_I \), the difference in reach is 200 km (Fig. 3, where the line \( S_I=50 \) intersects with the values associated with \( F_{int, n} = 0 \) and \( F_{int, n} = 2 \) at \( l_1=300 \) and \( l_1=100 \), respectively).

The transmission line attached to bus B which yields the maximum value for \( F_{ext} \) as function of \( l_2 \) and \( L_{br} \) determines the reach \( l_2^* \) of the algorithm on all lines attached to bus B. To ensure proper discrimination between internal and external faults, the threshold must be set above this maximum value. This value is determined by \( l_2 \) and \( L_{br} \) as shown in Fig. 3. The reach on the other lines is then, in the worst case, also limited to \( l_2^* \), with * indicating the line length of the critical transmission line.

If a reach higher than \( l_2^* \) is required, the algorithm must be complemented by alternative algorithms or communication to avoid non-selective tripping of the breaker at bus A. These are in this paper not considered.

### IV. Case Study

The test system for the case study considers a HVDC grid with six converters, split into three protection zones (indicated by red, orange and blue dashed lines in Fig. 4). The protection zones are chosen such that, in case of a fault in one of the zones, the other zones can continue operation as a point-to-point link. Protection zone configurations were chosen to demonstrate the possibilities and limitations of the proposed algorithm. For practical application, optimization of protection zones should be done on a project-base bound to specific project requirements.

### TABLE I

**CONVERTER AND GRID PARAMETERS**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated apparent/active power</td>
<td>1265/1200</td>
<td>[MVA/MW]</td>
</tr>
<tr>
<td>Rated dc voltage</td>
<td>± 320</td>
<td>[kV]</td>
</tr>
<tr>
<td>Rated transformer voltages</td>
<td>400/333</td>
<td>[kV]</td>
</tr>
<tr>
<td>Transformer leakage impedance</td>
<td>0.18</td>
<td>[pu]</td>
</tr>
<tr>
<td>Arm capacitance ( C_{arm} )</td>
<td>22</td>
<td>[µF]</td>
</tr>
<tr>
<td>Arm inductance ( L_{arm} )</td>
<td>42</td>
<td>[mH]</td>
</tr>
<tr>
<td>Arm resistance ( R_{arm} )</td>
<td>0.6244</td>
<td>[Ω]</td>
</tr>
<tr>
<td>Converter dc smoothing reactor</td>
<td>10</td>
<td>[mH]</td>
</tr>
</tbody>
</table>

To divide the protection zones at the DC side, HVDC circuit breakers are placed in lines \( L_{12}, L_{14}, L_{25} \) and \( L_{45} \) at the buses connected to converters 1 and 5, respectively. The inductance of the series inductors associated with the breakers is 100 mH. At the ac side, every protection zone is bounded by ac circuit breakers.

The converter parameters and line lengths are given in Tables I and II, respectively. The converters are modeled with the continuous model described in [18] and protected according to the overcurrent criterion described in [19]. The converter ac breakers are opened within 60 ms after detecting an arm overcurrent. The HVDC circuit breakers are modeled as hybrid breakers with an opening time of 2 ms. The simulation time step is 5 µs.

In the case study, the protection associated with the breaker at line \( L_{12} \) is investigated. First, suitable thresholds were determined based on Fig. 3. Second, these thresholds were compared with the results obtained in PSCAD. Third, the algorithm and fault clearing sequence was assessed for a solid fault located 25 km from converter 2.

### A. Threshold Determination

The algorithm associated with the breaker located at \( L_{12} \), \( Br_{12} \) must not trip for a solid fault at bus 5. The maximum value for \( S_I \) is obtained for the case in which only \( L_{12} \) and \( L_{25} \) are in the path between this fault and the measurements at \( Br_{12} \). From Fig. 3, this value is 19.3. The test system
implemented in PSCAD provides a result of 19.78. The threshold $S_{thr}^1$ should thus be at least 19.3. Taking a margin into account, the threshold is in this paper set to 25.

### Table II

<table>
<thead>
<tr>
<th>Fault Location</th>
<th>$U_{dc}$ (pu)</th>
<th>n</th>
<th>Converter 2</th>
<th>Reduced</th>
<th>PSCAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{25}$ (at $Br_{25}$)</td>
<td>0.95</td>
<td>1</td>
<td>in service</td>
<td>29.53</td>
<td>29.08</td>
</tr>
<tr>
<td>$Br_{5}$</td>
<td>1.05</td>
<td>0</td>
<td>out of service</td>
<td>19.30</td>
<td>19.78</td>
</tr>
</tbody>
</table>

### Table IV

<table>
<thead>
<tr>
<th>Fault Location</th>
<th>$U_{dc}$ (pu)</th>
<th>$n$</th>
<th>Converter 2</th>
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</table>

C. Fault Clearing Sequence

The fault clearing sequence is illustrated using a solid fault on $L_{25}$ located at 25 km from converter 2.

The fast action by the protection algorithms and HVDC circuit breakers avoids voltage collapse and excessive fault currents in the healthy part of the system. During fault detection and opening of the breakers associated with the faulted protection zone, the voltage in the healthy part of the grid decreases quickly whereas currents increase fast (Fig. 5, time interval [2-4.2] ms). After opening of the HVDC circuit breakers in lines $L_{12}$ and $L_{14}$, the voltage in the healthy part of the grid exhibits a transient overvoltage due to insertion of the breaker surge arrester prior to reaching a stable value (Fig. 5a), whereas the current reduces to zero (Fig. 5b).

Due to the fast action by the protection, power flow in the healthy part of the system can continue whereas the power flow in the faulted part is reduced to zero (Fig. 6). After opening the breakers, Converters 1 and 3 and Converters 5 and 6 continue power exchange in a point-to-point connection. In this paper, the oscillations in the active power seen in Fig. 6 have not been subject to in-depth analysis and converter controls were not optimized to dampen these.

Restoration of the faulted part using switches without fault current interruption capability might only be possible after several hundreds of milliseconds. In the faulted part of the system, the fault current shows a slow decrease after opening the HVDC circuit breakers and converter ac breakers (Fig. 7). The slow decrease in the current is due to the release of stored energy in the arm inductors. If switches without current breaking capability are used to isolate the faulted line, opening must be delayed until the current has decayed to zero, which in this case is at $t = 0.64$ s ($i < 0.1$ kA).

V. Conclusion

Fast fault discrimination in HVDC grids with reduced use of HVDC circuit breakers is challenging due to the potential large distances within, and the complexity of, the intermediate grid between the fault and the measurement location. This paper
investigated a communication-less principle based on traveling waves to quickly discriminate faults within the protection zone from external ones. Although the algorithm is able to detect faults in remote parts of the grid, the reach of the proposed protection algorithm is limited since traveling waves are attenuated, distorted and only partly transmitted before reaching the measurement location.

A sensitivity analysis using a reduced model showed that the reach of the proposed algorithm increases with increasing inductance of the breaker inductor between the protection zones, decreasing length of transmission lines and decreasing complexity of the grid topology within the protected zone. The results obtained in the sensitivity analysis were confirmed by a comparison against a detailed test system implemented in PSCAD. Finally, successful fault clearing in the faulted zone and continuous operation of the healthy zones within this test system was demonstrated.

REFERENCES


