Grid topology and technology influences on selective protection concepts for multi-terminal medium voltage DC grids

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Abstract: The integration of distributed renewable energy resources in combination with advancements in power electronics make the application of multi-terminal medium voltage DC grids a promising and flexible solution. Fast and selective protection concepts in combination with DC (disconnecting) switches for fault handling are required to ensure high reliability and safe grid operation of these systems. Medium voltage DC grids may be realised based on several converter technologies with different fault clearing capability. Depending on the converter technology, switches for isolating faulted branches or DC circuit breakers (CBs) for fault clearance become necessary. DC medium voltage CB concepts have already been proposed. However, the switching times of these CBs vary significantly depending on the presence or absence of mechanical components resulting in different requirements for fault detection. This contribution evaluates the relations between different converter and DC CB technologies, DC grid topologies and fault detection methods according to selective fault clearing. Transient simulation studies are carried out for the development of protection concepts. Based on the results, reasonable technological combinations of the above-mentioned technologies are identified. Special consideration is given to the dimensioning of series reactors as fault current rise limiting devices.

1 Introduction

The energy transition to a renewable and sustainable power supply results in the integration of high shares of volatile generation, mostly in low and medium voltage networks. Key enabling technologies for medium voltage DC (MVDC) distribution networks are cross-linked polyethylene (XLPE) cables for DC applications and advancements in power electronics [1]. Collecting grids for renewable energy resources, e.g. at off-shore wind farms, industry facilities with high amounts of inverter-fed drives or automation of buildings are possible fields of application for MVDC networks. MVDC represents a promising solution to connect renewable energy resources, mostly wind and photovoltaic, with energy storage systems and heat pumps running at variable frequency [1, 2]. Finally, MVDC networks represent a possibility to couple distribution networks of different grid operators even over country borders, reducing vertical power flows in the electrical supply system.

On the one hand, multi-terminal MVDC networks allow low-loss transmission and enable flexible power flow control [2]. Furthermore, the price regression of power electronics faces the steadily increasing price of transformers due to growing costs for copper [1]. On the other hand, the most lossy and bulky grid-side converters of renewable energy resources together with line filters in order to fulfill the grid code requirements for sinusoidal voltages become obsolete [2, 3].

Since the continued operation of MVDC systems and a local limitation of the fault event are essential for the realisation of these systems, a fast fault clearing is necessary. The development of protection concepts in coordination with the hardware technology is one major challenge, which has to be overcome. The converter technology determines the fault clearing process and hence the requirements for switching devices. Converters with fault current controllability, like the dual active bridge (DAB) or modular multilevel converters (MMC) with sub-modules in full-bridge topology are capable of active fault current control and only need transfer switches with low current interrupting capability to isolate faulted branches. Instead, MMCs with half-bridge submodules (SMs) need CBs for fault clearing. Several DC CB concepts are presented for medium voltage application [4]. The usage of mechanical CBs causes longer switching times compared to solid-state switches or breakers. Thus, the way of fault detection is impacted. Additionally, the grid topology affects the fault detection process with regard to selective fault clearing.

Within this investigation, selective protection concepts for multi-terminal MVDC grids are developed taking into account the fault clearing capability of both types of converter topologies. Since the realisation possibilities for multi-terminal MVDC grids are still unknown, influencing parameters are identified. At first, an overview of MVDC technology is given introducing possibilities for grid design, converter technologies and DC CB concepts. After presenting the modelling approach, the protection concepts are introduced and a comparison between both converter technologies is presented.

2 Realisation options for MVDC distribution networks

Multi-terminal MVDC distribution networks are the subject of current research. Since no standardisation regarding topology and technology is available at present, this section provides feasible realisation options.

Distribution networks are typically realised as radial or ring topologies, as mixtures of aforementioned or as meshed grids, usually based on cable technology. AC distribution networks are typically interrupted by transfer switches into radial feeders in order to limit short-circuit currents (open ring bus concept in the load centre with transfer switches) [5]. In case of short circuits, the separation point is shifted to the faulted branch. Consequently, AC cables are often oversized in order to resume the power transfer after shifting the separation point during fault clearance ensuring (n-1) security [1]. MVDC distribution networks with fast fault clearing overcome these disadvantages and allow meshed structures with a higher cable utilisation.

MMC technology represents the state of the art for multi-terminal HVDC application, but is also applicable in medium voltage distribution grids [6]. MMCs provide flexible control possibilities of AC quantities like fine waveforms reproduction without additional filtering and are capable of fault current control
In total, three hybrid concepts [snubbed mechanical CB (SMCB), conventional hybrid CB and hybrid HVDC CB], the active current injection CB and two solid-state devices (solid-state DC CB (SSCB) and Z-source CB) are analysed in [4]. Each CB concept is evaluated concerning technical behaviour, reliability, acquisition costs and operating expenses, mainly due to losses. The evaluation of the different criteria is summarised in Fig. 1. The smaller the area within this diagram, the better the overall performance of the specific CB.

The evaluation identifies the solid-state CB concepts as the MVDC CB concept with the best technical performance. Next to a good reliability, the fast switching capabilities result in a fast turn off time and low current amplitudes. However, the solid-state DC CBs have high losses, making the conventional hybrid CB and the SMCB promising concepts with a good overall performance [4]. Nevertheless, the switching times of these CBs vary significantly due to the presence or absence of mechanical components, resulting in different requirements for fault detection. Hence, CB technology, network parameters and the protection concept have to be treated as a coupled optimisation problem [7].

3 Modelling approach

This section describes the modelling approach for the transient simulation studies conducted in PSCAD™|EMTDC™ in order to develop protection concepts.

3.1 Grid design

The simulations are carried out for a multi-terminal ring distribution grid with four converter stations as indicated in Fig. 2. Each line of the test system has a length of l = 10 km. The lines are modelled using the frequency-dependent Universal Line Model, whereby the parametrisation is adjusted according to $V_f = 12\, \text{kV}$ XLPE medium voltage cables with a cross-sectional area of $A = 70\, \text{mm}^2$ to allow rated currents of $I_r = 271\, \text{A}$ for each conductor [8, 9]. The cables are connected to a bus bar with DC switches and additional series reactors, which are parametrised according to the protection concept to limit the impact of fault events. The results can therefore be transferred to any other grid topology. All surge arrestors are rated to $V_{IS(2)} = 1.25\, V_{DC}$. Each cable is divided into two parts to consider pole-to-ground faults at the end and in the centre. Faults are modelled as permanent with a fault resistance of $R_{f,a} = 0.5\, \Omega$. High ohmic faults are analysed as validation of the protection concept.

3.2 Converter technology

MMCs with full- and half-bridge SMs are used for the simulations. Since the DAB is also capable of fault clearance, the proposed protection concept for MMCs with full-bridge SMs is applicable for DAB converters as well.

MMC consists of six phase arms with a series connection of several SMs, an arm resistor $R_{arm}$ and an arm inductor $L_{arm}$ according to Fig. 3a. Each SM consists of two respective four insulated-gate bipolar transistors (IGBTs) with antiparallel diodes and a capacitor, which can be inserted into the arm or bypassed. This allows voltage control in fine voltage steps. In case of DC-side faults, the control is changed into a protection mode. All IGBTs of half-bridge SMs are blocked and the diodes conduct current similar to a B6 diode rectifier. The advantage of full-bridge SMs (c.f. Fig. 3c) is the possibility to switch in the capacitor with negative voltage to apply a counter voltage and force the fault current to zero [4].

All converter stations contain two MMCs forming a bipolar HVDC system with positive (P) and negative (N) pole and a dedicated metallic return conductor, which is grounded at converter station C 1. During steady-state operation, C 4 is in DC voltage control mode while the other stations control the DC power. Converters C 2 and C 4 are in inverter mode while C 1 and C 3 are in rectifier mode operating at nominal power. The power flow scenarios are altered in order to validate the protection concept. Table 1 gives an overview of the converter station ratings.
3.4 Fault detection

The fault current gradients in MVDC networks are extremely high since the fault propagates fast due to short line lengths. Lower grid impedances, e.g. due to the lack of transformers, result in higher fault current amplitudes compared to AC systems. Together with the limited current capability of power electronics, fault detection and clearing has to be performed within a few milliseconds to avoid impermissible fault current amplitudes [13]. Additional series reactors at line ends (c.f. L_{\text{Grid}} in Fig. 2) delay the fault current rise and influence the resulting voltage shape increasing the chances of selective fault detection [14].

During a fault situation, the voltage at the fault location \( V_{\text{Fault}} \) drops down close to zero. The current increase \( \Delta i \) within the timespan \( \Delta t \) depends on the voltage drop over the series reactor \( L_{\text{Grid}} \) and can be estimated to

\[
\Delta i = \frac{V_{\text{DC}} - V_{\text{Fault}}}{L_{\text{grid}}}
\]

with the voltage at the fault location \( V_{\text{Fault}} \). Specifying an maximum rated switching current for both CB concept of \( I_{\text{CB,max}} = 1.6 \text{ p.u.} \) (400 A) during the SMCB, respectively \( t_{\text{SSCB}} \), necessary inductances can be determined according to Fig. 5.

The additional inductances of the converter stations and the cables enable a significant reduction of \( L_{\text{Grid}} \) in contrast to (1). Transient fault simulations for the exemplary grid structure are carried out to determine the necessary inductance. In case of SMCBs, \( L_{\text{Grid}} = 74 \text{ mH} \) is used whereas \( L_{\text{Grid}} = 5 \text{ mH} \) is necessary in case of SSCBs.

Faults produce travelling waves on the line, which are reflected at line ends due to the change in the surge impedance. In order to ensure a reliable, fast and selective system protection, the detection decision has to be made based on the first travelling wave arriving at the line ends. Consequently, travelling wave based fault detection is used utilising both voltage and current gradients according to the following equation [13]:

\[
d\frac{V}{dt} \cdot \frac{dI}{dt} \leq -\epsilon_{\text{ef}}
\]

The product of current and voltage gradients becomes negative due to the voltage drop if the fault is within the related protection zone. For faults outside of the related protection zone, the product becomes positive in case of decreasing current due to current commutation into the faulted branch, increasing the possibility for selective fault detection [13].

### 4 Parametrisation and evaluation of protection concepts

In the following, protection concepts for both types of converter technology are developed and a comparison of the concepts is given.

4.1 Without fault current controllability

The protection concept utilises DC CB and the detection criteria presented in Section 3.4. For determining detection thresholds, ideal fault detection based on travelling wave runtime is used. The CB's switching delay enables the analysis of the first incoming travelling waves without any interference with the switching action. All fault locations are analysed for the presented power flow scenario in Section 3.2 with power flow from converter stations 1 and 4 to stations 2 and 3. Faults are simulated between the P-pole and ground as a low-ohmic short circuit with \( R_{\text{Fault}} = 0.5 \Omega \). The thresholds for fault detection are identified for both SSCB and SMCB independently.

The products of current and voltage gradients for all fault locations are depicted in Fig. 6 for the SMCB, distinguishing between faults inside and outside of the related protection zone. Based on these results, a detection threshold is determined as the

<table>
<thead>
<tr>
<th>Converter station ratings</th>
<th>Rating</th>
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<tbody>
<tr>
<td>rated power ( S_r )</td>
<td>5 MVA</td>
</tr>
<tr>
<td>rated DC pole voltage ( V_{\text{DC,r}} )</td>
<td>± 10 kV</td>
</tr>
<tr>
<td>rated DC current ( I_{\text{DC,r}} )</td>
<td>250 A = 1 p.u.</td>
</tr>
<tr>
<td>rated AC voltage ( V_{\text{AC,r}} )</td>
<td>10 kV RMS</td>
</tr>
<tr>
<td>number of SMs per arm ( n_{\text{SM}} )</td>
<td>30</td>
</tr>
<tr>
<td>rated SM voltage ( V_{\text{SM,r}} )</td>
<td>400 V</td>
</tr>
<tr>
<td>arm inductance ( L_{\text{arm}} )</td>
<td>42.4 mH</td>
</tr>
<tr>
<td>arm resistance ( R_{\text{arm}} )</td>
<td>100 mΩ</td>
</tr>
<tr>
<td>SM capacitor ( C )</td>
<td>4.5 mF</td>
</tr>
<tr>
<td>DC-side output inductance ( L_{\text{DC}} )</td>
<td>1 mH</td>
</tr>
</tbody>
</table>

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<tr>
<th>Table 1 Converter station ratings</th>
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<tr>
<td>Parameter</td>
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<tr>
<td>rated power ( S_r )</td>
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<td>rated AC voltage ( V_{\text{AC,r}} )</td>
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<tr>
<td>number of SMs per arm ( n_{\text{SM}} )</td>
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<tr>
<td>rated SM voltage ( V_{\text{SM,r}} )</td>
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<tr>
<td>arm inductance ( L_{\text{arm}} )</td>
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<td>DC-side output inductance ( L_{\text{DC}} )</td>
</tr>
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</table>

![Fig. 4 Bidirectional MVDC CB](image)

(a) Snubbed mechanical breaker SMCB, (b) Solid-state DC CB SSCB

![Fig. 5 Determination of the inductance \( L_{\text{Grid}} \)](image)

The simulation step size is set to \( \Delta t = 10 \mu s \) in accordance with the recommended sample rate of measurement technology for instrument transformers [10].

3.3 DC circuit breaker

Based on the evaluation of MVDC CB concepts, the SMCB and the SSCB are analysed. A topology of these concepts is shown in Fig. 4 according to [11].

After opening the SMCB's mechanical CB the current has to commutate into the parallel branch consisting of two antiparallel thyristors and a capacitor \( C_{\text{Snubber}} \) (c.f. Fig. 4a). The voltage limiting capacitor enables the arc extinction in the mechanical CB. In the following, the thyristors are turned off to suppress the resonant circuit between the capacitor and the line inductance [4, 11]. The snubber capacitor is parametrised with respect to the grid impedance and is set to \( C_{\text{Snubber}} = 3875 \mu F \) for this investigation [11]. Time delay of \( t_{\text{MechCB}} = 2 \text{ ms} \) for the mechanical switch according to [12], \( t_{\text{Thyristor}} = 10 \mu s \) for the thyristor turn off and additionally \( t_{\text{Signal,Processing}} = 25 \mu s \) for signal processing according to [10] are considered, resulting in a total switching delay time for the SMCB of \( t_{\text{SMCB}} = 2.035 \mu s \).

The SSCB uses active power semiconductors for current interruption resulting in a total switching delay time of \( t_{\text{SSCB}} = 125 \mu s \). Low-loss gate commutated thyristors are used in order to reduce the losses in the main current path [11].

Since fault clearing for bus bar faults results in an isolation of the entire node and consequently adjacent feeding lines (even in case of bidirectional CB the node becomes isolated), unidirectional CB are used for fault clearing. Bidirectional CB are only necessary at converter station terminals for clearing of internal converter faults.
near converter station C 4 represent worst-case fault scenarios concerning fast rising fault currents and the necessity of fast fault detection due to the voltage control mode of C 4. For the reference power flow, fault location F 6 represents the worst-case scenario, which is depicted in Fig. 8.

The fault is detected \( t = 40 \, \mu s \) and \( t = 120 \, \mu s \) after fault occurrence at CB 42 and CB 24, respectively, for both types of CB. The current interruption of both CB starts before exceeding \( I_{\text{UL}, \text{max}} = 400 \, A \), forcing the current into the surge arrestor. Even in case of higher utilisation of the line, the CB’s maximum switching current is not exceeded.

The determination of gradients requests high technical demands on the measurement technology. For increasing the accuracy and minimising interferences, a low-pass filtering might become necessary. To identify this influence, the signals are filtered with a third-order low-pass filter with Butterworth characteristic. Fig. 9 shows the resulting detection thresholds for limit frequencies of \( f_{\text{Limit}} = 10 \, kHz \) and \( f_{\text{Limit}} = 5 \, kHz \).

Low-pass filtering reduces the detection thresholds but still allows selective fault detection and subsequent clearing for limit frequencies down to \( f_{\text{Limit}} = 5 \, kHz \). Additional requirements from the measurement technology, e.g. greater delay times than \( t_{\text{signal}} = 25 \, \mu s \) influence the fault current rise and have to be considered for the determination of the series reactors \( L_{\text{Grid}} \).

4.2 Fault current controllability

Full-bridge-based MMCs are able to limit and control fault currents after their detection by adjusting the converter’s DC voltage \( V_{\text{DC}} \) in order to control the current \( i_{\text{DC}} \) close to zero [15]

\[
V_{\text{DC}} = V_{F} + R_{L} \cdot i_{\text{DC}} + (L_{G} + L_{\text{Grid}}) \frac{d}{dt} i_{\text{DC}} \tag{3}
\]

where \( V_{F} \) is the voltage at the fault location, \( L_{\text{Grid}} \) is the grid reactance, \( R_{L} \) is the line resistance and \( L_{G} \) is the reactance. Fig. 10 shows the simplified control loop. The residual current depends on the amount of SMs and the measurement accuracy. Consequently, DC switches become necessary to interrupt the residual currents, superseding DC CB. The requirements on DC switches have to be specified in further research. The protection concept for converter technology with converters providing fault current controllability comprises the following steps:

1. Unselective fault detection and controlling the current close to zero at all converter stations.
2. Isolation of the faulted branch.
3. Voltage recovery and resumption of power transfer.

The fault current control should react as fast as possible in order to ensure a high availability of the grid since the whole power transfer stops during fault clearance. The control constants are a tradeoff between fast fault clearance and control deviation as residual current amplitude as the required current demodulation rating of the DC switches. In order to limit the current rise and avoid blocking of the converter station semiconductors \( L_{\text{Grid}} = 5 \, mH \) is used.

Fig. 11 shows the line currents at each line end for the exemplary fault scenario F 6 as a worst-case scenario concerning fault current rise. Undervoltage detection is used for unselective fault detection at the converter stations. After fault detection, the converters control their output currents close to zero. Assuming a tolerance band of \( \Delta = \pm 5\% \) of rated current (\( \pm 12.5 \, A \)) as a criteria for successful fault current control, the fault can be interrupted after \( t_{\text{clearance}} = 5.56 \, ms \). All investigated fault scenarios can be interrupted after \( t_{\text{clearance}} = 8.16 \, ms \). The starting time of the voltage recovery and subsequent resumption of power transfer depends on the specifications of the DC switch.

Selective fault detection for the residual DC switch of the faulted branch can be realised with the proposed detection criteria based on voltage and current gradients. The series reactors \( L_{\text{Grid}} \) average between the minimum value for all fault scenarios outside the related protection zone (tripping prohibited for selective fault clearance) and the maximum value for faults inside the protection zone (tripping necessary; cf. related curves in Fig. 6). The curves responsible for the determination of the detection thresholds are highlighted as dotted bold lines. The second increase of the product shortly after \( t = 2 \, ms \) is caused by impacts due to switching operations. The detection criterion is robust against these interferences and prevents unselective triggering.

The multiplication of the gradients yields to significantly smaller values for faults outside of the protection zone. The series reactors \( L_{\text{Grid}} \) decouple the faulted branch and result in low current gradients. Hence, the detection principle provides a high robustness for ensuring selectivity.

The detection thresholds are identified analogously for the SSCB and are presented in Fig. 7. The smaller series reactors \( L_{\text{Grid}} \) result in higher voltage and current gradients and consequently higher thresholds for fault detection. However, the detection criteria is still able to distinguish between faults inside and outside of each protection zone and provides even higher robustness compared to the results for the SMCB.

The relays of each CB are parametrised uniformly in accordance to the determined thresholds. Subsequently, all fault scenarios result in a selective fault detection, even under variation of different power flow scenarios. The simulations show that faults...
decouple the converters from the faulted branch leaving the first incoming travelling wave unaffected from the fault current control. Thus, the detection criterion is applicable for selective fault detection in case of converters providing fault current controllability, too.

Fig. 12 shows the detection limits under consideration of low-pass filtering. Analogously to the results for the converter technology without fault current controllability, low-pass filtering up to $f_{\text{limit}} \leq 5$ kHz does not affect the detection.

4.3 Comparison and discussion of protection concepts

Selective fault detection is achieved with both hybrid and solid-state CB concepts, which differ significantly in their switching times. Series reactors are necessary to limit the fault current rise and enable fault currents on an interruptible level. These reactors represent an effective possibility to limit the effects on the faulted line and thus utilise the protection concepts to other grid topologies.

The SMCB needs inductances exceeding $L_{\text{Grid}} \geq 74$ mH at each line end to allow selective fault clearance, making the SMCB unsuitable for MVDC distribution networks. The conduction losses of the SSCB's power semiconductors have to be compared to the losses of the series reactors in case of SMCB. However, significant increase of the SMCB's rated switching current or an open grid approach (open of all CB and selective reclosing [16]) represent possibilities to overcome the disadvantages.

For converter technologies with fault current controllability, the control capabilities are used for fault clearance. The profit due to the lack of DC CB causes higher costs for DC switches and additional semiconductors in the SMs. The fault clearance is comparable to SSCB. Assuming mechanical breaker as disconnectors comparable to the SMCB's mechanical breaker, fault clearance is possible within $t \approx 10$ ms. During fault clearance, the complete pole is shut down until the DC switches isolate the faulted line. However, fault clearing is still faster compared to conventional MVAC distribution grids equipped with vacuum CBs. The application of semiconductors for fault clearance is most suited for the realisation of future MVDC distribution grids.

5 Conclusion and outlook

Selective protection concepts are investigated for multi-terminal MVDC distribution grids and validated during transient simulation studies. Special attention is given to the fault current controllability of the converter technology exemplified by the MMC. For converters without fault current controllability, pure solid-state and hybrid CB are utilised for fault clearance. The current rise is limited with series reactors. High inductances in case of hybrid CB concepts due to the switching time of the mechanical breaker represent disadvantages preferring power semiconductors for current interruption. Additionally, a protection concept for converters with fault current controllability is provided based on fault current control and DC switches for isolating the faulted branch. Specifications for residual current breaker have to be determined in order to optimise the protection concept in future work.

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7 References


