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1200V, 200A Laboratory prototype for series LC DC Circuit Breaker

D. JOVCIC,
University of Aberdeen,
United Kingdom,

SUMMARY

A new concept of series LC DC Circuit Breaker is presented and experimental results on *1200 V, 200 A* hardware demonstrator are shown in this article. This mechanical DC CB topology converts DC fault current into AC current by inserting a series capacitor. The AC current can be interrupted by a conventional AC CB at one of the zero crossings and will not be increasing because of series capacitor. Only mechanical switches are used including the commutation switch. The commutation switch has design with lateral contact overlap which facilitates current commutation without arcing.

The experimental 1200V, 200A scaled demonstrator LC DC CB which commutates DC current in 0.4 ms is described. A fast air disconnector is used as the commutating switch. This disconnector has 3mm contact distance and 2 ms total opening time in the scaled laboratory hardware. The experimental tests confirm that arc-less current commutation into a parallel capacitor using a mechanical switch is possible. The main advantage of the proposed topology is the high operating speed. The results show that it is possible to apply increasing voltage stress across disconnector contacts while contacts are moving apart without causing dielectric breakdown.

The initial design parameters are presented for a 320kV DC CB based on the same concept. The initial conclusion is that expected performance and size of components are encouraging.

KEYWORDS

DC Circuit Breakers, DC Transmission Grids, HVDC

d.jovcic@abdn.ac.uk.

I. INTRODUCTION

There is significant interest to advance HVDC transmission technology into multiterminal DC and DC grids worldwide. There are multiple technical, operational and cost-related difficulties to achieve this goal, but the lack of DC CB (Circuit Breaker) with acceptable performance and affordable costs is the most prominent technical challenge.

In the last 7-8 years multiple manufacturers have demonstrated prototypes of basic modules of HV DC Circuit Breakers at around 80kV, 16kA [1]. Several DC CBs rated at 160 kV and 200 kV have been installed in China recently [2], which indicate operators' confidence and demand for the DC CBs. All DC CB technologies can be grouped into two families: semiconductor (or hybrid) and mechanical [1][3].

The hybrid IGBT-based DC CB [4] is the fastest operating technology, where opening time is specified as 2 ms (time to DC voltage to recover and current to peak). It also provides low-loss operation in the closed state. A unidirectional version requires a semiconductor valve rated for full DC voltage, while more-likely bidirectional version will require two such valves which is a clear disadvantage. Semiconductors are most beneficial for applications with repeated fast switching, while DC CB requirements are not ideal for semiconductors. The energy dissipation will amount to 10-30MJ for a typical 320 kV device, which implies large energy absorbers.

A fully mechanical DC CB has also been developed to a high voltage (70kV) prototype by two manufacturers [5],[6] and 160 kV mechanical DC CB was installed at Nan'ao project in 2017 [2]. It has no semiconductors, but it requires two vacuum AC CBs with faster driving mechanism. The main vacuum switch has contacts which are capable of sustaining arc and it has arc-extinguishing chamber. As a consequence of arcing, this DC CB has heavy contacts which in turn leads to much longer operating time (typically around 8-10 ms). Slower operation implies larger peak current and therefore a large amount of energy should be dissipated, which may reach to 30-70 MJ. The simplicity and compactness of the switches gives significant incentive for developing further mechanical DC CBs.

In terms of performance, the fastest hybrid DC CB is still not sufficiently fast to avoid converter blocking in case of DC faults. Assuming 2.5ms total time between fault initiation and peak fault current, the peak current will reach 6-9kA before the fault is isolated, and this will cause (temporary) blocking of MMC HVDC converters. This blocking is a loss in capacity and may become an important drawback in DC grid development, since system reliability aspects will be crucial as DC grid grows into very large size. It is clear that further improvement in speed and reduction in DC CB costs/size is much desired.

Both: mechanical and hybrid DC CBs have improved opening speed recently, because of the introduction of the high-speed driving mechanism in the mechanical switches [7][8]. They normally employ Thomson coils which provide very high initial force to enable adequate acceleration.

High-speed disconnectors have the highest contact separation velocity and lowest costs. Nevertheless, the current breaking capability of disconnectors is minimal, and as an example, it is listed as 1 A in [8]. The arc-less commutation is a prerequisite in any DC CB based on disconnectors. In the hybrid DC CB, disconnector current is brought to zero by using high-voltage semiconductor bypass branch which is maintained in closed state until disconnector fully opens. This requires the crucial 2ms dead-time in the hybrid DC CBs which occurs while waiting for disconnector contacts to fully open, in order to apply blocking voltage [4]. Such operating principle is based on a conservative assumption of static electric stress on disconnector (either fully open or close).

This paper will introduce new DC CB concept utilizing dynamic voltage stress across disconnector, which depends on the instantaneous gap distance, in order to provide faster counter voltage across the DC CB and faster fault neutralization.

II. SERIES LC DC CB

A. Topology

The schematic of the new DC CB is show in Figure 1. It consists of a fast mechanical switch S1 (a disconnector), capacitor Cs, series AC Circuit Breaker S2 and energy absorber SA. S1 opens on trip signal and commutates current into capacitor Cs which converts DC fault current into AC current. S2 is a standard vacuum AC CB with fast driving mechanism.

This new fast DC CB concept is built on the following 4 premises:

a) Controlled dynamic dielectric stress across a mechanical switch S_1,
b) The DC current commutation into capacitor Cs without arcing,
c) Mechanical switch S1 with high contact separation velocity,
d) The DC current conversion into AC current using a series capacitor,

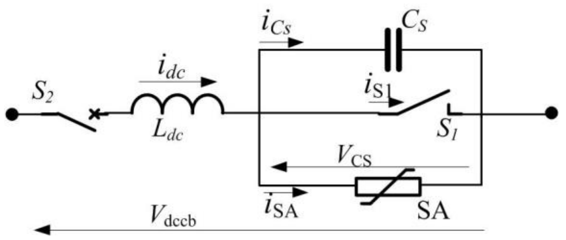

Figure 1. Topology of series LC DC Circuit Breaker.

B. Controlled dynamic dielectric stress across a mechanical switch.

Voltage withstand across a switch is commonly provided as a static parameter (contacts are fully open). In this concept, a dynamic voltage withstand is considered, which depends on the instantaneous gap between the contacts. A substantial advance in DC CB operating speed is possible if voltage stress across a mechanical switch is proportionally increased while the switch contacts are moving apart. This enables early insertion of blocking voltage in the DC fault current path, and benefits in lower peak fault current than with traditional approaches. This concept has been demonstrated on 1200V, 500A hardware in the recent study in [9] where it is concluded that peak current reaches only 60% of the value with comparable hybrid DC CB. However study in [9] uses power electronics to control the voltage gradient by inserting individual arresters.

In the topology in Figure 1 the gradient of dielectric stress across a switch is controlled using capacitor Cs (since dV/dt=I/C). The design ensures that dielectric breakdown does not occur while the contacts are separating. This can be achieved if the velocity of S1 contact separation is known.

C. The DC current commutation into a capacitor without arcing.

Mechanical DC CBs always have arcing. Conventional LV DC switchgear (in traction) employ various methods to extend DC arc and generally they can reliably interrupt 20-100A with voltage stress below 200-300V. At higher DC currents/voltages, additional resonant current is injected and the arc is interrupted when current crosses zero [5][6]. Arcing is undesirable since it implies large energy dissipation, high temperature, heavy contacts and wearing of the contacts.

Figure 2 shows a generic design of fast disconnector with lateral contact overlap (OL). This lateral overlap allows contacts to accelerate while there is still current conduction, and consequently contacts have non-zero velocity at separation. The non-zero velocity at point of separation and the limited voltage gradient (using a parallel capacitor) enable commutation without arcing. The initial studies have shown that there is direct correlation between the velocity at contact separation (v), dielectric strength of insulator (d), capacitance (Cs) and magnitude of current Idc0 which can be commutated:

$$v\, d > I_{dc0} / C_s, \quad z = 0, t = t_{sep} \tag{1}$$

This is the theoretical condition for DC current commutation into a capacitor, which can be derived analytically by differentiating the basic formula for dielectric breakdown at the singularity (z=0).

The presence of parasitic will impose practical limits on the concept in equation (1). Nevertheless, as it will be shown by the experimental results below, the hardware demonstration generally confirms validity of equation (1).

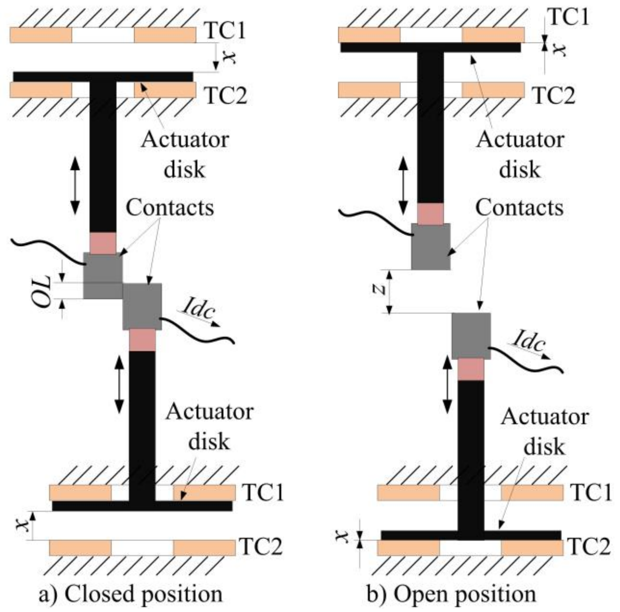

Figure 2. Fast disconnector with lateral contact overlap.

D. Mechanical switch with high contact separation velocity.

Contact separation velocity is the key parameter in (1). Higher contact velocity will reduce the size of passive components (capacitor) and increased the current that can be commutated (I_{dc0}). The practical limits for contact velocity are in the range *10m/s-20m/s* because of materials physical constraints. However, fast disconnectors with *10m/s-20m/s* contact velocity have been demonstrated at *320kV* [8]. Further improvements in contact separation velocity is possible if multiple break points are adopted.

E. The DC current conversion into AC current using a series capacitor.

Converting DC current into AC current (by inserting a series capacitor) is a new approach in DC CB design which brings multiple benefits:

a) Once AC current is established then traditional AC CBs can be employed (S_2 in Figure 1).
b) Inserting a series capacitor will permanently limit the fault current magnitude, normally at around *2pu*, (of load current). Such low current can be equally interrupted in any of the subsequent zero crossings. Therefore there is no urgency to rapidly interrupt fault current.
c) It is possible to operate DC CB with zero energy dissipation, since the main current has zero average value. This however would imply peak voltage in the range 2-2.5pu. If arresters are used, the energy dissipation will be much lower than with other topologies.

III. DESCRIPTION OF HARDWARE DEMONSTRATOR LC DC CB

Figure 3 shows the photograph of the hardware set up at the Aberdeen HVDC research centre laboratory. The DC CB test circuit is capable of supplying over *500A* fault current with controllable DC voltage of *900V*, and it is described in some detail in [10].

The fast disconnector has total contact gap of around *3 mm*, and achieves fully open state in *2 ms*. It is based on 4 Thomson coils and it is described in some detail in [11]. It is shown in Figure 3b). The gap distance of *3 mm* is conservatively designed for safety, since theoretical voltage withstand in air would be *dxz=3x3=9kV*.

Figure 3c) shows photograph of the demonstrator LC DC CB. It employs disconnector from [11] as S_1, while commercial *900 V* Kilovac AC contactor is used as switch S_2. The energy absorbers are commercial EPCOS arresters. The parameters of the test system are shown in Table I.

The photograph of the disconnector contacts in the open state is shown in Figure 4. They have *20mm* width and in closed state the overlap is *1.5mm* which results in around *30* mm^2 contact area in closed state. The contact assembly ensures adequate lateral force in closed state.

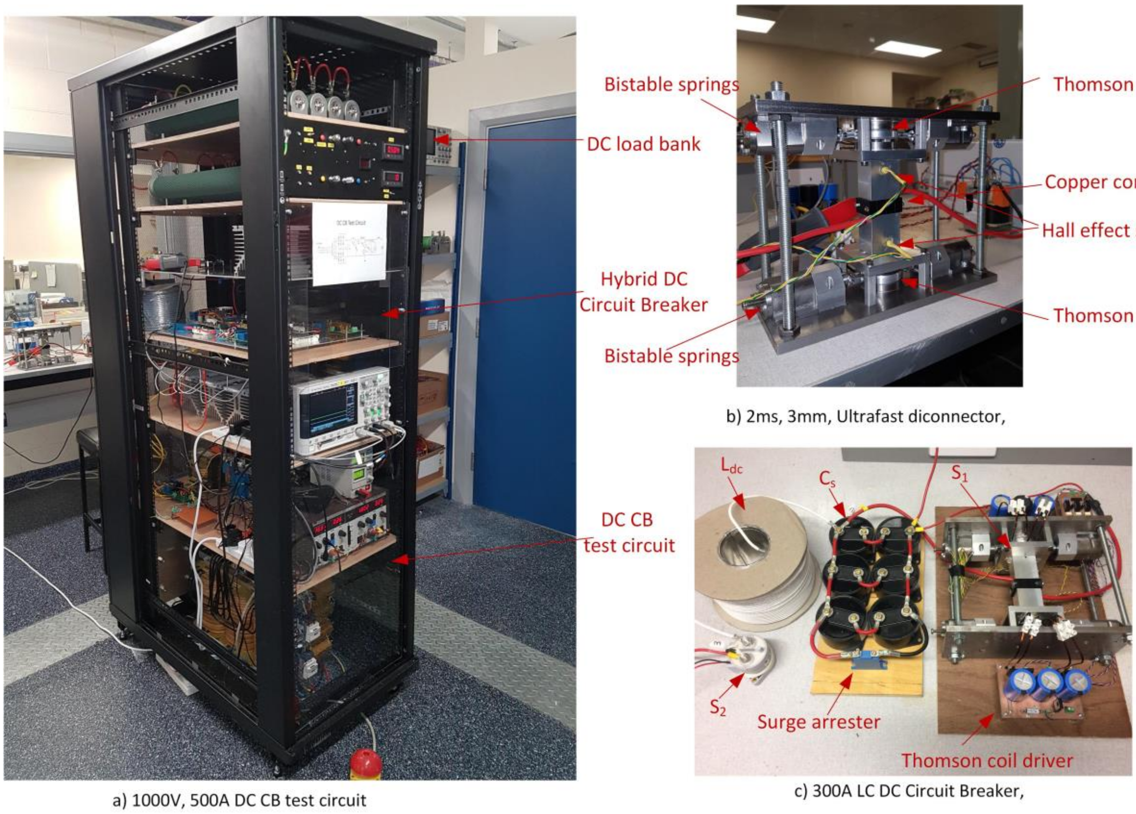

Figure 3. Laboratory demonstrator: a) 900V DC CB test circuit, b) *3 mm*, *2 ms* fast air disconnector, c) Series LC DC Circuit Breaker.

Table I Parameters of the 900V, 200A, LC DC CB.

PARAMETER	VALUE	description
Vdc	900 V	
Idcn	30 A	
t_{max}	2 ms	In house built high-speed disconnector [11]
OL	1.5 mm	
Dielectric stress (air)	0.5 kV/mm	
Z_{max}	3 mm	
L_{dc}	3.5 mH	6mm2, 100m, 77mm core, 14x18
C_s	150 µF	6x Cornell Dubilier 100µF, 0.8kV
S2	900 V	Kilovac EV200HAANA
SA	1.2 kV	EPCOS, B40K550

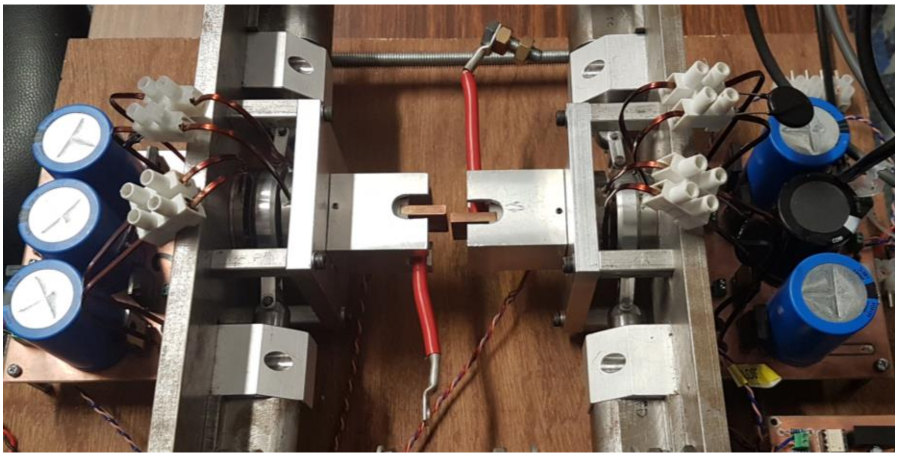

Figure 4. Internal view of contacts assembly of fast disconnector.

IV. EXPERIMENTAL RESULTS

The employed measuring equipment is:

- The contact position x_1 (on one rod) is measured using a hall-effect sensor. Contact separation z is estimated as $z=2x_1-OL$. Separation velocity v is estimated by differentiating z.
- Currents are measured using Agilent, *2MHz*, *1500A* DC probes,
- Voltages are measured using TESTEC, *100MHz*, differential probes.

Data is captured over *8 ms* on Agilent *200MHz* oscilloscope. The time is synchronized with S_1 trigger.

Figure 5 shows one set of experimental results. A fault is applied on *920V* DC bus at $t=-0.2s$. The trip signal is sent to S_1 at $t=0$, and contacts begin to move. Contacts are initially sliding in closed state, and begin to separate at $t=0.4ms$, while full $z=3$ *mm* separation is achieved at $t=2ms$.

The contactor S_2 is a slow switch with around *3.5ms* opening time. It begins to arc at around $t=4ms$ and complete current interruption occurs at $t=4.5$ *ms*.

It is seen in Figure 5a) that disconnector current sharply reduces to zero at the instant of contact separation. A current of *130A* is commutated without arcing, but higher values have also been obtained with different parameters. Figure 5b) illustrates capacitor current which takes full fault current at the contact separation instant. The voltage across contacts (capacitor voltage) is increasing as contacts are moving as shown in Figure 5c). The dielectric withstand of contacts is larger than voltage stress at any point in the stroke, and arcing is not occurring.

The disconnector variables are shown in Figure 5d). The contact position reading x_1 begins to reduce soon after the trip signal, and the gap velocity reaches $v=2m/s$ (each rod is moving *1 m/s*). The gap distance z, begins to increase at *0.4 ms* and reaches maximal value of *3 mm* in *2 ms*.

In the presented case the test conditions and equipment is similar as in the tests with the hybrid DC CB presented in [9], for comparison. The same disconnector S_1, and L_{dc} are used and trip signal timing is similar. Studies in [9] use hybrid DC CB topology and the main semiconductor valve takes full fault current until disconnector is fully open as this is normal operating principle with hybrid DC CB [4]. It takes disconnector *2 ms* to fully open and the fault current peaks at *500 A* in [9]. In the proposed LC DC CB the voltage across the same disconnector is applied as soon as contacts begin to separate (by inserting capacitor) and this results in much lower peak current of approximately *190A* as seen in Figure 5a). The time to peak current is *1.2 ms*, while it is *2 ms* in [9].

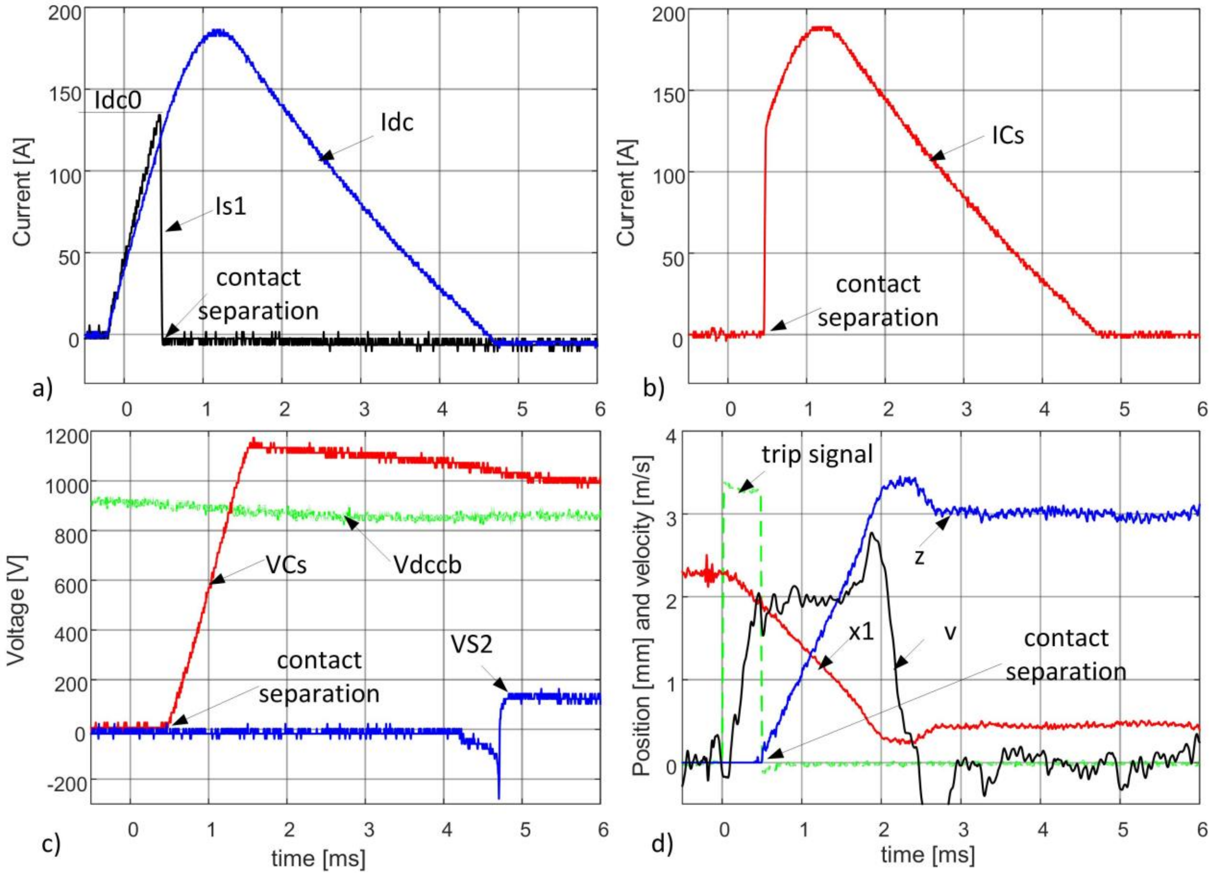

Figure 5. Experimental responses for LC DC Circuit Breaker.

V. LC DC CB SCALING TO 320KV

A simulation-based design study is performed to estimate components and performance for a high voltage LC DC CB. Table II shows the parameters of a preliminary design for *320kV* DC CB, assuming that *320kV 2ms* fast disconnector is employed as S_1. It is seen that the expected performance would be excellent because of fast opening speed and low energy dissipation. It is concluded that capacitor size of *13uF* (which includes a safety margin) would be acceptable at *490 kV* voltage.

Table II Parameters and performance of the 320kV LC DC CB.

PARAMETERS	**Value**	**description**
V_{dc}	320kV	Nominal dc voltage
I_{dcn}	2kA	Nominal dc current
L_{dc}	200mH	Series inductor
t_f	0.35ms	Protection operation time
I_{dc0}	3.5kA	Current at commutation
C_s	13μF (489 kV)	Parallel capacitor
S_1	Fast disconnector	Commutating switch
S_2	Vacuum switch	Main AC breaker
V_{dcp}	489 kV	Peak voltage
t_{max} (V_{dcmax})	2.0 ms	Time to peak voltage
I_{dcp}	4.4 kA	Peak current
t_{IDCP} (I_{dcpeak})	1.65 ms	Time to peak current
E_s	5.7 MJ	Energy dissipation
t_{S2} (I_{dc}=0)	7.5 ms	Time to current zero

VI. CONCLUSIONS

A new concept of LC DC Circuit Breaker is presented and experimental results on *1200 V, 200 A* scaled hardware demonstrator are shown. The experimental tests verify that DC current commutation into a parallel capacitor using a mechanical switch is possible without arcing. The main advantage of the proposed topology is the high operating speed. The results show that it is possible to apply increasing voltage stress across disconnector contacts while contacts are moving apart without causing dielectric breakdown.

The initial design parameters are presented for a *320kV* DC CB showing that the expected performance and size of components are encouraging. Scaling up of this technology to transmission voltages and currents requires further research and development.

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