Use of Fast Circuit Breakers to Mitigate Overvoltages in VSC HVDC Point-to-Point Schemes

Willem Leterme, Mudar Abedrabbo

Abstract—**Sustained DC-side overvoltages in HVDC point-to-point schemes may occur on the healthy pole when DC-side pole-to-ground faults occur. Until now, the impact of these DC-side overvoltages on cable systems is not well known. Several mitigation methods have been proposed until now, including actively switched DC- or AC-side surge arresters. This paper investigates the potential of using fast AC-side or DC-side circuit breakers for mitigating DC-side overvoltages using EMT analysis. To reduce peak overvoltages, any AC- or DC-side circuit breaker solution must be sufficiently fast acting, even though all investigated solutions show limited potential. All investigated solutions show that sustained overvoltages can be mitigated, thereby reducing DC-side surge arrester requirements at a limited energy absorption requirements of the AC- or DC-side circuit breaker. The simulation-based study should be complemented with investigations towards the practical realization of such solutions.**

Keywords—**AC circuit breaker, DC circuit breaker, high-voltage DC, symmetrical monopole, voltage source converter**

I. Introduction

VSC HVDC point-to-point connections in combination with underground or submarine cables have been deployed over the past decades, and their use is expected to increase in the future power system. The early VSC HVDC schemes made use of two-level VSCs whereas the latter made use of half-bridge modular multilevel converters (MMCs). Recent point-to-point links mainly assume the symmetrical monopolar configuration with a pole-to-ground voltage of 320 kV [1]. Symmetrical monopolar configurations rely on two poles with equal but opposite voltage, without grounding point at the DC side [2]. The future point-to-point links in Europe will most likely be bipolar with a pole-to-ground voltage of 525 kV [3]. These links use two poles operated with equal but opposite voltage, and are low-impedance grounded at the DC-side. Depending on the bipolar scheme, a third conductor, i.e., the dedicated metallic return is used [4]. Until now, point-to-point VSC HVDC schemes rely on ac-side circuit breakers to clear DC-side faults [5].

In VSC HVDC schemes, temporary overvoltages in the range of 1.4-1.7 p.u., and lasting for tens of milliseconds, may occur on the healthy pole due to a DC-side pole-to-ground fault. These overvoltages occur in symmetrical monopolar schemes because of the high-impedance nature of the DC-side grounding, and are limited by the DC-side surge arresters [6], [7]. In bipolar schemes, these overvoltages occur due to the large fault currents together with the total resistance of the fault current path [8]. In general, symmetrical monopolar schemes lead to higher DC-side overvoltages compared to bipolar systems. In both schemes, the overvoltages last until AC-side circuit breakers interrupt the fault current, with a typical break time within 100 milliseconds [6].

For symmetrical monopolar configurations, the analysis of these overvoltages and the impact on DC-side equipment such as surge arresters has been discussed in recent literature, e.g., in [7–9]. The difference between a delta-winding configuration and a star-winding configuration grounded through a surge arrester is described in [10]. In [11], the temporary overvoltages are named by the term "long TOV", as the overvoltages are longer in duration (that is, lasting for several tens of milliseconds) than the considered lightning and impulse overvoltages.

These overvoltages may form a threat to the cable or its accessories, as discussed in [11], [12]. This study concludes that although loss-of-life estimates from long TOVs show very low values, there may be threats if long TOVs trigger dynamic phenomena that cause accelerated aging of the insulation. Furthermore, new high-voltage test circuits have been designed recently to test for such TOVs [13]. With an increase in extruded cable nominal voltages, going from 320 kV to 525 kV and beyond [14], it may become increasingly important to manage transient overvoltages as to guarantee the reliability of the cable.

Several possibilities exist to mitigate overvoltages, of which the most common is installing DC-side surge arresters [7]. As an alternative, in [15], an AC-side surge arrester connected to ground is proposed given that a neutral connection point exists. Furthermore, in [16], the impact of several DC-side fault clearing options in HVDC grids on overvoltages on cables have been discussed. It was shown that fast fault clearing such as using DC-side circuit breakers (e.g., an overview can be found in [17]) or fault blocking converters (e.g., described in [18]) could lead to significant reductions in cable overvoltages. Nevertheless, these options come at an increased cost in the form of the DC-circuit breaker itself or an increase of the power-electronics and losses compared to state-of-the-art fault feeding converters. By contrast, the effects of fast fault clearing at the AC side on DC-side overvoltages

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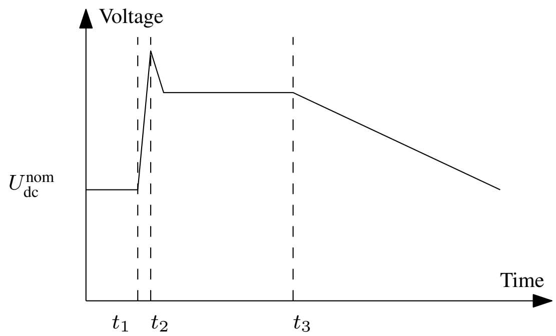

Fig. 1: Schematic overview of stages of DC-side overvoltage on the healthy pole for a DC pole-to-ground fault in a symmetric monopolar system.

have not been investigated yet. Such fast fault clearing may be enabled through recent advances in AC breaker technology or through applying DC-side breakers at the AC side.

To fill this gap, this paper investigates the potential of mitigating DC-side overvoltages that involve installing circuit breakers with fast fault clearing capability at the AC side. The advantage of such an arrangement may be a reduction in breaker dimensions compared to DC-side counterparts, leading to lower physical dimensions and weights. The paper compares the new approach to existing approaches and alternative arrangements of fast circuit breakers, e.g., those installed at the DC side, with respect to system impact (overvoltage mitigation) and impact on component dimensions. The focus of the paper is on systems with symmetric monopolar configurations.

The paper is structured as follows. First, in Section II, existing approaches to overvoltage mitigation are elaborated. Second, the proposed approaches using fast circuit breakers are elaborated in Section III. Third, a case study is performed in Section IV, comparing the proposed approaches in system and component impact. Finally, a discussion on alternative design approaches and a conclusion are provided in Sections V and VI, respectively.

II. Overvoltages in Symmetrical Monopolar Point-to-Point Links

Several stages can be identified in the development of overvoltages on the healthy pole due to a DC pole-to-ground fault in a symmetrical monopolar point-to-point link (Fig. 1). In the first stage (t_1-t_2), the DC voltage steeply rises in a few milliseconds to a peak value. In the second stage (t_2-t_3), the DC voltage reaches a steady level, also called the plateau voltage. In the absence of surge arresters, the voltage reaches 2 p.u.. In practical cases, the voltage is limited by the DC-side surge arresters and maintained by the AC-side fault current. The DC-side surge arresters have a knee point in the order of 1.6 to 1.8 p.u.. The second stage lasts until AC circuit breaker opening (t_3). After AC circuit breaker opening ($t_3 - ...$), the voltage decays to a lower value, potentially sped up if the cable is connected to the earth with an earthing switch.

Several options have been proposed in the literature to mitigate overvoltages during DC-side pole-to-ground fault

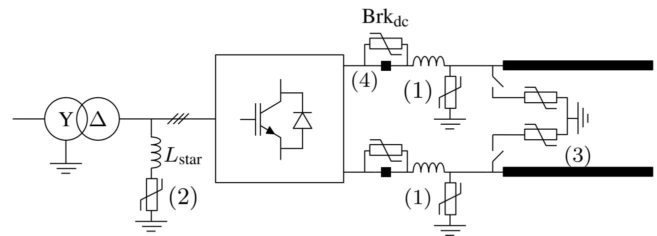

Fig. 2: HVDC converter station with cable and pole overvoltage mitigation options.

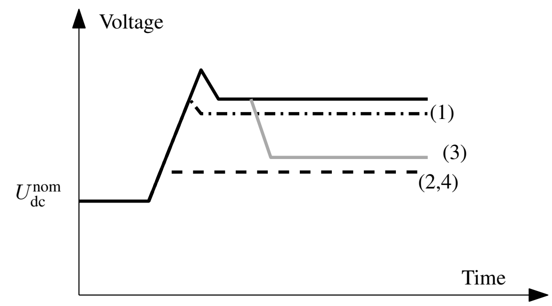

Fig. 3: Effect of different overvoltage mitigation options on healthy DC-side pole overvoltage, before any other actions are taken.

(Fig. 2), each having a particular effect on one of the three overvoltage features described above (Fig. 3). First, lowering the knee-point voltage of the DC-side surge arresters (1) can have an impact on lowering the maximum voltage and the value of the sustained overvoltage [19]. The limit on this approach is determined by the leakage currents during normal operation, which increase with lower kneepoint selection. Second, a surge-arrester neutral grounded point at the AC side (2) can lower the peak and the sustained overvoltages seen at the DC-side [15]. This requires the presence of a neutral point at the AC-side, e.g., through the transformer winding configuration or a zig-zag transformer [15], [20]. Third, an active surge arrester grounding device (3) can be used to limit the value of the sustained overvoltage and even rebalance the poles [21], [22]. Fourth, converters with fault blocking capability or fast DC circuit breakers (4) can reduce the maximum and sustained overvoltages, as e.g., shown in the context of a HVDC grid in [16].

III. Overvoltage Mitigation Using Ultra-fast Circuit Breakers

This section introduces three options for mitigating DC-side overvoltages on the healthy pole. The first two options include fast breakers at the AC side, whereas the last option is the DC-side circuit breaker.

A. AC-side Fast AC Circuit Breakers (Type A)

Fast AC-side circuit breakers that interrupt fault currents at current zero-crossings but in a period of half- to a full AC cycle, have the ability to reduce the time duration of the second stage. If interruption is achieved after the first or second zero crossing, the operating time is (considering 50 Hz) in the range of 10-20 milliseconds. In case these breakers are applied, the interruption capability of the AC-side breakers must still be such that three-phase faults at the breaker terminals can be interrupted.

B. AC-side Fast DC-Type Circuit Breakers (Type B)

Circuit breakers that induce artificial current zero-crossings are at present typically dubbed DC circuit breakers. Examples of such circuit breakers are hybrid-type (combining mechanical switches with power-electronic breakers) [23] or resonant-type (combining mechanical switches with a resonant circuit) [24], [25]. When used at the AC-side, these circuit breakers may induce artificial zero crossings even sub-cycle. As such, depending on their opening time, they can speed up the interruption process compared to fast AC-type circuit breakers. Typical operation times are in the range of 2 to 8 ms.

Two options exist for dimensioning these circuit breakers. First, the DC breaker capability can be used for all types of faults. In this case, the breaker must be dimensioned for interrupting the peak AC current that can occur for a three-phase fault at its terminals. Second, DC breaking capability can be used only for DC-side pole-to-ground faults. In this case, the breaker must only be dimensioned for the peak AC current associated with a DC-side pole-to-ground fault, whereas AC breaking capability (i.e., the mechanical breaker only) is used to interrupt all other types of faults. As this might significantly reduce breaker dimensions (especially with surge arresters), the second case is considered in this paper.

C. DC-side Fast DC Circuit Breakers

Instead of using breakers at the AC side, circuit breakers may also be placed at the DC side. In this case, only the DC circuit breakers can be used. The difference between interrupting at the DC- or at the AC-side is the absence of an uncontrolled discharge of elements (typically inductors) post-breaking. In case of interrupting at the AC side, all energy charged within the inductors is discharged into the cables, whereas in case of interrupting at the DC side, the DC-side currents are actively driven to zero and energy is absorbed by the breakers.

As for the DC-side fast circuit breakers, two options exist for dimensioning. First, the DC breaker capability can be used for DC-side pole-to-ground and pole-to-pole faults. In this case, the DC breaker and its inductors must be dimensioned for the peak current that may occur during a pole-to-pole fault. Second, the DC breaker capability can be used only for pole-to-ground faults. In this case, the DC breaker and its inductors must only be dimensioned for the peak current associated with pole-to-ground faults, resulting in a reduced design.

IV. Case Study

A. System under Study

The system under study considers a point-to-point VSC HVDC scheme with symmetrical monopolar configuration. The AC systems are modeled by a voltage source and equivalent 50-Hz grid impedance. The circuit breakers at the AC-side either have normal AC circuit breaker behavior or fast AC circuit breaker behavior. In the AC circuit breaker case, the circuit breakers are modeled as delayed switches (Type A, 60 ms opening time), and can interrupt the current only at the current zero-crossing. In the fast circuit breaker case, two modeling approaches are considered. In the first approach, the circuit breakers are modeled as a delayed switch such that the interruption occurs at the current zero crossing (Type A, 8 ms opening time). In the second approach, the circuit breakers are modeled as delayed switches (2 and 8 ms opening time) in parallel with a surge arrester branch (Type B), such that current can be interrupted even at non-zero current through the switch. In the DC circuit breaker case, the breakers are modeled as delayed switches in parallel with a surge arrester branch (Type B, 2 ms and 8 ms opening time). The VSCs assume a half-bridge modular multilevel converter topology and are modeled using the model described in [26]. The cables are 150 km long, modeled by a frequency-dependent phase model and take the parameters as given in [27]. The parameters of both converter models and AC grids are the same as for "Converter 1" in [27]. A DC-side inductor of 10 mH per pole is present in all cases, complemented by an additional DC-side inductor for the DC breaker cases, whose value is given in Table I. The surge arrester rated voltages for the DC-side surge arresters have been increased such that the knee voltage is 1.6 pu. Pre-fault power flow has been set at zero and has not been varied, given its limited influence on overvoltage profiles during DC-side faults [19]. All simulations are performed using EMT-type software [28] with a time-step of 10 μs. The paper considers a pole-to-ground fault at $t = 0.1$ s in the middle of the positive pole.

Case	Type	Location	Opening Time	DC-side inductor
1	A	AC	60 ms	-
2	B	AC	8 ms	-
3	B	AC	2 ms	-
4	A	AC	8 ms	-
5	B	DC	8 ms	81 mH
6	B	DC	2 ms	22 mH

TABLE I: Simulation Cases

B. AC-side Circuit Breakers (Case 1)

The base case shows the characteristic behaviour, i.e., a maximum absolute voltage, sustained voltage and time of sustained voltage determined by the DC-side surge arrester and AC breaker characteristics (Fig. 5). In this base case, the maximum absolute voltage is 1.62 pu, and the voltage remains above 1.5 pu for 63 milliseconds. In this case, the DC-side surge arresters absorb 32.7 MJ.

C. AC-side Fast Circuit Breakers Type B (Cases 2 and 3)

Both AC-side fast circuit breakers have the ability to reduce the time of the sustained voltage, whereas only the fastest breaker has the ability to reduce the peak voltage (Fig. 6a and b). The time of the sustained overvoltage is linked to the breaker opening time, i.e., for the 8 ms breaker there is 7 ms of sustained overvoltage. The 2 ms breaker is able to reduce

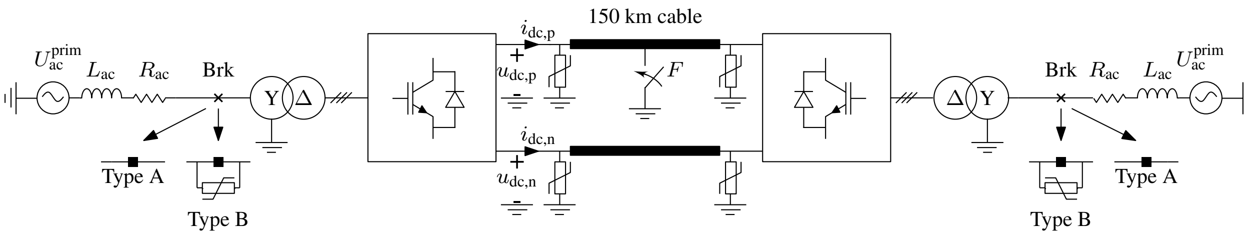

Fig. 4: Symmetrical monopolar scheme with fast circuit breakers applied at AC-side.

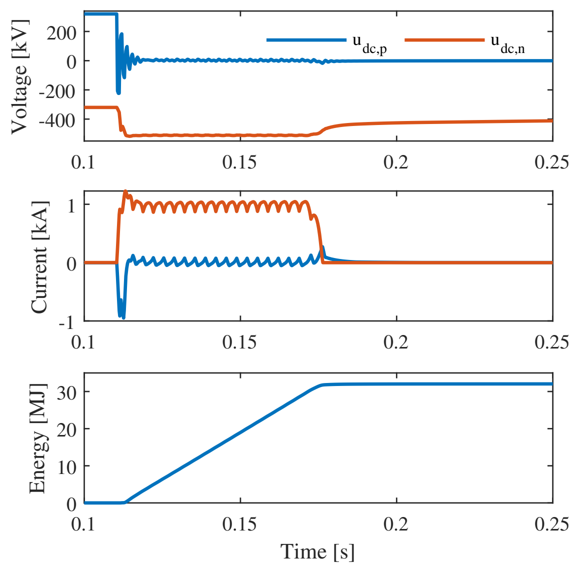

Fig. 5: DC-side voltages and DC-side currents for Case 1.

the peak voltage to 1.52 pu (meaning a reduction to about 94 % of the base case), and the sustained overvoltage is less than 1 ms. This is also translated into the surge arrester energies, with 4.3 and 1.1 MJ for the 8 and 2 ms breaker, corresponding to 13 and 3 % of the base case.

D. AC-side Fast Circuit Breakers Type A (Case 5)

Compared to the Type B breaker, the Type A breaker has a longer period of sustained voltage whereas the peak voltage is the same (Fig. 6c compared to a and b). The time above 1.5 pu (i.e. period of sustained overvoltage) is now 12.9 ms, which results in a surge arrester energy of 6.5 MJ, which is about 20 % of the base case.

E. DC-side Circuit Breakers (Case 6)

Both DC-side circuit breakers show slightly improved behavior to their AC-side counterparts. In the case of 8 ms, the maximum overvoltage is 1.59 pu and the period of sustained overvoltage is 5.5 ms. In the case of 2 ms, the maximum overvoltage is the lowest, i.e., 1.42 pu and there is no period of sustained overvoltage. The DC-side surge arrester energies are 4.4 and 1.1 MJ.

F. Comparison

Fast circuit breakers at AC and DC-side reduce the time of the sustained overvoltage, and hence arrester energy, but, unless they act very fast, they do not reduce the DC

TABLE II: Comparison of different cases

Parameter/Case	1	2	3	4	5	6
Maximum overvoltage [pu]	1.62	1.62	1.52	1.62	1.59	1.42
Sustained overvoltage [ms]	63.4	7	0.6	12.9	6.5	0
Pole Arrester Energy [MJ]	32.7	4.3	1.09	6.4	4.4	1.1
Breaker Arrester Energy [MJ]	0	0.095	0.025	0	0.164	0.113
Maximum overvoltage [%]	100	100	94	100	99	88
Sustained overvoltage [%]	100	11	1	20	10	0
Pole Arrester Energy [%]	100	13	3	20	14	3

overvoltage peak. All of the fast breakers, applied at AC or DC side, achieve a reduction of sustained overvoltage time, and hence also surge arrester absorbed energy, with about 80 to 90 %. By contrast, only the 2 millisecond breaker is able to reduce the maximum overvoltage, albeit with only 6 % when applied at the AC side and with 17 % when applied at the DC side.

It should be noted that, to interrupt pole-to-ground faults, there is not a large penalty involved in arrester energy of the breakers. Indeed, the breaker arrester energy is only a fraction of the pole arrester energy (compare breaker arrester energy in MJ to the pole arrester energy in Table II). This is due to the fact that, during pole-to-ground faults, currents are naturally limited due to the grounding scheme and the DC-side pole surge arresters.

V. Discussion

It is clear that increased speed of interruption both at AC or DC side may mitigate the DC-side overvoltages. Nevertheless, towards practical realization of the proposed concepts, the dimensioning and operation of the circuit breakers requires special attention:

- To achieve high-speed AC-side circuit breakers without DC current interruption capability, traditional SF_6-breakers may be too slow. When vacuum interrupters are used, the opening time can be decreased to a few milliseconds as demonstrated in [29], but a number of vacuum interrupter units in series is required to achieve the required voltage. For instance, in case a 100 kV unit is used, four vacuum circuit breakers should be put in series in case of a 380 kV AC grid. The vacuum interrupters could be actuated by a fast actuator that achieves a sufficiently large gap within a few milliseconds, such as a Thomson coil actuator [30]. Vacuum circuit breakers rated for higher voltages, e.g., 245 kV have recently been in development [31].

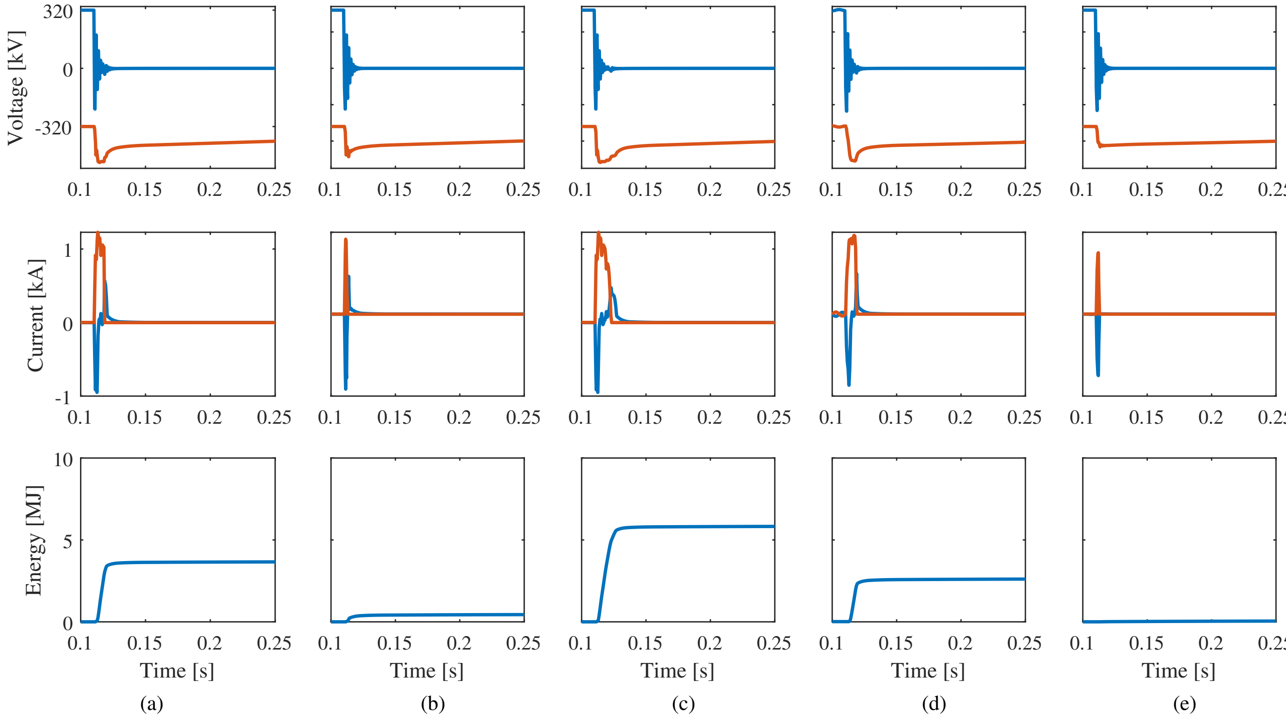

Fig. 6: DC-side voltages, currents and negative pole surge arrester energy for cases 2 to 6.

- In case of DC-side interruption capability, two parallel paths should be provided, i.e., a commutation path and an energy absorption branch. The commutation path requires either a combination of capacitors and inductors or power-electronic circuits. Several concepts have been developed for HVDC circuit breakers (e.g., [17]). For AC distribution networks, pilot projects with hybrid circuit breakers have recently demonstrated fast interruption capability [32].
- In case of AC-side circuit breakers with DC-current interruption capability, DC-current interruption capability could be used only for pole-to-ground faults. In such cases, detection and operation logic should be developed such that the commutation path and breaker arresters are not overloaded during other fault types.
- Using fast circuit breakers with DC interruption capability at the AC side may offer reduction in weight and volume compared to installing DC-side breakers. Moreover, further reduction can be achieved by installing only two fast DC circuit breakers at two phases in a neutral-isolated system, whereas a normal AC circuit breaker is installed at the third phase. This is theoretically valid as the fault clearance in two phases leads to current interruption in the third phase.
- The impact of fast AC circuit breaker operation on the surrounding AC-side equipment should be studied. This includes a study of the events that may happen in case of breaker failure.

Besides application to cable point-to-point schemes, the application of fast AC-side circuit breakers may offer improvements to system performance in other application areas:

- In point-to-point schemes, as well as multi-terminal HVDC systems protected by a non- or partially selective fault strategy, fast AC-side circuit breakers may reduce the DC-side fault clearing time.
- In bipolar schemes, using breakers with DC interruption capability at the converter-side of the converter transformer may solve the non-zero crossing phenomenon for AC-side pole-to-ground faults. AC-side pole-to-ground faults at the valve-side may be characterized by the absence of zero crossings and hence require special solutions [33], [34]. Installing a breaker with DC interruption capability (type B) may assist in clearing these faults and eliminate the need for alternative solutions.

VI. Conclusion

Fast circuit breakers at AC or DC side can mitigate DC-side overvoltages for DC-side pole-to-ground faults. All solutions limit the time an overvoltage persists, whereas only the fastest solutions are able to reduce the peak DC-side voltage. In all cases involving DC current interruption capability, for breakers installed at the AC as well at the DC side, the pole arrester energy is heavily reduced (up to 97%) at only a moderate breaker arrester energy (less than 1 MJ). The use of fast AC-side breakers without DC current interruption capability already reduces the need for DC-side pole arresters but does not reduce peak DC-side voltages. Even in case of a DC-side breaker, maximum overvoltages were only reduced by 12 %. The use of fast AC-side breakers or AC-side breakers with DC current interruption capability may bring additional benefits in other schemes such as non- or partially selectively protected multi-terminal HVDC schemes.

The practical implementation of the proposed solutions has been commented. Concepts for high-speed interruption at AC- and DC-side exist, but may require future work towards scaling up to high voltages. Furthermore, further research is required into the exact dimensioning and practical realization of fast AC circuit breakers with or without DC current interruption capability. The impact on surrounding AC-side equipment, e.g., caused by any fast transients that may be induced during switching, should be investigated as well. The application and benefits for HVDC multi-terminal systems could be verified through detailed simulations in an EMT-type software.

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