Unidirectional hybrid circuit breaker topologies for multi-line nodes in HVDC grids

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Abstract
Interest in HVDC transmission increases, but still fault handling is difficult because fault currents rise faster than in HVAC transmission. Therefore concepts for a fast turn off of DC lines, especially in case of a short circuit fault, are needed. Turning the complete DC-transmission system off is too slow and not suitable for large grids. To overcome this, several bidirectional HVDC circuit breaker topologies have been developed. However, fast bidirectional circuit breakers contain a huge number of semiconductors. As alternative unidirectional circuit breakers can be used, which have a lower number of semiconductors. This paper focuses on the applicability of unidirectional hybrid circuit breakers, which are derived from four bidirectional circuit breaker concepts. In addition, a detailed comparison of the unidirectional circuit breaker topologies is presented.

1 Introduction
In recent years, the interest in HVDC transmission has increased. One reason is the increased need for offshore energy transmission for windfarms, which is limited to short distances with AC technology due to cable capacitances. Another reason is the need to transmit the energy of wind or solar parks over long distances where HVDC has lower losses than AC. Additionally, the increasing power ratings of semiconductors now allow the use of voltage source converters (VSC), which enable a power reversal in a transmission line without a voltage reversal, being a first step to a meshed multi-terminal DC (MT-DC) grid with low transmission losses.

One of the remaining problems of HVDC transmission is to interrupt the power flow in lines, especially in case of a fault, where currents rise quickly to high values, because of the low inductance and the high capacitance encountered in HVDC systems. Three basic possibilities to isolate a fault are summarized in [3, 4]. The easiest solution currently used for HVDC links is to deenergize the whole DC transmission line by triggering all AC circuit breakers of the lines feeding the HVDC-system. This method, however, needs several 100 ms up to a few seconds and is only suitable for point to point transmission lines. Another possibility is to use a topology for the AC/DC converter (e.g. M2C with full bridge modules), that has the ability to limit the DC side current and to switch off the grid. Here again, the complete grid is shut down until isolation switches have isolated the faulty part [3]. A third possibility is the use of DC circuit breakers (CB) for isolating only the faulty part of the DC grid. Such a DC CB needs to be very fast (1-3ms) to limit the disturbance of the grid by a fault and must be able to break a current several times the value of the nominal current.

In [5] and [6] three concepts for DC CBs are proposed and compared. The first is the resonant circuit breaker, which uses a resonant branch parallel to a mechanical breaker to produce a zero crossing and to extinguish the arc in the mechanical breaker. The time for breaking the current is in the range of several ms for actively excited resonant circuit breakers and several tens of ms for passive resonant circuit breakers. A faster possibility is the second concept of a pure semiconductor CB. This only needs few microseconds for breaking the current. The
disadvantages of this breaker type are the high number of semiconductors, the high conduction losses generated by the current through the semiconductors and the required cooling of the semiconductors. Finally, in the third concept a mechanical switch (MS), conducting current in nominal operation, is combined with semiconductors for a fast turn off process. These so-called hybrid circuit breakers (hCB), gain increased interest, since the time for current breaking is in the range of few ms and the conduction losses in nominal operation are low. Several concepts for hCB have been presented and prototypes have been tested [7–10]. For hCB basically two types of MS can be used. Mechanical circuit breakers (MCB) are used for concepts, where the MS is opened with an arc and the current must be interrupted in the MCB [9]. In contrast to this, the concepts for hCB presented in [7, 8, 10] avoid an arc in the MS so that ultra-fast disconnectors (UFD) can be used for the MS.

All the in [7–10] presented hCB are designed for bidirectional current breaking. However, unidirectional current breaking designs suffice in most cases as will be discussed in this paper.

First, a short overview of possible DC grid configurations and grounding concepts for MT-DC grids, faults in MT-DC grids and different switching operations, which must be performed by unidirectional CBs, are presented in section 2. In section 3 an overview of unidirectional hCB concepts is shown. The performance of the unidirectional designs and the advantages of their use instead of bidirectional designs are investigated. The requirements for the unidirectional CBs are derived from four bidirectional CB concepts. Design guidelines for the unidirectional version of the CBs are given and the CBs are compared in terms of performance. The focus is on MT-DC grids, for which the development of CBs is essential. The section concludes with an unidirectional concept for hCBs for a node with multiple lines. In section 4 the main results are summarized.

2 DC line configurations and protection

Recently several MT-HVDC grid concepts have been presented to transport energy over long distance with low losses to enable a better integration of renewable energy sources. Such transmission systems are, for example, the European continental overlay HVDC grid proposed in [11] or the North Sea Super Grid in [12]. With the installation of large wind farms and the connection to the onshore AC-grid with HVDC lines, the North Sea Super Grid already becomes reality and grids for simulating and testing HVDC topologies are derived from it. Two commonly used test grid structures are shown in Fig.1. A typical single node of such a grid (e.g. T4 from Fig.1b) is shown in Fig.2. It interconnects three lines to other nodes and a VSC AC/DC converter station. Between the node and the converter an inductor and a DC-filter (DCF) are placed to damp harmonics. CBs for clearing faults are placed at each end of the lines and between the node and converter. Possible line configurations and grounding schemes of such grids are discussed in section 2.1. Fault types and the influence of the line configuration and grounding scheme on the fault behavior are investigated in section 2.2. The required switching operations of the CBs are discussed in section 2.3.

2.1 DC line configurations and grounding

An HVDC grid may be realised with a symmetric monopolar, an asymmetric monopolar or a bipolar configuration [13]. Apart from the configuration, the grounding scheme has also a significant impact on the nominal operation and the fault behavior [14]. The grounding may be a solid grounding or a high impedance grounding with resistance or inductance to limit short circuit currents. Each configuration (Fig.3) has some special advantages and disadvantages:

a) Asymmetric monopolar configurations (Fig.3a) require only one full isolated conductor and one line on ground potential. The disadvantage of the ground return is that in a system with several solid grounding points earth currents can occur. The use of only one solid grounded station and all other stations with a high impedance grounding avoids these earth currents. However in that case the voltage between the ground line and the earth can cause the need for isolating the ground return. Stations comprise a converter and a transformer to avoid ground currents over the AC-grid. An advantage over the symmetric monopolar topology is the possibility to extend the asymmetric monopolar topology easily to a bipolar topology with double the nominal voltage and double transmission capacity.

b) Symmetric monopolar configurations (Fig.3b) require two full isolated conductors and two lines on ground potential. The disadvantage of this configuration is the need for isolating the ground return, which can be avoided using high impedance grounding. However this leads to a high voltage between the ground line and the earth, which can be a problem for the adjacent configurations.

c) Bipolar configurations (Fig.3c) require four full isolated conductors and two lines on ground potential. The advantage of this configuration is that it can be easily extended to a bipolar topology.

Figure 3: HVDC line configurations showing one link between a node with four DC lines and a node with two DC-lines and a AC/DC converter: a) asymmetric monopolar b) symmetric monopolar c) bipolar

Figure 2: Test case for a node consisting of converter station, four terminal node and line faults of a HVDC grid.
b) Symmetric monopolar configurations (Fig. 3b) uses two lines with half the pole to pole voltage from each pole to ground. Therefore, in nominal operation only half the nominal voltage of a line is applied between pole and ground. The symmetric configuration is also advantageous for converters and transformers on the AC-side. Due the use of two converters, the transformer can also be omitted. The line configuration may be ungrounded or use a high impedance grounding. The symmetric configuration needs two CB for each pole with half the nominal voltage since single pole to ground faults of both lines must be disconnected without overvoltages.

c) Compared to symmetric monopolar configurations bipolar configurations (Fig. 3c) use a metallic return path, which only conducts a current in case of a fault or an asymmetric operation. A disadvantage of the configuration is the need for two VSCs and transformers. In normal operation no ground currents occur and the possibility to use only a single pole in case of an outage of one pole exists. Bipolar topologies can have a solid or a high impedance grounded metallic return path.

Depending on the configuration and the grounding, the same fault type can differ. In the following section, these differences are discussed.

2.2 Faults in HVDC grids

Faults in HVDC grids can be single pole to ground or pole to pole short circuit faults with different fault impedances. These two fault types result in a voltage drop in the line and therefore in a fast increasing fault current. Another type of DC fault are single pole or dual pole open circuits, which are not discussed in this paper, since CBs do not have to clear these type of faults. The task of CBs is to interrupt short circuit currents and to dissipate the energy required to clear these type of faults. Here the CBs must still be able to turn off the short circuit.

b) Pole to ground short circuits in symmetric monopolar configurations with transformers differ from pole to ground faults of other topologies. The line to ground capacitances of the faulty line are discharged, while the line to line voltage stays the same. Therefore, the healthy line is charged to double its nominal voltage. The lines and the transformer must therefore be able to isolate the full system voltage in case of a fault. Depending on the grounding scheme, high transient currents are possible, but there is no steady-state fault current. To switch off a pole to ground fault each line needs two CBs. The pole to pole fault is the same as for the asymmetric monopolar configuration.

c) Bipolar configurations have the advantage that pole to ground short circuit faults are only with half the voltage compared to pole to ground faults in monopolar configurations. The CBs must be designed for disconnecting the faulty line with half the maximum line to line voltage to avoid overvoltages between line and ground. Pole to pole faults have the advantage, that in both lines current limiting inductances are used, so that the fault does not lead to higher fault currents than for pole to ground faults. However, for fault clearing, both CBs have to break the fault current and share the voltage equally. Ideally, both CB work synchronously, so that the current breaking process for a CB is equal to the current breaking process of a pole to ground fault. A delay of one CB can lead to a higher stress of the CBs or even lead to a failure of the current breaking process. As alternative, CBs may be designed for current breaking with half system voltage and full system voltage, enabling the CB to clear pole to ground and pole to pole faults without the need to synchronize with a second CB. A special fault scenario, which can only occur in a bipolar configuration, is the combination of a single pole to ground short circuit and an open circuit fault (asymmetric dual pole fault). Here the CBs must still be able to turn off the short circuit.

Pole to pole faults of a monopolar asymmetric grid include the worst case single pole to ground fault of the monopolar asymmetric configuration. Pole to pole faults in a symmetric monopolar grid or a bipolar grid can both be cleared with a single CB and hence show equal behavior like in the asymmetric grid or use two synchronous CB for half the nominal voltage, which show the same behavior like a CB in an asymmetric grid with half the nominal voltage. This is also the case for the bipolar pole to ground fault in solid grounded systems. Pole to ground faults of symmetric grids and asynchronous operation of two CB for half the nominal voltage in case of a pole to pole fault in a bipolar grid have to be investigated separately for each grid, since it depends mainly on the grid topology and its grounding. Therefore, they are not further investigated in this paper and the investigation of unidirectional CBs in the following section is for pole to pole faults of a monopolar asymmetric grid.
2.3 Switching tasks of line-CB

In Fig.4 possible fault locations \( f_{1.1}, f_{1.2} \) in a typical HVDC grid are shown. Depending on the line configuration and the location of the CB, the CB has to perform different switching tasks. An overview of these tasks is given in [15]. It is advantageous to distinguish between CBs for lines (line-CBs) and CBs between a node and a single converter station (station-CBs), since they have different requirements. The focus of this paper is on line-CBs, since the design of station-CBs also depends on the converter topology.

Apart from faults, the CB must be able to switch the lines on and off under nominal conditions. Thus, it must also be able to switch a current between zero and nominal current off and connect uncharged lines with open ends with low oscillations.

For line-CBs, as shown in Fig.4, the fault behavior depends on the place of the fault. While bidirectional CBs, which are able to break current in both directions, are independent of the current direction, fault clearing for unidirectional CBs differs with the current direction. Unidirectional CB can conduct the current in both directions, but can only break the current for one direction. For the design of an unidirectional line CB different possible faults are important and are exemplified for \( CB_{1.1} \) of Fig.4. Different cases for \( CB_{1.1} \) are depicted in Fig.5. \( I_{\text{DC}} \) is either positive or negative. The fault occurs at \( t_f \) and is cleared at \( t_{\text{CB}} \). After \( t_{\text{CB}} \) the energy in the line is dissipated.

- **Fault \( f_{1.2} \):** A fault at some distance to \( CB_{1.1} \) is the standard fault scenario. The line inductance limits the current rise, but also generates oscillations in the line due to the line capacitance. Depending on the line parameters and the fault location, the oscillations may be important for the design.
  - \( I_{\text{DC}} > 0 \): The current increases with a slope depending the inductance to the fault location \( L_{\text{line},1.1} \). \( CB_{1.1} \) has to break this current and deenergize the line.
  - \( I_{\text{DC}} < 0 \): First the current decreases and reverses its direction. Depending on the speed of \( CB_{1.1} \) and the current slope, \( CB_{1.1} \) can then turn off at zero current or the current direction changes and \( CB_{1.1} \) has to break a positive current.

- **Fault \( f_{1.1} \):** This fault close to \( CB_{1.1} \) results in the highest fault current and often current limiting inductors \( L_{a,b}/L_{a,b} \) are used to limit the current to a level, which \( CB_{1.1} \) is able to handle. Current limiting inductors can be either on the line side of the CB \( L_{a,b} \), on the node side \( L_{a,b} \), or both. Since the other lines and the converter connected to the node also have inductances (e.g. \( L_2 \), \( L_3 \) and \( L_4 \) in Fig.2), an equivalent inductance \( L_{\text{line},n1} \) is used for simulation of a single line. This inductance already limits the current rise and allows to decrease \( L_{a,b} \) of \( CB_{1.1} \).
  - \( I_{\text{DC}} > 0 \): The current increases fast and reaches the maximum current \( I_{\text{max}} \), which \( f_{1.1} \) must be able to break and is therefore the worst case in terms of current amplitude and rate of rise. For short lines this is the also worst case in terms of energy dissipation, since the high currents imply high stored energies in the line inductances.
  - \( I_{\text{DC}} < 0 \): The current decreases fast and changes direction. The unidirectional CB then has to break again a positive current. The current stays below the maximum current of the same fault location with positive current, since the current must first reverse its direction.

- **Fault \( f_2 \):** A fault behind \( CB_{1.2} \) means, that the full line inductance and the current limiting inductances of \( CB_{1.2} \) limit the current rise.
  - \( I_{\text{DC}} > 0 \): The current increases slowly, however, \( CB_{1.1} \) has to dissipate the energy of the full line and current limiting inductances. Depending on these inductances this fault can be the worst case in terms of energy dissipation, since the energy of the nominal current in an inductance of a long line can be higher than the energy of the high current in a fault directly after the CB.
  - \( I_{\text{DC}} < 0 \): The current decreases slowly. After the current reaches zero, \( CB_{1.1} \) is switched off. Since \( CB_{1.1} \) is unidirectional, it is not able to break the negative current. However, this is beneficial, since the negative current discharges in this case the line and feeds energy back into the grid.
Fault $f_3$: The fault current is limited by the full line inductance $L_{line,1.1} + L_{line,1.2}$ and the current limiting inductances $L_i$. Regardless of the current direction $CB_{1,1}$ cannot switch the line off, since the CB is not designed to interrupt a current into the node.

- $I_{DC} > 0$: The current decreases to zero and $CB_{1,2}$ isolates the line and the faulty node $N_1$ from the node $N_2$.
- $I_{DC} < 0$: The negative current increases until $CB_{1,2}$ has cleared the fault. This is the case with the longest duration of a negative overcurrent, which the CB must be able to handle.

Fault $f_{1,2}$ with positive current is the fault with highest currents and also has the highest energy in the considered relatively short line (Tab.I). However, unidirectional CBs do in this case not differ from bidirectional CBs, since changes in design only affect faults on the node side of the CBs. For the design changes, faults $f_2$ and $f_3$ are interesting. Fault $f_2$ is the fault, which in case of bidirectional CBs is cleared by $CB_{1,2}$, but in case of unidirectional CBs must be cleared by $CB_{1,1}$. Fault $f_3$ is also important for the design of the nominal current branch of the unidirectional CB, since $CB_{1,1}$ has to be designed so that the opening of the MS of $CB_{1,1}$ does not lead to an arc in the UFD or damage the MCB.

### 3 Unidirectional circuit breaker concepts

Most CB concepts are proposed as bidirectional current breaking devices. However, a bidirectional device is more complex and more expensive than a unidirectional current breaking device. In an MT-DC network the line must be able to conduct current in both directions, but as shown in section 2.3 the use of an unidirectional breaker is sufficient. In the following, first four originally bidirectional topologies are modified for unidirectional use according to the design parameters in section 3.1 and their performance is compared with respect to the parameters listed in section 3.2. In addition, concepts for multi-line CBs are presented, which use parts of the CB for fault clearing in several lines reducing volume and cost of the node equipment.

#### 3.1 Design parameters

For comparing the unidirectional concepts, all CBs are designed for a line of a MT-DC grid with parameters listed in Tab. I. The used cable parameters are given in Tab. II. A fault detection time of 2 ms is assumed. If an UFD is used, the MS is opened 2 ms [16] after the overcurrent is detected. During the opening of the UFD, it is assumed that the withstand voltage of the MS increases linearly with time as the distance between the contacts is assumed to increase linearly with time. In case a MCB is required, the MS opens in 2.3 ms [17]. When the MCB is open, the arc can be extinguished. After the arc extinction the allowed voltage slope is assumed to be 1 kV/μs as the contacts of the MCB already have reached the full distance. Since the unidirectional CB is not designed to break a current in reverse direction, the CB must have the ability to conduct the current in reverse direction after opening the MS. Usually this is performed by a diode. Since an arc in an UFD must not appear, measures have to be taken to commutate the current to this diode, before the UFD is opened. If an MCB is used, the diode can be omitted, since the MCB can cope with the current.

#### 3.2 Comparison parameters

To compare the performance of the different CB concepts, the following parameters are used:

- **Volume**: As indicator for the volume and cost of passive components, the maximum energy stored in the capacitors $E_C$ and the inductors $E_L$ is used. For comparing volume and cost of varistors and resistors the maximal dissipated energy $E_{dis}$ is used.
- **Semiconductors**: The number and type of used semiconductors have a significant impact on cost and reliability of the CB and their characteristics can have considerable influence on the CB design.
- **Consumed fault energy**: The main task of a CB in a grid is to disconnect a faulty line with low distortions of the connected grid. Thus, the major criterion is not the time until the current is broken, but the additional energy consumed by the fault $E_f$ resulting in the disturbance of the healthy part of the grid.
- **MS voltage**: All topologies use the same MS in terms of maximum current. However, the maximum blocking voltage of the MS $V_{MS, max}$ is another parameter for comparison, since it defines to some extent the voltage of a MS and has an influence on the breaker performance.
- **Additional features**: The term is used for comparing additional features of CBs, which are not included in other parameters, like integrated over-voltage protection. The possibility to use the CB for turning the line on and off with low distortions in the line and the possibility to use only one CB for pole to pole faults and pole to ground faults in bipolar lines are discussed. Also the behavior of two CB in a bipolar line turning off asynchronously is shown.

In the following four sections, the topologies used for comparison are presented. Individual design considerations, simulation results and comparison of the topologies are presented.
3.2 2-terminal circuit breaker

3.3.1 2-terminal circuit breaker with IGBTs: 2TSEM

The CB proposed in [7] uses a load commutation switch (LCS), consisting of isolated gate bipolar transistors (IGBT), in series to an UFD to commutate the current in case of a fault from the main current branch with low losses to the parallel current breaking branch. The current breaking branch consists of IGBTs with antiparallel diodes and snubber circuits. For breaking the fault current, the IGBTs are turned off and the current is commutated to varistors, generating the transient interruption voltage and deenergizing the faulty line.

The unidirectional 2TSEM is shown in Fig. 6a). Compared to the bidirectional design, the number of semiconductors and snubbers of the main breaker are halved. The LCS remains the same, since the current commutation from the UFD to the main breaker is necessary for both directions to avoid an arc. The number of varistors remains the same since they are used in the bidirectional design for current breaking operation in both directions. In case of a fault, the current breaking process of the CB is the same as for the bidirectional CB. By switching off the IGBTs individually, the current is commutated to the maximum allowed number of varistors to establish the maximum allowed blocking voltage at any point of time.

Additional features: By turning off only a share of the IGBTs, a low number of varistors can be inserted to turn off the nominal current without disturbing the grid. Switching on a share of the IGBTs before the CB is fully turned on allows to precharge the line to nominal voltage and so to switch on the MCB without disturbances. For a bipolar line and a 2TSEM CB designed for the full voltage this would also allow to switch a pole to ground fault off with only half the blocking voltage and to use the full blocking voltage to clear a pole to pole fault without synchronizing with a second CB. On the other hand, in case of an asynchronous turn off with two CBs, the CB, which turns off first, commutates the current to its varistors. The current increases further until the second CB also reaches the full blocking capability. If the varistors are designed for the additional thermal stress of the maximum delay between two CB, current breaking is still successful.

3.3.2 Circuit breaker with thyristors: 2TDB

The 2-terminal breaker proposed in [8] with LCS and UFD in the nominal current path uses IGBTs for commutating the current from the nominal current branch to the auxiliary branches, which are turned on with thyristors. Each auxiliary branch uses capacitors with paralleled varistors. The current commutates into the uncharged capacitors and charges the capacitors to the threshold voltage of the varistors. As soon as the MS can block higher voltages, the current is commutated to the next branch with a higher threshold voltage of the varistors. After the last of these commutations, the line is deenergized with a varistor, which blocks the full voltage. A disadvantage of this CB is the long recovery time of high voltage thyristors. The recovery time of the thyristors after current commutation to the next auxiliary branch must be kept to prohibit an unwanted reignition, which would prevent a successful current breaking. In Figure 7, an optimization of the recovery time is shown. Capacitors $C_2$ and $C_3$ and the maximum voltage of $C_2$ are variable. $C_1$ is defined by the
maximum current and maximum voltage slope of the MS. The maximum voltage of $C_1$ is limited by the blocking voltage of the LCS, the maximum voltage of $C_3$ is the blocking voltage of the CB. Depending on the recovery time, the voltage of the MS is lower than the maximum possible and leads to a higher fault current. The maximum fault current in the worst case for recovery times $t_{q1}$ and $t_{q2}$ are given in Figure 8. Even for fast thyristors this limits the maximum voltage increase over the MS and though the overall performance.

Compared to the bidirectional design, the unidirectional design shown in Fig.6b) uses half the number of thyristors. Here again the LCS must be bidirectional to avoid an arc in the UFD. An additional diode for conducting the current in reverse direction must be added.

**Additional features:** To turn off a nominal current without fault, the current commutation from auxiliary branch 2 to auxiliary branch 3 is not performed, so a lower blocking voltage is used to turn off with less disturbances in the grid. In the turn on process of a line, a thyristor branch could be used to limit the maximum inrush current, but disturbances can not be avoided. For a bipolar grid, the blocking voltage of the varistor in the second branch could be adapted to block half the line voltage and so the same CB could be used for blocking pole to ground faults and pole to pole faults without the aid of a second CB. However, the performance of the CB would decrease, since the maximum blocking voltage of the second auxiliary branch is not any more optimized for current breaking with nominal voltage. As an alternative, an additional branch could be used. On the other hand, clearing a pole to pole fault in bipolar grids can also be performed by two CBs, since for an asynchronous turn off the current commutates to the varistor and if the varistor is designed for the maximum delay between the unsynchronized CBs, fault clearing is successful.

### 3.3.3 2-terminal circuit breaker with line to ground varistors for energy dissipation: 2TBYP

In [10], a 2-terminal breaker is proposed, which uses an UFD and an LCS in the nominal current branch. The main breaker uses IGBTs in the current breaking branch with current injection for zero current switching. In contrast to the other 2-terminal topologies, this CB uses two varistors between line and ground to dissipate the fault energy of the line.

Compared to the original design, for the unidirectional operation, the diode rectifier can be neglected, which has been used for bidirectional operation of the unidirectional main breaker. The unidirectional CB is shown in Fig.6c). To enable the charging of the capacitors, a diode at the end of the main breaker is needed. Again the LCS must be bidirectional to avoid an arc in the UFD. An antiparallel diode is added to enable a current in opposite direction.

**Additional features:** The turn off of the CB for a current without fault does not differ from fault clearing, since the energy of the line inductances are dissipated like in case of a fault. Therefore, the voltage over the MS is the same as in case of a fault. The turn on of the CB is without precharging the line, disturbances in case of an uncharged line can not be avoided. Using one CB for breaking a pole to pole fault is not possible, since the energy dissipation bases on the connection between line and ground. However, an asynchronous turn off of two CB is possible. The fault current on the node side commutates to the MOV between pole and ground and on the line side again to the freewheeling diode. As long as the MOV and the resistor are designed for to the thermal stress of the delay, the turn off of the second CB still clears the fault. An advantage of this type of energy dissipation is the inherent overvoltage protection by the MOV.

### 3.4 T-type circuit breaker with pulse generator: TPG

The T-type CB concept proposed in [9] uses a pulse generator (PG) between line and ground. After fault detection, the MCB is opened with an arc. When the MCB is open, the pulse generator injects a reverse current in the MCB. At zero current, the arc is extinguished and the current commutates into the antiparallel diode. When the injected current decrease, the diode blocks and the fault current commutates to the varistor in the pulse generator and the resistor $R_r$.

The unidirectional design depicted in (Fig.9) has one MCB with antiparallel diode less than the original design. Moreover, the second energy dissipation path can be omitted. For the unidirectional design, the PG capacitance is slightly decreased, since the generated reverse current is only needed for one energy dissipation path. The inductance of the PG is the same since the major design constraint, the nominal voltage, remains unchanged.

**Additional features:** A turn off of the CB without fault is not possible without high disturbances in the grid, since the turn off includes the firing of the PG and therefore a decrease of the line voltage in the CB below zero. In the turn on process of the CB also disturbances can not be avoided, since the MCB is just closed to an uncharged line. Usage of the CB for turning off pole to pole and pole to ground faults with different blocking voltages is also not possible, since the energy dissipation bases on the connection between line and ground. However, an asynchronous turn off of two CB for a pole to pole fault means a current commutation in the first CB to its MOV and resistor. As long as the resistance and the MOV are designed for this thermal stress, the fault can be cleared with the delayed CB. Again the energy dissipation with the MOV between line and ground also represent an inherent overvoltage protection for the line.
3.5 Unidirectional CB for nodes: CBN

Each line only requires a MCB unit with a MCB and antiparallel diode, a current limiting inductor and a branch with diode and resistor for the pulse current. A CBN for 4 lines is shown in Fig.10. Since the maximum allowed current of the MCB stays the same, the current limiting inductors for a CB with four connected lines must be adapted to limit the current of three feeding lines, resulting in an 50% increased output inductance $L_{s4}$. Since the injected current in all MCB units are the same, the PG capacitance must be larger than in the unidirectional design to supply all four MCB units with the same current as in the unidirectional design. Since the nominal voltage is not modified, the PG inductance stays the same as in the original design.

The current breaking process is basically the same as in the original design and an example is shown in Fig.11. The voltage of the capacitor and the current in the PG inductor are depicted in the first graph. The current in the lines and in the freewheeling diodes of all four connected lines are depicted in the next four graphs. In line 4 a pole to pole fault $f_{12}$ in 25 km distance at 0 ms happens, line 1 feeds the original 625 A into the node, the MCB of line 2 is already in off-state and in line 3 not only the MCB is in off-state, but also the line is physically disconnected. The last plot depicts the voltage over the MCB of the faulty line. The pole to pole fault leads to an increasing current not only in the faulty line and line 1, but also in line 2 despite of the MCB in off-state, since the antiparallel diode allows a current into the node. After 2 ms the MCB of the faulty line is opened. To extinguish the arc after the opening time, the PG is triggered after 4.25 ms. After discharging, capacitor $C_{PG}$ is charged in the opposite direction and discharges inductance $L_{PG}$, leading to zero current in the thyristor. The negative voltage generates a current through each diode branch and the MCB, if turned on, otherwise through the antiparallel diode. As can be seen, this current through the freewheeling diode is independent of the MCB state, the line current or if a line is physically connected or not. With zero current after 4.3 ms, the arc in the MCB of the faulty line is extinguished. As soon as the reverse current of the PG is lower than the fault current, the fault current commutates to the freewheeling diode and the energy in the faulty line is dissipated. The current of the feeding lines charges at first the capacitor and thus determines the voltage rise over the MCB and finally commutates to the varistor. The CBN is therefore able to turn off a fault current independent of the state of the healthy lines. However, a disconnector in each line is needed to prohibit a current in the turned off lines. This disconnector is no additional element, since these are used as residual current breaker (RCB) for other topologies to turn off the residual currents in the varistors.

**Additional features:** In terms of applicability the CBN has inherited the properties of the TPG design.

The 2TSEM and 2TDB can not be used as CB for nodes, since they are connected between two terminals and every branch is parallel. The 2TBP can at least use $MOV_4$ for all lines. However, the use of the main breaker for all lines is not possible.
### 3.6 Comparison of unidirectional CBs

For comparing the unidirectional CBs, the relevant design parameters are given in Fig. 12. The maximum stored magnetic energy $E_L$ of the presented 2-terminal breakers directly depends on the maximum current during the turn off process. The use of an MCB needs higher inductances to limit the fault current during the opening time and the whole energy of the pulse current must be stored. The capacitive energy $E_C$ is mainly determined by the task of the capacitors. While the capacitors of 2TSEM are solely used as snubber circuits, 2TDB and 2TBYP use them for shaping the voltage over the UFD. Since TPG and CBN only store the energy for a short pulse current, both need only small capacitances, which scale with the number of lines. The energy dissipation in varistors and resistors $E_{MOV}$ of the first two designs is much higher than the other topologies. This is caused by the lack of capacitive storage elements in the 2TSEM and the long turn off process.

The number of semiconductors of all components are reduced compared to bidirectional designs. This especially applies to the 2TSEM and 2TDB. But while the 2TSEM uses IGBTs with antiparallel diodes, which are already used in the bidirectional design, the 2TDB and 2TBYP need additional antiparallel diodes for the MS. The 2TBYP, the TPG and the CBN all require a high pulse current and therefore need a high number of semiconductors in parallel. For all topologies, fast thyristors are needed, which have in general a lower nominal voltage compared to IGBTs and Diodes [18]. Thus the number of series connected semiconductors is higher for topologies with thyristors.

The energy from the source $E_{VSC}$ and the maximum voltage over the MS are linked. The 2TSEM and the 2TDB both have a maximum voltage of about 120kV over the MS, with the effect of a slower fault current decrease compared to designs, which dissipate the energy of the input and output inductances separately and therefore generate higher voltages over the MS. However, separated energy dissipation bases on connections between line and ground (or to the second pole) with varistors and resistors. The separated energy dissipation leads therefore for distant faults to higher fault currents with higher energies to dissipate. An important result for the use of unidirectional breaker is the low stress for $CB_{1,1}$ while clearing fault $f_2$ in Fig. 4. Since the full line inductances $L_{line,1} + L_{line,2}$ and the current limiting inductances $L_{x,x}$ limit the current increase, the energy drawn from $N_1$ during the fault is lower than for a fault in the line. The probability of a failure of $CB_{1,1}$ and therefore the need for a second possibility to clear this fault is thus lower than for faults in the line $f_{1,1}$ or $f_{1,2}$.

The energy drawn from the source in case of faults. $f_{1,1}$ is the fault at 25km distance, while $f_{1,1}$ is a fault directly after the CB. $f_2$ is a fault in the distant node. The numbers for the CBN are the sum of all feeding lines.

### Table V: Energy drawn from the source in case of faults.

<table>
<thead>
<tr>
<th>Type</th>
<th>2TSEM</th>
<th>2TDB</th>
<th>2TBYP</th>
<th>TPG</th>
<th>CBN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{f_{1,1}}$ [MJ]</td>
<td>1.75</td>
<td>3.3</td>
<td>1.82</td>
<td>1.78</td>
<td>2.1</td>
</tr>
<tr>
<td>$E_{f_{1,2}}$ [MJ]</td>
<td>4.2</td>
<td>5.64</td>
<td>2.74</td>
<td>3</td>
<td>3.15</td>
</tr>
<tr>
<td>$E_f$ [MJ]</td>
<td>1.17</td>
<td>2.76</td>
<td>1.6</td>
<td>1.01</td>
<td>1.473</td>
</tr>
<tr>
<td>$V_{max}$ [kV]</td>
<td>121</td>
<td>122</td>
<td>158</td>
<td>179</td>
<td>180</td>
</tr>
</tbody>
</table>

![Figure 12: Comparison of all parameters of the unidirectional CBs. The numbers for the CBN are one fourth of a CBN for a node with 4 lines.](image-url)
4 Conclusions

In the paper it is shown, that the use of unidirectional CB with a lower number of components compared to their bidirectional counterparts allows to isolate faults without increasing the isolated part of the grid, since two unidirectional CB at each end of a line enable fault clearing. For a fault in the node, where the distant CB has to turn off the fault current, the maximum current and energy to handle are lower than in other fault scenarios, since the line inductance and resistance limit the fault current increase. Therefore the worst case for the unidirectional CB is not changed compared to bidirectional designs. Since the unidirectional CB in the off-state is still able to conduct a current in opposite direction, a residual current breaker (RCB) is needed to disconnect a line completely. However, most bidirectional topologies need also RCBs since the varistors after current breaking still conduct a small current. The use of unidirectional CB with a lower number of components in HVDC grids is therefore possible without disadvantages such as higher fault currents and energies, and should therefore be considered as alternative to bidirectional CBs. Furthermore, a CB for a node with 4 lines has been investigated and it was shown that these need less components than 4 CB for a single line reducing the overall cost of a HVDC grid.

References