MVDC distribution grids and potential applications: Future trends and protection challenges

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Abstract
This paper presents the fundamental system components of medium-voltage direct current (MVDC) grids, including an overview of power electronic converters and protection schemes against DC fault currents. In addition to this, the lack of standardization and the development of efficient and reliable circuit breakers (CBs), which are today considered as showstoppers, are also analyzed in detail. The performances of three DC CBs, namely mechanical breaker with active current injection, solid state CB and hybrid CB are evaluated in terms of clearance times, fault peak current, residual energy dissipation and power losses using simulations. Last but not least, an overview of potential onshore and offshore future applications of MVDC grids is also presented by identifying targeted voltage and power ratings.

Introduction
Today, even though electric power is transmitted using either high-voltage Alternating Current (AC) or high-voltage Direct Current (DC) systems [1], [2], it is only medium-voltage (MV) AC grids utilized for electricity distribution. The main reason to this is the easiness in voltage conversions at various levels between transmission and distribution AC power grids due to the development of highly efficient and reliable transformers [3], [4]. However, during the last 5 decades, the evolution of high-voltage and high-current power semiconductor devices pave the way to design sophisticated high-power electronic converters suitable to perform DC voltage conversions at considerably high efficiencies [2]. As a result, not only DC transmission, but also DC distribution grids are today considered as more feasible and with lower cost compared to previous decades [5], [6]. In addition to these, the liberalization of the energy market leads to the need for MVDC technology development [2], [6], despite the fact that today, this faces several barriers. However, another significant aspect to consider is that an MVDC grid is mostly an innovative infrastructure aiming to several potential applications and it is not a simple downscaling of voltage level compared to HVDC counterparts [2]. The realization of MVDC grids will facilitate the use of a lower number of required energy conversion stages both on the supply and load sides [2], [7]. Thus, distribution of electricity will be performed at not only higher efficiencies but also with higher control flexibility.

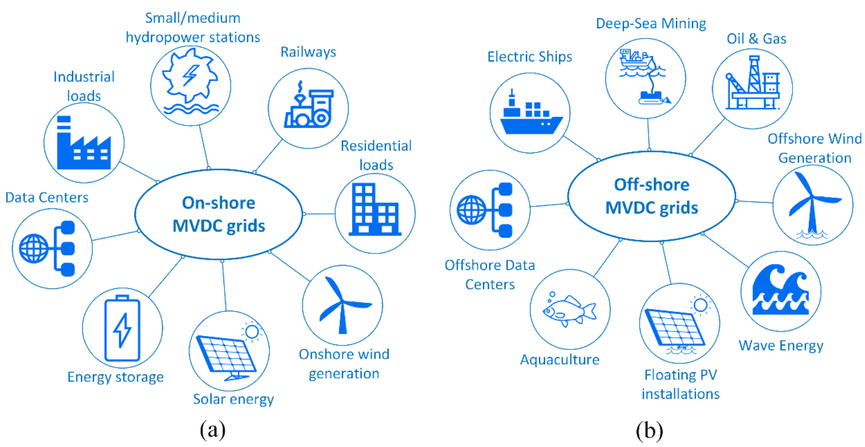

Fig. 1: Potential (a) onshore and (b) off-shore applications of MVDC grids.

The key advantage of DC power systems compared to AC counterparts is the higher efficiency of power transmission and distribution under the same voltage levels [3], [7], [8]. Apart from that, frequency synchronization is not required , and there is no need for reactive power compensation [5]. A DC grid can be found ideal to interface multiple energy sources (e.g. renewable energy sources, batteries, fuel cells) operating under various voltage and frequency conditions [5],[5], [9]. On the other hand, the drawbacks of DC grids are the higher investment and installation costs of power converters compared to corresponding costs of low frequency transformers [10] and the more sophisticated protection schemes required against short-circuit currents [3].

In literature, several potential applications of MVDC grids have been identified. These can be categorized in onshore and offshore applications as illustrated in Figs. 1(a) and 1(b), respectively. Regardless of operating as distribution systems either onshore or offshore, the design of MVDC grids requires several vital components. These are power electronic converters, such as passive and active rectifiers, DC/DC converters and DC/AC inverters, protection schemes and implementations of various control strategies that have to operate efficiently, reliably and at a considerably low cost.

Currently, a showstopper for the further development and establishment of MVDC grids is the lack of specific standardization related to their operation, performance and safety [11]. In addition to these, rules for safety, required stress tests on DC equipment (e.g. cables), and permissible voltage tolerances must be investigated by the competent authorities as shown in [2]. Besides this, a crucial challenge that detains the further expansion of MVDC grids is the development of efficient and highly performant DC CBs [3], [4].

The purpose of this paper is to present and analyze the MVDC grid crucial components, applications and expected showstoppers. In Section II, the standardization requirements for MVDC grids are discussed. Section III presents the potentially future MVDC applications, while the performance of suitable power electronic converters with respect to inherent protection capability used in a MVDC grid is analyzed in Section IV. Sections V and VI show the modeling and performance evaluation of various CB concepts proposed for MVDC grids. Finally, Section VII describes the potential challenges that will arise on the required protection schemes implemented on MVDC grids.

Standardization of MVDC grids

In order to accept the MVDC grids as an established concept for electricity distribution, it is important to define regulations and standards related to their characteristics, operation and performance [2]. In this line of thinking, several aspects must be considered. Firstly, a legislative framework for the distinction between low, medium and high voltage levels is required. Presently, the established regulations for MVDC grids, concern mostly applications of MVDC systems in railways and ships. The majority of standards governing DC power systems has mainly been defined by IEC and IEEE and is presented below.

1) A framework regarding electrification of electric ships using MVDC have been set by IEEE [5]. The purpose of this is "*to recommend a methodology for analysis and specifications parameters for 1 kV to 35 kV MVDC power systems on ships*". Moreover, the preferred interconnection interfaces and performance characteristics for reliable integration of all electrical components involved in the on-board MVDC grid are described. Lastly, among others, this framework defines recommended voltage levels at 1.5 kV, 3 kV, 6 kV, 12 kV, 18 kV, 24 kV, or 30 kV. In addition to this, the DC voltage tolerance limits should be ± 10% of the rated DC voltage. Finally, the proposed rated withstand overvoltages (short duration) for various MVDC components, except of power electronics, are given along with safety, quality of power, galvanic isolation and grounding standards that have to be met.
2) Standards and regulations for DC (3200 V and below) Power Circuit Breakers Used in Enclosures are given in [12]. This framework covers preferred ratings and testing requirements of enclosed DC power circuit breakers operating at maximum voltages of up to 3200 V, and aspects such temperature, humidity, altitude, size, test procedures etc. are also defined.
3) A guide for planning DC links terminating at AC locations is divided into two parts and it is presented in IEEE Std 1204-1997. Part I presents the effects of various aspects of the AC/DC

interactions, while in Part II, the planning and the preliminary design of these interactions are discussed in details.

4) Standards for interconnecting distributed resources with electric power systems [13] have been established also by IEEE. They contain regulations regarding the performance, operation, testing, safety, and maintenance of the interconnection of distributed resources with the main grid.
5) Standards for Railway applications–supply voltages of traction systems have been set by IEC, namely IEC 60850. This framework dictates the characteristics of the supply voltages to traction systems, including auxiliary devices. It is mentioned that this content is applicable for railways, mass transport systems, tramways, light trains, trolleybus, low speed maglev trains and it excludes mine traction systems in underground mines, cranes, suspended cable cars and funicular railways. Along with this framework, IEC has also established more specific standards for railway applications, which are related more to protection aspects. These are summarized in IEC 61992:2006.
6) Standards for short-circuit current in DC auxiliary installations in power plants and substations divided into three parts are presented in the IEC 61660. In IEC 61660-1, the calculation of short-circuit currents in DC grids is analyzed, IEC 61660-2 describes the impact of the short-circuit current on the equipment (i.e. capacitors, rectifiers, motors, batteries), and finally, the last part, IEC 61660-3 which is a technical report, illustrates some additional considerations for the aforementioned calculation via a correction factor σ_j .
7) Framework for power installation exceeding 1.5 kV DC is set by IEC and it is presented in IEC TS 61936-2. The content on this framework includes common rules for the design and the erection of electrical power installations in systems with nominal voltages above 1.5 kV DC, to provide safety and proper functioning for the targeted application.

The standards described above concern general DC grids and systems. This means that they might not apply to MVDC systems. For HVDC and LVDC, IEC and mostly IEEE, have established several standards and regulations. This is beyond the scope of this study and, therefore, they will not be treated. Last but not least, general standards related to power electronics including modeling and simulation recommendations for equipment level analysis at power quality, transients, thermal management and power balance are presented in IEEE Std 1662-2016. The main purpose of this framework is to analyze the impact of power electronics on size, life cycle cost, weight, fuel efficiency and risk mitigations. Even if in this framework, there is no direct connection to MVDC grids, one should consider this practice when has to design a MVDC system because of the wide spread of power electronics which are vital components of every type of electrical power system.
Besides the aforementioned standards, which have already been established for the existing DC grids, it is obvious that specific standardization and regulations for every design and operating aspect of MVDC grids, regardless of their voltage level, application area, power and operating conditions is missing. Thus, it is very crucial to create a specific framework for the design and operation of MVDC grids that will facilitate the expansion of these grids in a variety of applications.

Potential applications of MVDC grids

At present, MVDC grids are still at an early stage of their development. However, the first commercially available MVDC converter solution [14] constitutes the cornerstone that will enable more MVDC grid solutions penetrating into the market. As already mentioned, MVDC grids are found beneficial in a variety of onshore and offshore applications. Figs. 2(a) and 2(b) illustrate the voltage and power ratings of reported MVDC applications with respect to published year. The listed applications are: (i) offshore wind power, (ii) marine vessels, (iii) microgrids with renewable energy sources (RES) integration, (iv) transportation, (v) subsea electrification, (vi) electricity supply to data centers and buildings, (vii) electrification of oil and gas rigs and (viii) others (i.e. DC homes, electrification of a university campus, mine site). One observation on this figure, is that there is a tendency for the voltage level to reach 40 kV, while the power ratings can be at least 100 kW.

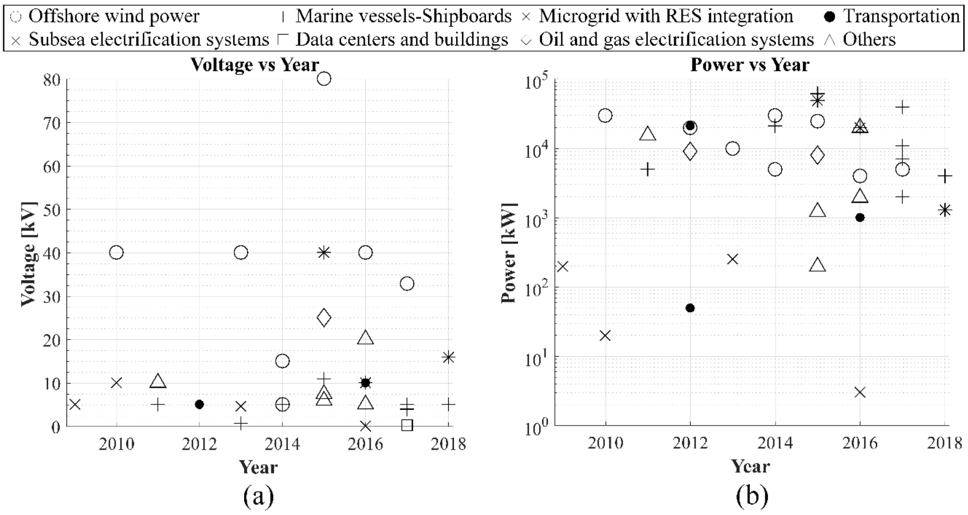

Fig. 2: A scatter diagram of reported MVDC applications, listed with respect to: a) voltage (kV) as a function of year and b) power as a function of year in logarithmic scale.

The MVDC concept seems to be the ideal solution for offshore wind power generation [2], [15]. In particular, collector grids operating with MVDC is proven to be more advantageous over AC counterparts, mostly in terms of efficiency [16].

Besides offshore wind power generation, the electric energy distribution on vessels using MVDC is also under consideration [5], [17]. The reasons for the transition from MVAC to MVDC on ships are basically the fuel efficiency, weight, footprint of the electric equipment and the power control flexibility of DC systems [18]. Specific aspects related to electricity distribution using MVDC grid in a shipboard have already been addressed and been presented in [5].

Another significant area that MVDC grids would show a beneficial performance is microgrids with integrated RES and battery energy storage systems (BESS) [19]. The main reason is the easier integration and more flexible power flow control enabled due to the common DC bus used.

Apart from the above, another potential application of MVDC grids is related to onshore transportation [9]. More specifically, MVDC realization in electrified railways will enable several performance improvements, fewer conversion stages and mostly higher efficiency compared to MVAC. In [9], a comparison is presented and it reveals that an urban railway rated at 10 MW and supplied with 10 kV DC exhibits better performance for high power (beyond 0.25 MW, with a maximum efficiency of 98.6%), while the AC system achieves higher efficiency for low power applications.

Electric energy distribution for subsea loads is also among the potential applications of MVDC grids. The higher efficiency and lower cost of subsea distribution (in terms of required cables) count as the the two advantages of using a DC system compared to AC [11]. A description of all the required components which compose a MVDC infrastructure for subsea power distribution is discussed in [20]. The power and voltage ratings were defined at 20 kW and 10 kV respectively, where the considered system exhibits an efficiency of 90%. Furthermore, a Modular Multilevel Converter (MMC) based MVDC subsea distribution system having a power rating of 250 kW at 4.6 kV DC is investigated in [21], having design constraints such as reduced number of active switches, lowering costs and increasing reliability. In addition to this, the electrification of a deep sea mining electrical equipment using MVDC is also of high interest as identified in [22].

During the last decade, due to the increasing demands of data processing and storage (i.e. big data), a significant number of data centers have been installed worldwide [23]. The majority of the loads in a data center is supplied with DC power. As a result, a DC power distribution system seems to be a better solution compared to AC counterparts in terms of efficiency and lower number of power conversion stages [24]. Data centers located at either remote places or subsea [25], will benefit from the future development of MVDC grids, which will be the ideal grid solution for high-efficiency power supply to data centers.

Another potential application of MVDC grids is identified in the electricity distribution on offshore oil and gas rigs, while MVDC has also been proposed as a potential interface of offshore wind power generation with oil and gas rigs [2].

Last but not least, there are few other potential applications where MVDC grids would be perfectly suited. These could be a "DC home" [26] (at 5 kV with 1.95 MW load), the electrification of an entire university campus [27] (at 10 kV with 15.5 MW load) and the power distribution on an onshore mine site [28] (at 6 kV with 1.2 MW load).

Power electronic converters for MVDC grids

DC/DC Converters. A crucial step towards the realization of MVDC grids is the development of efficient, reliable and simultaneously low-cost components. Two trends have contributed to this: the rapid technology improvements of power electronics [29] and the need for distributed generation (DG). The paradigm shift from AC distribution grids to DC counterparts is basically due to the development of high-power DC/DC converters having high voltage gains [30], which pave the way to replace low-frequency, bulky AC transformers. Nevertheless, a significant drawback of these power converters is the low efficiency when a high voltage ratio is required. Today, this challenge seems to be addressed not only due to the development of sophisticated power electronic converter topologies, but also due to the availability of advanced power semiconductor devices having high-voltage ratings and exhibiting low power losses. Several DC/DC power converters with high voltage gains have been demonstrated. Among these, the dual active bridge (DAB) topology seems to be a very promising concept, providing high efficiency and galvanic isolation when a high voltage ratio is required [31]. Besides this, configurations with multiple resonant converters in series and/or in parallel connection in order to achieve high current and high voltage could operate with high efficiency due to soft switching [32]. DC/DC converters based on switched-capacitor have also been identified as potential concepts that enable high-efficiency electrical energy conversion in MVDC grids [16].
DC/AC Converters. Apart from DC/DC converters, there is also need for performing AC/DC electric energy conversions. These AC/DC converters, namely Voltage Source Converters (VSCs), must be able to operate in a bidirectional power flow mode, and thus interfacing variable frequency energy sources and loads with the MVDC grid. The most significant AC/DC topologies in MVDC grids are categorized as: (i) two-level VSCs, (ii) three-level Neutral Point Clamped (NPC) VSCs and (iii) Modular Multilevel Converters (MMCs) [33], operating either using half bridge (HB) or in full bridge (FB) submodules. It is worth to mention that one may also find the thyristor-based line-commutated converters (LCCs), which have been a reliable and attractive solution in HVDC transmission grids. However, due to the limiting controllability of thyristors, the VSCs (mostly based on Insulated Gate Bipolar Transistors, IGBTs) seem to gain more attention towards the development of MVDC grids, since the current technology of power semiconductor devices enables higher blocking voltages by using IGBTs and IGCTs (Integrated Gate-Commutated Thyristors). Finally yet importantly, considering the aforementioned VSCs, it is only the FB-based MMC and the LCC that have an inherent ability to interrupt the current without the need of CBs. The FB-based MMC topology uses 4 IGBTs in full bridge configuration in each submodule and therefore, the voltage can be suppressed by these FBs (thus, full controllability is achieved, since there is no path for current to flow undesirably through freewheeling diodes). In the LCC topology, there are no antiparallel diodes connected that can prevent the converter to operate as a passive rectifier under a fault case.

MVDC Circuit Breakers topologies

Apart from the missing standards as analyzed above, another significant showstopper for establishing MVDC grids is the gap on specific protection schemes against short-circuits [34]. A crucial challenge, therefore, is the development of highly performant DC circuit breakers. The term "*highly performant CB*" refers to low conduction power losses during normal operation, fast clearance times of faults and minimization of design complexity (thus enhanced reliability) [34]. However, neither the well-established AC breakers that operate with very low conduction losses [35] nor the HVDC hybrid breakers meet the MVDC CBs requirements. In a DC grid there is no natural zero crossing of the fault current, and thus conventional mechanical AC breakers cannot clear the fault. This is due to the arc developed in mechanical AC CBs that can only be extinguished at zero current. Furthermore, in a DC line both the line inductance, which is significantly lower compared to the inductance of AC grids, and the absence of transformers, and thus no leakage inductance, result in high fault current derivatives. Therefore, the instantaneous fault current can reach high peak values and causes serious damages in the entire grid equipment. Lastly, in a MVDC grid the line/cable inductance is lower (and thus the rate *R/L* is higher) compared to the inductance in a corresponding HVDC grid due to the relatively shorter distances or/and the use of cables instead of lines. Thus higher peak fault current can be anticipated [36]. On top of that, the commercialized HVDC hybrid breakers currently use fault current limiters (i.e. additional inductor) in series with the CB, which leads to higher volume, weight and installation cost of the CB. Moreover, additional losses must be considered. However, in several MVDC applications, the aforementioned parameters (i.e. volume, weight) may be of high importance, resulting the HVDC hybrid CBs to be inappropriate solution for these applications.

A simplified explanation of these facts can be given by considering the circuit diagram shown in Fig. 3 and Equations 1 and 2. The purpose of this simplified explanation is to identify and to highlight the arising problem of short-circuit currents in DC grids. The parameters R_{s1}, R_{s2}, L_{s1} and L_{s2} are the line resistances and inductances prior and after the fault position, respectively. Therefore, when the short-circuit occurs, an RL circuit is created. The fault current will be $i_{(t)}=V_{DC}/R_{s1}(1-e^{-R_{s1}t/L_{s1}})$ and as a result, the importance of the line resistance and line inductance involved in a DC grid can be observed. A significant conclusion is that as the line inductance is kept low, the fault current will be high.

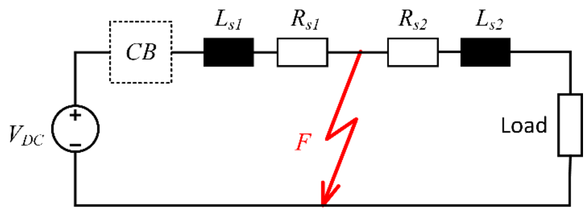

Fig. 3: Simplified schematic diagram of a DC grid.

Based on their circuit configuration, three types of MVDC CBs for fault current interruption have been presented in the literature. These are the mechanical CB with active current injection (or active resonance), solid-state and hybrid CBs, as illustrated in Fig. 4. The mechanical breakers with active current injection (Fig. 4(a)) have low on-state resistance, exhibit slow operation and they require maintenance due to inherently mechanical parts [34]. The operating principle is to create an artificial zero crossing point for the current that flows through the mechanical breaker by activating the LC resonance circuit via the series-connected active switch (e.g. thyristors). The capacitor must be pre-charged and hence, the generated oscillating current by the LC branch, i_{LC}, is added to the fault current when the active switch is turned on, creating the required zero current points, allowing the mechanical breaker to be able to extinguish the generated arc.
On the other hand, the solid-state CBs (Fig. 4(b)) achieve fast clearance times, require less maintenance compared to the mechanical breakers, but they have high conduction losses due to the power semiconductor devices connected in the main current path [34]. Either IGBTs or IGCTs can be employed as the semiconductor switches [37]. The operating principle of that CB type is to turn off the power devices when the fault is detected, and hence the current will be commutated through a turn-off snubber circuit, consisting of a resistor, a capacitor and a diode (RCD).

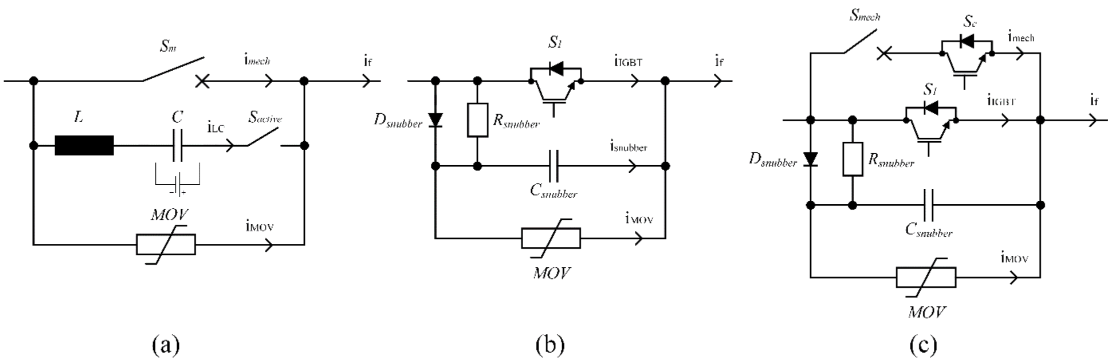

Fig. 4: Schematic diagrams of the basic types of DC CBs: (a) mechanical CB with active resonance, (b) solid-state CB and (c) hybrid CB.

Fig. 4(c) shows the hybrid CB which combines the characteristics of the mechanical and solid-state CBs and, hence, exhibits faster response times compared to mechanical CBs with active current injection and lower conduction losses compared to solid-state breakers [38]. By using this CB concept, the current flows through the mechanical branch in normal operation, and under a fault condition, the current is

commutated to the solid-state branch. The commutation is performed by means of an IGBT (i.e. S_c in Fig. 4(c)) connected in series with the mechanical breaker.
For each of these CB types, a variety of alternative implementations and circuitry has been proposed, but the main operating principles are the same as they were described above. Regardless of the specific CB type, a metal-oxide varistor (MOV) is connected in parallel to the CB in order to protect the equipment against over-voltages and to enable residual energy dissipation of the DC line.
An initial consideration against fault currents in MVDC grids was the use of conventional mechanical CBs on the AC side. However, the relatively long response times anticipated, might expose the power semiconductor devices of the voltage source converters to severe and probably permanent damages, unless they are overrated for these. On the contrary, the solid-state CBs seem to be favorable due to the inherently fast breaking capability, at a cost of higher conduction power losses. It is, therefore, clear that design trade-offs should be found when choosing the most appropriate CB concept suitable to operate with the lowest conduction losses and under the shortest response times. Along with these, the overvoltage across the CB must also be considered in order to avoid breakdown of the semiconductors. In terms of overvoltage and blocking voltage capabilities, series-connection of several single-chip devices and use of snubber circuits might be necessary to ensure a safe operation of the CB.

Simulations results of the comparative study

In this study, a simplified MVDC grid was adopted as illustrated in Fig. 3. The grid and modelling parameters are the line inductance prior and after the fault position, L_{s1}=1 mH and L_{s2}=1 mH, respectively. The DC voltage was set to 15 kV and the rated power of the load equals 22.5 MW, that corresponds to a nominal current of I_{nom}=1.5 kA. The short-circuit occurs at the time instant t_{sc}=100 msec. When the fault current exceeds 2 pu (i.e. 3 kA) the CB is triggered. The performance of the three CBs, (Fig. 4) has been evaluated in terms of the peak fault current, fault clearance time, residual energy dissipation and power losses under normal operation. The electrical performance of the three individual CB cases is presented as follows:

1. Mechanical CB with active current injection

The operating principle of this CB has been shown in the previous section. For the purpose of the performance comparison, the components of the *LC* tank have been set to *L*=4.29 μH and *C*=23.3 mF, so that the resonant frequency to be 500 Hz and the capacitor was pre-charged at 5 kV. These values were considered based on the required frequency and amplitude of the injected current in accordance to the circuit parameters [39] and the value of the fault current. The current generated from the LC tank opposes the fault current, forces it to cross zero and allows the mechanical breaker to open. If the current derivative is relatively high, the developed arc may be maintained at the first zero crossing point. Therefore, it is recommended to design this CB in such a way, so that the current crosses from zero point more than one time. Regarding the modelling of the mechanical switch and the developed arc, the Cassie arc model was used [40].
Fig. 5 illustrates the currents that flow in each branch of the CB, as well as the total fault current in the DC line. One important observation is that, the current that flows through the mechanical switch crosses zero twice until it becomes zero. Apart from that, the peak fault current that flows through the DC lines is approximately 50 kA, which can cause severe damages to the MVDC grid equipment, if it is not dimensioned properly. Lastly, the fault clearance time is approximately 15 msec.

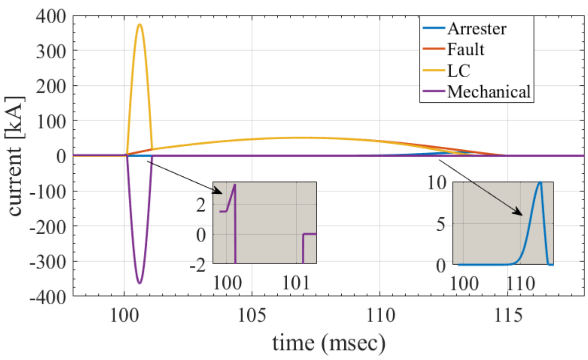

Fig. 5: Simulation results of various current contributions in mechanical CB with active current

2. Solid-state DC CB

The solid-state DC circuit breaker (Fig. 4(b)) consists of series-connected IGBTs to meet the transient voltage blocking requirements during turn-off process, a RCD snubber circuit and a MOV. Taking into account the design parameters of the investigated MVDC grid, 5 series-connected IGBTs are required. The ratings of the considered IGBTs are given in [41]. Fig. 6 shows the various currents that flow through the three branches of the solid-state CB and the total fault current. From this figure, it can be seen that the fault current commutates from the IGBTs branch to the snubber branch and finally to the arrester. The peak fault current is approximately equal to 3.2 kA, and the fault is cleared within 0.6 msec.

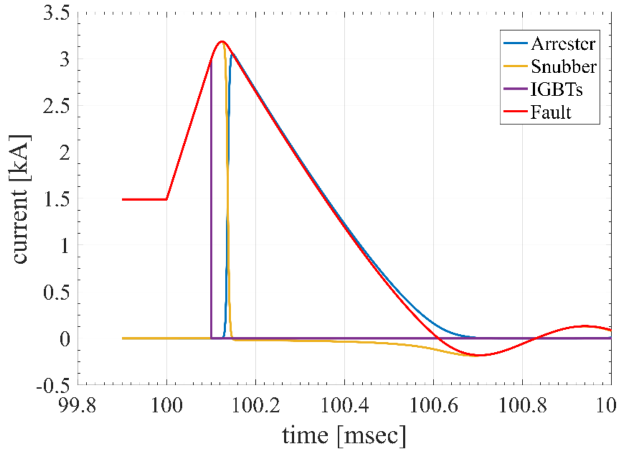

Fig. 6: Simulation results of various currents in solid-state DC CB.

3. Hybrid DC CB

The fault clearance procedure using the hybrid CB, which combines the characteristics of the two other breakers, is presented in Fig. 7. To ensure a fair comparison with the other two types of CBs, similar design parameters for the MVDC grid have been used. In Fig. 7, the current commutation from the mechanical switch to the series-connected IGBTs is forced due to the turn-off process of the commutation switch. As can be seen from this figure, the peak fault current reaches almost 20 kA while the fault is cleared within less than 3.5 msec.

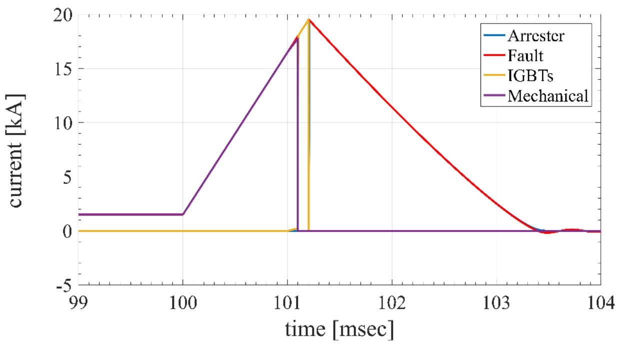

Fig. 7: Simulation results of various currents in hybrid DC CB.

Fig. 8(a) illustrates a comparison of the fault currents between the three types of CBs under investigation. A significantly longer clearing time for the fault current is observed for the mechanical CB with active resonance compared to the solid-state and hybrid counterparts. Therefore, a larger amount of residual energy and a more excessive stress for the power electronic converters employed in the grid are anticipated. This can also be seen by comparing the residual energy dissipation in each CB case (Table I): mechanical CB: 645 kJ, hybrid: 246 kJ and solid-state: 1.4 kJ. During the energy dissipation intervals, the CBs experience a transient overvoltage (Fig. 8(b)), which is governed by the choice of the MOV breakdown voltage (in this case V_{MOV}=16.5 kV). A higher breakdown voltage of the MOV, however, results in faster energy dissipation at a cost of higher overvoltage stress across the CBs.

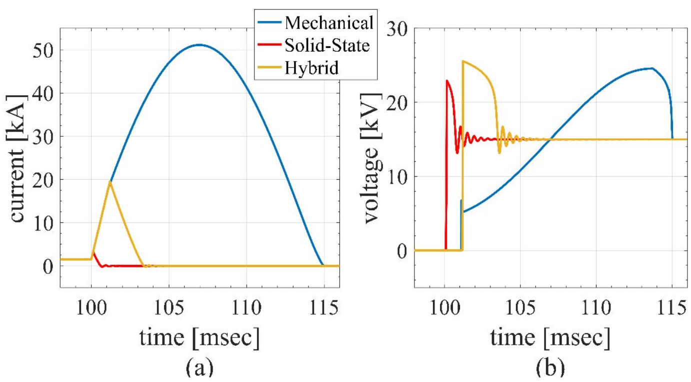

Fig. 8: Performance comparison using three types of CBs in terms of (a) fault current and (b) transient voltage across the

Last but not least, the power losses associated to each CB under nominal operation were calculated as shown in Table I: mechanical CB: 230 W, hybrid: 8.3 kW and solid-state: 30 kW. This result clearly highlights the main barrier of solid-state CB realization, that is the relatively high conduction losses.

Table I: Summary of the performance comparison of the CBs

CB type	Fault current [kA]	Clearance time [msec]	Residual Energy Dissipation [kJ]	Power losses (kW)
Mechanical	51.1	15	645	0.23
Solid-State	3.18	0.6	1.4	30
Hybrid	19.5	3.4	246	8.3

Future Protection Challenges in MVDC grids

From the analysis so far, it became clear that the protection against short-circuit currents in MVDC grids is very challenging and the need for developing high-performance CBs is more urgent than ever before. The high-performance of CBs can be quantified by itemizing the desired design and operating characteristics of CBs for MVDC grids. These are:

- Fast fault clearance, which is also associated with preventing power electronics equipment from facing severe damages.
- Low conduction power losses that will enable higher energy efficiencies in the grid.
- Over-voltage protection of the CB during the fault clearance procedure in order to avoid breakdown of semiconductors in the case of solid-state CBs or re-ignition of the arc when hybrid or mechanical CBs are used.
- Fast residual energy dissipation to completely de-energize the fault line and set the CB ready for reclosing operation.
- Development of specific standards that will govern the design and operation of CB for MVDC applications. At present, the lack of such standards detain the further establishment of MVDC grids.
- Reliability of CBs for MVDC grids is related to the repeatable performance of the breaker under various fault conditions (e.g. fault position), as well as under normal operation in the MVDC grid.

These challenges can also be seen from the perspective of each individual CB type that is analyzed in this paper.

Mechanical CB with active current injection. This DC CB concept exhibits the lowest conduction power losses among all three CBs under investigation. However, the fault clearance time is relatively long, while arc re-ignition might be caused if the rate of change of the current is high or the transient voltage across the mechanical switch is beyond safety limits. The design of the *LC* resonant tank is also very challenging. The tuning of the frequency and peak injected current from the resonant tank depends on the choice of the values for *L* and *C*, and it might be very sensitive. Thus, the fast and reliable fault clearance might be very challenging.

Solid-state CB. A pure solid-state DC CB operates with significantly higher conduction power losses compared to the mechanical counterpart. On the contrary, the clearance times are several orders of magnitude shorter. A great challenge faced in solid-state DC CBs is related to the series-connection of semiconductor switches in order to reach the blocking voltage requirements in the MVDC grid. This complicates the overall design of not only the power circuit layout, but also the design of gate drivers. Furthermore, overvoltage protection of the solid-state DC CB is achieved by means of connecting snubber circuits, which have to be accurately tuned for reliable operation. Silicon Carbide (SiC) semiconductors can initiate a new era in solid-state CB. This is mainly due to the wider energy bandgap of SiC that enables the design of single-chip switches having higher rated blocking voltages compared to Silicon counterparts. If this is seen from the design complexity point-of-view, a lower number of SiC switches might be required for the same DC line voltage compared to Silicon. This also softens the design complexity of gate drivers and snubber circuits.

Hybrid CB. Apart from the mechanical switch on the main current path, the hybrid CB concept also requires a current commutation switch connected in series with the mechanical switch. This not only contributes to higher conduction power losses, but also complicates the overall design of the breaker. The same challenge of series-connected semiconductor switches is also faced in the hybrid switch, while a rigorous snubber design is still required. Turn-off sequence of the series-connected switches can also be challenging if the transient voltage must be controlled and maintained within certain limits to avoid re-ignition of the arc.

Conclusion

Several challenges must be tackled before the transition from MVAC to MVDC grids. Among these challenges, the lack of standardization and the design of highly performant protection schemes for MVDC grids are listed. This paper presented the status of standardization for MVDC grids, as well as a review of potential future MVDC applications. In addition to this, an overview of suitable power electronic converters for MVDC grids and their DC fault handling capabilities was given. Last but not least, the operating principles of the most promising CB concepts enabling current interruption in MVDC grids were described, followed by a comparative performance study. In particular, a mechanical CB with active current injection, a solid-state CB and a hybrid CB were examined and compared with respect to their efficiency, clearing times and minimization of both fault current and residual energy dissipation. It was shown that the solid-state CB achieved the best performance in terms of clearance time and minimizing the short-circuit current, having on the other hand, the highest power losses under normal operation.

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