Modelling and Comparison of Common Functionalities of HVDC Circuit Breakers

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***Abstract*—The performance of AC circuit breakers (CBs) has been well analyzed and standardized, but current interruption with HVDC CBs is very different and therefore its functionalities will be different. Considering also that several fundamentally different HVDC CB technologies are emerging (IGBT-based hybrid, thyristor-based hybrid and mechanical), there is a need for a universal set of modelling requirements. This paper investigates a simulation test circuit set up and a set of PSCAD-simulated scenarios which reveal essential performance for most common HVDC CB technologies. Universal test circuit and tests will enable comparisons between technologies and set the ground for interoperability and standardization. Demonstration of low current interruption is required since it leads to longer interruption time for some DC CBs. Not all DC CBs are capable of interrupting reverse current, while others have different performance compared with positive current interruption. The study shows that various DC CBs respond differently under high current in circumstances where there is no trip signal from the protection system in which case its self-protection activates. DC CBs may respond differently with change in system parameters like different cable.**

***Index Terms*— DC power systems, HVDC transmission, HV Switchgear,**

I. Introduction

There is a growing interest in developing DC transmission grids because of numerous potential benefits like increased operating flexibility, better utilization of assets and increase in reliability, comparing with the existing 2-termianl HVDC [1]. The grid protection system including DC CB (Circuit Breakers) is one of the main technical challenges. In the last 10 years several manufacturers have demonstrated high-voltage DC CB prototypes [2]-[4]. DC CBs are substantially more complex than traditional AC CBs, and several fundamentally different technologies have emerged:

- Hybrid DC CB [2], using IGBT-based semiconductor valves for fast operation, which are bypassed by ultrafast disconnectors for reduced on-state losses.
- Hybrid DC CB [3] using thyristor-based valves,
- Mechanical DC CB with current injection method which have lowest losses [4].

There has been an attempt to identify common components and characteristics of DC CBs including some performance specifications in [5], but no modeling is addressed.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 691714.

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The simulation results reported by manufacturers differ significantly and it is difficult to understand advantages/limits of technologies or to make comparison between them.

The test circuits for DC CB have also been investigated recently [6][7]. Unlike with AC CBs, DC CB test circuits will be required to accommodate dissipation of large energy. The main focus in reported tests has been the demonstration of rated DC fault current interruption. It is not clear if DC CB test circuits proposed so far will be able to fully represent all the actual operating stresses. DC CB model-based demonstrations will play increasingly important roles.

The proposed protection methods for DC grids differ significantly in terms of operating speed, of (local or global) measurements used and of the need for repeated operations [8]-[10]. The type of protection will have impact on requirements, functionalities and stresses on DC CBs.

Test requirements for AC CBs have been well studied and standards have been developed [11]. The test requirements for DC CBs are emerging [7], and are expected to be different from AC switchgear. The main challenges include:

- HVDC CBs are based on several substantially different technologies.
- DC grid protection may involve new methods which place new operating regime and stresses on DC CBs.

It is likely that the DC CB manufacturers will be required to provide models for systems studies related to a particular project. The validation of these models, including new DC CB topologies, is best achieved with generalized circuits providing stresses as close as possible to those in service, based on test requirements independent of technology. Such "black box" requirements will help with future work on interoperability and standardization of DC CBs.

This study proposes generalized model/simulation studies and stresses which capture essential functionalities, enable development of performance specifications and comparisons. The analysis is not intended to replace system studies, which would be conducted at a later stage and should include more detailed DC grid and protection models.

This analysis is centered on available technologies, and it is not intended to list performance requirements for DC CBs.

A number of current interruption scenarios have been modelled for each of the studied DC CB technologies, but not all scenarios can be shown. Only those scenarios which indicate differences between DC CB properties are discussed.

II. Test Circuit for DC CB Simulation

Fig. 1 shows the proposed test circuit and Table 1 shows key parameters in this study. Some important aspects are:

1. An ideal DC source is used in order to provide adequate power for the interruption process. It represents a strong bus in a DC grid, considering a DC bus fed by multiple VSC converters in a DC grid [12]. The voltage swing during fault (bus strength) can be adjusted with the series resistance R_{dc}.
2. A DC cable is inserted between DC CB and the fault location to represent the dynamic voltage and current stress on the DC CB. The cable length can be adjusted.
3. The second DC cable (facing load) is required to properly represent DC CB stress for high impedance faults.
4. A load resistor is used to enable demonstration of opening and closing at load currents. Also, the load current before faults raises the operating temperature which is important for hybrid DC CBs using semiconductors.
5. The DC CB has a single input (K_{grid}=*1/0*, close/open).
6. Fault duration, frequency and resistance can be adjusted.

Table 1. TEST CIRCUIT PARAMETERS

Parameter	value
Vdc	320kV
Rdc	0.1Ω
Ldc	Hybrid DC CB 100mH; Mechanical 220mH
DC cable 1	10km distributed parameter model
DC cable 2	100km distributed parameter model
Rf (low impedance)	0.1Ω
Rf (high impedance	50 Ω
Rload (rated load)	160Ω
Rload (low load)	3400 Ω

III. DC CB TECHNOLOGIES CONSIDERED

Fig. 2 shows the IGBT-based hybrid DC CB [2] which has been widely studied. The model uses a number of simplifications (switches as ON/OF resistances) as in [13]. The parameters for the latest IGBTs are taken from [14].

The technology for a thyristor based hybrid DC CB is given in [3], the model from [14] is used, and is not repeated here.

Fig. 3 shows the considered current-injection mechanical DC CB [4]. The model from [15] is adopted and revised to include two current injection circuits (a and b) which enable multiple operations.

IV. SIMULATION WITH EXTERNAL TRIP SIGNAL

A. Opening on maximum fault current

This is the scenario when opening on maximum/rated fault current. It is an essential requirement, and this test has been reported in most references for particular DC CB technology.

B. Opening on low load current

DC CBs will be expected to open on low current, as an example for controlled line/load tripping.

The thyristor-based hybrid DC CB employs capacitors for commutating current between several delaying branches, which are designed for fast opening at rated fault current. At lower currents the charging time is longer resulting in longer opening time. The opening time at *0.1 kA* might be over *100ms* [14], which is many times longer than at maximum current.

With mechanical DC CB, interrupting low DC current implies higher derivative of oscillating current at zero-crossing [4] compared to rated fault current. This implies that interruption in the arc chamber is more challenging. With typical internal resonant frequency of around *3 kHz*, it may take several zero-crossings to interrupt current (a design trade off), and this implies a possible delay of the order of *1 ms*.

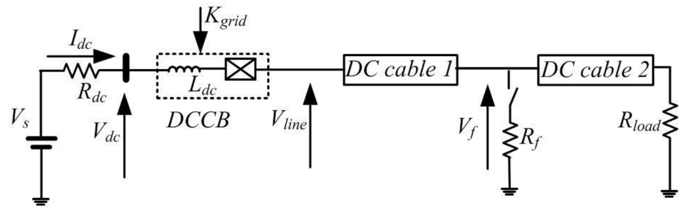

Fig. 1. Test circuit for simulation of DC CBs.

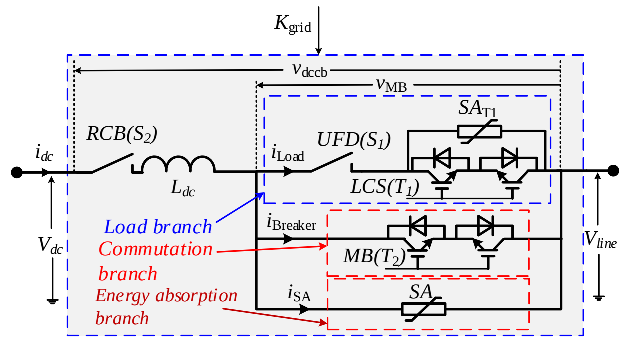

Fig. 2. IGBT-based hybrid DC CB.

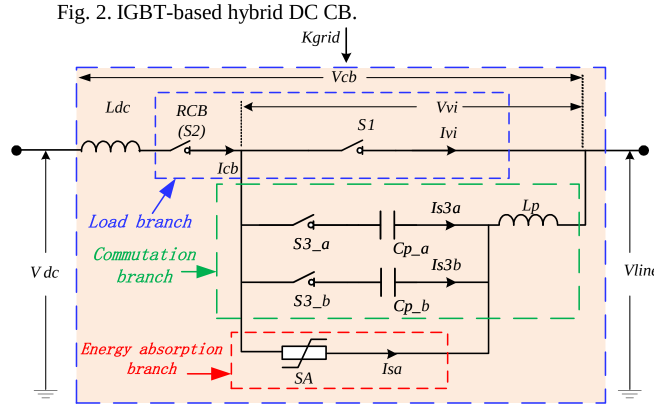

Fig. 3. Current injection type mechanical DC CB.

C. Closing on load current

Closing is generally not an issue for any of the DC CB technologies, although closing time might be different from the opening time for thyristor and mechanical DC CBs.

D. Repeated open-close operation

Repeated operation with DC CBs is required when reclosing is specified, typically with overhead lines, where typical dielectric recovery time is several hundred *ms*. However, some new DC cable protection methods require repeated operation within short period [10].

All DC CBs dissipate energy in the opening process, and this is achieved by converting electrical energy into heat. Because of large thermal constants of surge arresters, there will be certain dead time before absorption elements are ready for the next opening. Since the operating and reclose times are quite short with DC CBs, this implies that there might be need for multiple/larger absorption elements in practical DC CBs.

Some other DC CB components with longer re-charge time constants may also need duplication. As an example, the force in ultrafast disconnector is over *100 kN*, and the corresponding Thomson coil energy requirement is several kJ [17], which implies that recharge time may be longer than required DC CB reclose time. Similarly, the energy in the pre-charged capacitor in current-injection mechanical DC CBs is large [4], and recharge time may be long.

It is not clear how many open-close cycles will be typical DC CB requirement, but a safe assumption is that at least two open operations could be specified as shown in Fig. 4. In our demonstrations $T_{o1}=300\ ms$, while T_{c1} is as low as practically possible for a particular DC CB (closing in fault).

Fig. 5 shows the demonstration of a mechanical DC CB for the control sequence in Fig. 4, with labeling corresponding to Fig. 3. The first open command is sent at *0.1s*, and reclosing at *0.4s*. It is seen that two different current injection circuits are sequentially activated (a and b), and the total energy is large.

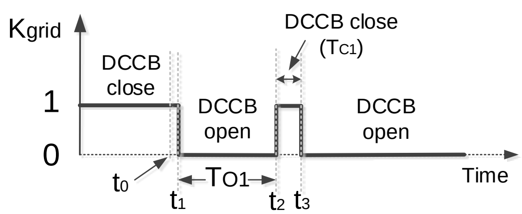

Fig. 4. Proposed open-close sequence.

E. Reverse current direction

The current direction is not relevant with AC CBs but plays an important role with DC CBs.

All semiconductor based DC CBs and hybrid DC CBs will be available as unidirectional or bidirectional breakers. The unidirectional hybrid DC CBs will have a single main semiconductor valve which is able to interrupt current in one direction only. If the current is high in the opposite direction the DC CB will be permanently closed. However, once open, a unidirectional DC CB is an open circuit in both directions.

The bidirectional hybrid DC CBs will have two series-connected semiconductor valves; one for each current direction. The operation in each direction should be identical.

The mechanical DC CBs will be able to interrupt in both directions with a single set of interrupters. However only a single current-injection circuit is typically employed using a fixed polarity of pre-charged capacitor. This implies that identical injected oscillating current is added into either positive or negative DC fault current

Fig. 6 shows the negative current interruption with mechanical DC CB (simulated by reversing DC CB polarity in Fig. 1). It is seen that injected current superimposes on the line current, contrary to the case with positive current in Fig. 5. The first current zero crossing now happens at the second half of the oscillating cycle, which implies a delay of some *150* μs (depending on frequency).

V. Operation without external trip signal

DC grid protection may utilize rate of voltage change [8], or differential current [9] on a DC cable, or grid-wide multiple measurements [10] to make trip decision. It is possible to envisage a scenario where DC grid protection fails, and therefore the DC CB becomes exposed to high fault current but there is no trip signal. This is an important scenario since DC fault current may rise to very high levels in short time and some DC CBs will be more vulnerable to thermal overload.

It has been recognized that DC CBs with semiconductors (hybrid DC CBs) will have very small overcurrent capability [5]. This implies the need for internal self-protection which will be activated when the current exceeds a threshold signifying danger of thermal damage [13]. It is understood that self-protection threshold can be raised by investing in more semiconductors in parallel.

A. Interrupting low-impedance fault

Presently, the peak interrupting current of hybrid DC CBs is around $I_{pk}=16\ kA$. Considering $T_b=2\ ms$ opening time with a $V_{dc}=320\ kV$ application, the tripping threshold is around *9.5kA* with $L_{dc}=100mH$, and it should be coordinated with primary and secondary DC grid protection. It is important that appropriate tests verify correct operation of self-protection.

In case of mechanical DC CBs, the self-protection strategy is to remain closed, since thermal dissipation is low with mechanical contacts.

B. Interrupting high impedance fault

High impedance faults will result in fault current lower than rated interrupting current but higher than nominal current. The thermal management of the load branch in Fig. 2 will determine the self-protection current trip threshold, which may be lower than the value for low-impedance faults.

VI. Operation with different parameters

A. Opening on low impedance fault with high L_{dc}

The series inductance L_{dc} is essential and will be an integral part of the DC CB installation. It is assumed that L_{dc} cannot be reduced during the life time of DC CB. However, the total series inductance in the fault path may be larger when the fault is further away from DC CB, or it may increase perhaps because of DC grid expansion or because of grid protection system redesign. Series inductance plays an important role in selectivity of some protection methods [8] and higher values may be required to achieve selectivity margins.

Increasing series inductance will decrease energy dissipation if CB opening time is the same, but increase energy dissipation if peak current is maintained, and this will correspondingly affect current neutralization time. A test with increased L_{dc} is therefore introduced to demonstrate that adequate margin is present in DC CB design. Fig. 7 shows the

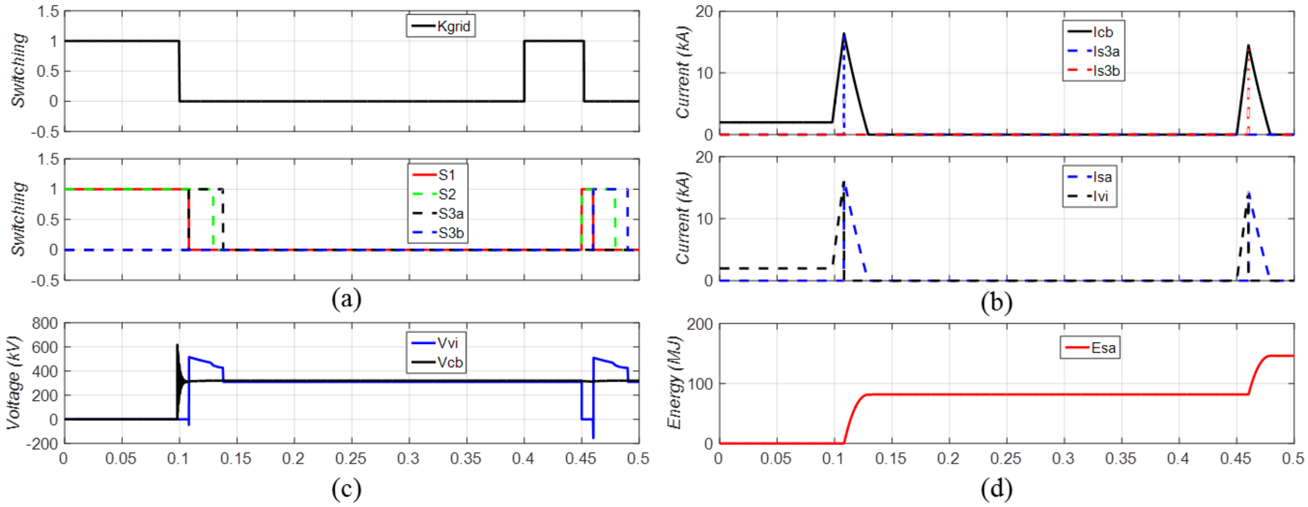

Fig. 5. Repeated open-close testing for mechanical DC CB.

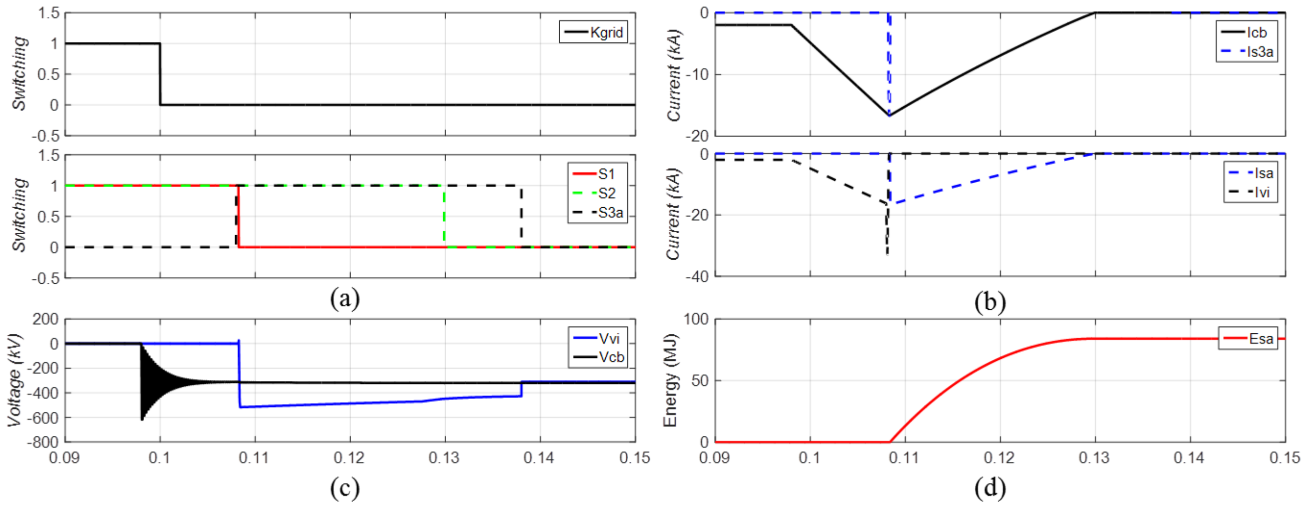

Fig. 6. Simulation results of mechanical DC CB for reverse current interruption.

simulation with the same peak current (self-protection is used) but with increased series inductance ($L_{dc}=0.2H$), which testifies that energy dissipation ($E_{sa}=82MJ$) is significantly larger comparing with original $L_{dc}=0.1H$, (around $E_{sa}=38MJ$).

B. Opening on low impedance fault with different cable parameters

Most reported DC CB testing considers DC fault located closest to the DC CB, which results in steepest current rise and largest peak current for a given opening time. This fault location however results in the lowest voltage stress on the DC CB and on the connecting cable, and it eliminates transient oscillating response of current and voltage.

DC CBs neutralize fault current by inserting surge arresters in series and considering that typical arrester clipping voltage is around *1.5 pu*, this raises possible voltage stress concerns.

Faults along the cable will result in oscillating voltage and current (with positive and negative intervals) DC CB stress.

The mechanical DC CBs insert L_pC_p in series with the DC cable, and initially $V_{Cp}=-1pu$ [4]. Different cable parameters will reveal the range of stresses on components.

The thyristor-based hybrid DC CBs use large series capacitors in the current path, which combine with the cable impedance in the fault current path resulting in voltage stress.

Therefore it is recommended that the cable length should be varied in the fault testing, in order to indicate the range of voltage and current stresses on the cables.

VII. Fault Current Limiting

The IGBT-based hybrid DC CB has the ability of limiting fault current magnitude, which is achieved using controlled insertion of varying number of surge arresters [2]. The maximal duration of fault current limiting will depend on the thermal management of the DC CB, current carrying capacity, but also the setting for current reference [18]. The self protection for thermal limits will be included, and tests should also consider capability of repeated operation.

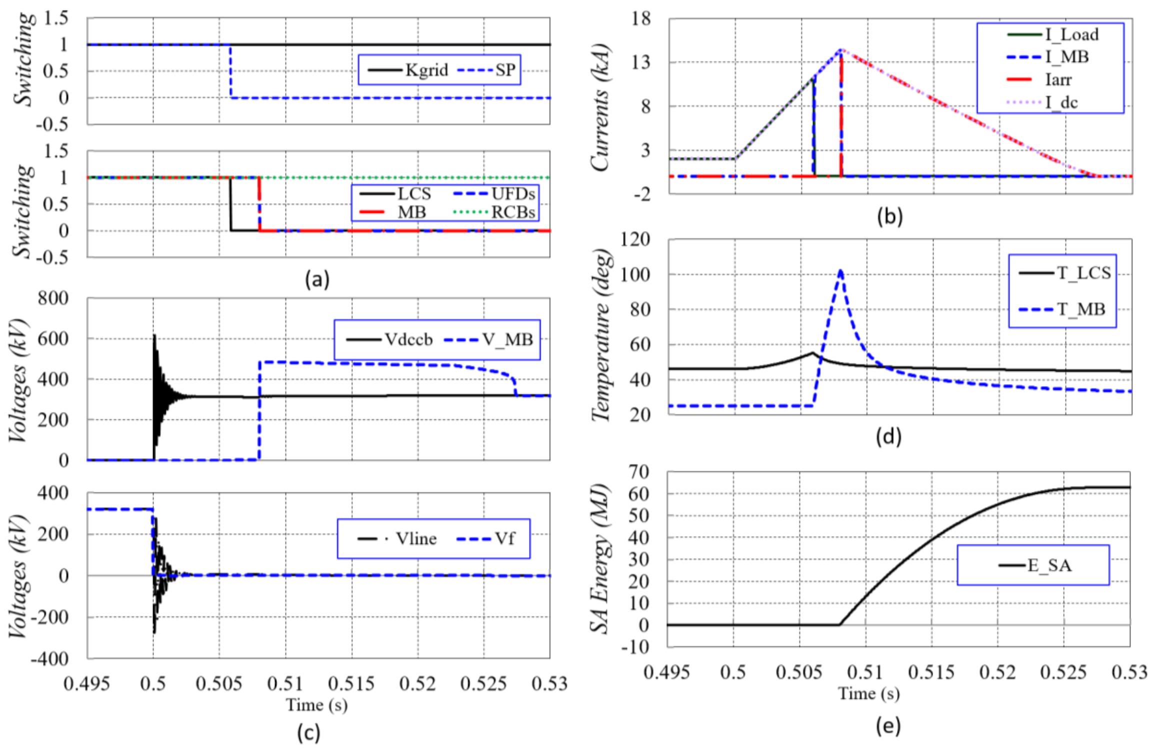

Fig. 7. High-current interruption simulation with L_{dc}=200 mH (IGBT-based hybrid DCCB).

VIII. Conclusions

The paper presented a range of scenarios and test circuit, for evaluating and comparing performance of HVDC CB models. Because of operating conditions in DC grids and the nature of DC CB technologies, it is expected that DC CB testing will be much different from AC CB testing.

It is concluded that low current interruption verification is essential with DC CBs since some topologies show different responses. The verification of negative current interruption is also required and some DC CB will have different responses depending on current direction.

The self protection is an important property of DC CBs and correct operation should be verified in appropriate tests.

The testing with different parameters (like series inductance or cable length) is required since DC CB operating performance will be affected.

IX. Appendix

The cables are represented by one core conductor, one sheath and two insulator layers with radius given in Table 2.

Table 2. DC Cable data (320 kV)

	Core conductor	Insulator 1	Sheath	Insulator 2
Radius (mm)	21	42	48	55

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