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## LC DC Circuit Breaker based on Pre-charged Capacitor Commutation

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# LC DC Circuit Breaker based on Pre-charged Capacitor Commutation

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**Abstract:** To overcome limitations of the peak DC fault current with previous LC DC Circuit Breakers, this paper studies using a pre-charged capacitor in the auxiliary branch which enables rapid commutation of the fault current from the disconnecter in the main branch. The analysis on the theoretical model concludes that the pre-charged capacitor should ideally have high capacitance and low voltage. The design for the practical test case of 5 kV, 2 kA LC DC Circuit Breaker is presented and shows that the pre-charged capacitor voltage requirement is low, at 10% of the DC CB rating. Both, film and electrolytic (lower size and cost) pre-charged capacitor are considered, and the experimental tests demonstrate successful DC current commutation of 2 kA at 5 kV. Successful breaking is also demonstrated on hardware for negative DC fault current and for very low currents, which represent difficult operating conditions. The experimental study further evaluates robustness to the change of timing of the current injection and the pre-charged capacitor voltage. The mechanical LC DC CB commutates DC fault current in very short time of 320  $\mu$ s, and the use of pre-charged capacitor makes this topology good candidate for applications in medium voltage DC systems.

**Keywords:** DC switchgear, HVDC protection, DC Circuit Breakers,

# I. Introduction

DC CB (Circuit Breakers), are essential components in DC networks, at all voltage levels. DC networks have been studied for many industrial applications in the past 10 years, like collection systems for renewables [1], distribution systems [2], marine propulsion [3] and railways [4]. First DC transmission grid is 525 kV Zhangbei project which includes 16 DC Circuit Breakers [5], and others are in the planning stages.

There are many possible DC CB technologies, but based on the commercialized technologies, there are 3 main families [6]: semiconductor breaker [3], mechanical [7] and hybrid DC CB [8]. Mechanical DC CB is particularly attractive because of low costs, low losses, and simplicity, although on the downside it has the slowest operation of all topologies. Mechanical DC CBs achieve current commutation at the end of contact stroke which generally takes  $3-10\text{ ms}$ . It is highly desired to improve DC CB operating speed in all applications, in order to reduce peak DC fault currents, passive components and energy absorbers.

Recent research has demonstrated that the speed of operation of mechanical DC CB can be improved using parallel capacitor across the main switch [9]. This approach enables faster current commutation but also possibly eliminates energy absorbers, although the concept has been demonstrated only at low ratings hardware of  $100\text{ V}$ ,  $50\text{ A}$  in [9].

The mechanical LC DC Circuit breaker is another topology that similarly employs parallel capacitor but requires a new design for the main switch which is based on the overlapping contacts [10]. The LC DC CB hardware testing in [11] demonstrates  $400\text{ A}$  solely arc-based commutation in  $300-400\text{ }\mu\text{s}$ , on  $1.3\text{ kV}$  test system. Most DC CB designs use fast switches with Thomson coils and traditional butt contact topology which achieves full stroke in around  $3-10\text{ ms}$  [12]. Some designs with overlapping contacts have been commercialized [13], which in addition to short opening time ( $2-3\text{ ms}$ ) also enable multiple break points.

The key reason for fast operation of DC CBs with parallel capacitor is that they enable commutation at the beginning of the stroke of the mechanical switch. In order to advance parallel-capacitor DC CB to higher currents and voltages, the primary challenge is commutation of high current from the main branch to the parallel capacitor. The parasitics in the commutation circuit rapidly increase as the voltage and current rating increase and the arc voltage is no longer sufficient. There are many possible ways to achieve DC current commutation and reference [14] provides good overview.

In the most recent research in [15] LC DC CB has been demonstrated on hardware at 5 kV with 2 kA commutating current in 290  $\mu$ s. The study however uses semiconductor-based LCS (Load Commutation Switch) in the main branch which closely resembles LCS in the commercial hybrid breakers [8]. The drawback of such approach is that LCS causes losses with the load current, but also affects reliability since it requires continuous gate drive supply and cooling system.

This article reports on the studies to develop an alternative commutation method to advance LC DC CB concept to medium DC voltages and currents of several kA. The study assumes that only mechanical switch is located in the main branch, and considers new equipment in the auxiliary branch in order to facilitate commutation. The theoretical study will be tested on 2 kA, 5 kV DC CB prototype in a University laboratory considering wide range of test conditions.

Section II presents the basic LC DC CB test system design. Section III describes the design of the commutation circuit using pre-charged capacitors. Section IV presents hardware tests on 5 kV, 2 kA prototype, and conclusions are given in Section V.

## II. LC DC CB description and 5 kV, 2 kA design

Fig. 1 shows the proposed topology of LC DC CB with the pre-charged capacitor in the auxiliary branch. This section gives summary of the LC DC CB design without pre-charged capacitor, which is based on the study in [10], i.e. assuming only  $C_s$  in the auxiliary branch. The main components of this topology include:



There are multiple conditions for the calculation of the capacitance  $C_s$  [10] but the most stringent one is related to the instant of commutation. Assuming that the dielectric strength (air) is  $d_{air}$ , the design equation for commutating current  $I_o$  is

$$v_0 d_{air} > I_o / C_s \quad (1)$$

Assuming no parasitics in the circuit, this capacitance value would ensure current commutation.

Table I shows the parameters for the 5 kV, 2 kA which is used as the test case, and which is based on the system described in [15]. With these parameters, equation (1) gives capacitance of  $C_s > 133 \mu F$ . In order to provide adequate margin because of uncertainties with  $d_{air}$ , and parasitics,  $C_s = 400 \mu F$  is selected. Also, the total capacitance across switch will be lower because of series connection with  $C_h$ .

Table I Parameters of the test LC DC CB with pre-charged caps.

| Label                  | Description                                    | Value/rating         |
|------------------------|--|----------------------|
| Ultrafast disconnecter |  |                      |
| $T_{UFD}$              | UFD opening time                               | 1.5 ms               |
| $T_o$                  | Time to contact separation                     | 320 $\mu s$          |
| $Z_{max}$              | Maximum gap distance (1 break point)           | 3 mm                 |
| OL                     | Contact overlap in closed state                | 2 mm                 |
| $d_{air}$              | Dielectric constant of air                     | 3 kV/mm              |
| $v_0$                  | Contact gap velocity at separation             | 5 m/s                |
| $I_o$                  | Fault current at contact separation            | 2 kA                 |
| $V_{dc}$               | Rated test circuit DC voltage                  | 5 kV                 |
| DC CB Components       |  |                      |
| $L_{dc}$               | Series inductor                                | 4.2 mH               |
| $C_s$                  | Main capacitor, General Atomics                | 400 $\mu F$ , 6.5 kV |
| $C_h$                  | Film pre-charged capacitor, KEMET              | 4200 $\mu F$ , 900 V |
|                        | Dielectric pre-charged capacitor, BHC          | 4700 $\mu F$ , 400 V |
| $T_t$                  | Thyristor IXYS, MCMA140P1200TA                 | 140 A, 1.2 kV        |
| $D_t, D_{ch}$          | Diode SEMIKRON, SKR130/12                      | 165 A, 1.2 kV        |
| $SA_{cs}$              | Series EPCOS B60 K550, B60 K350, and V172 BB60 | 6100 V, 8 kJ         |
| $SA_t$                 | EPCOS, B40K150                                 | 350 V                |
| $SA_{ch}$              | With film cap. EPCOS, B60K350                  | 850 V                |
|                        | With electrolytic cap. EPCOS, B60K150          | 350 V                |

### III. Design of the pre-charged capacitor circuit

#### A. Basic assumptions

The proposal in this study is to commutate the main branch current by injecting a reverse current using a pre-charged capacitor in the auxiliary branch. A capacitor  $C_h$  is introduced, which will be pre-charged at  $V_{cho}$  and it in series with capacitor  $C_s$  when discharged by turning ON  $T_t$ . With the aim of medium and high DC voltage applications,  $V_{cho}$  should be significantly lower than the main breaker voltage, to reduce costs. The following equipment will be stressed at low voltage:  $C_h$ ,  $SA_{Ch}$ ,  $T_t$ ,  $D_t$ ,  $SA_T$  and the charging circuit, although they should be located on an insulation platform for adequate insulation to ground. Therefore, only  $C_s$  in the auxiliary branch is stressed for high voltage. Alternatively, it is possible to not use  $C_h$  and just pre-charge  $C_s$  but in such case the charging circuit would be exposed to high voltage when DC CB opens, and another high-voltage switch would be required.

As a comparison, the mechanical current-injection DC CBs employ pre-charged capacitor, but they also use an additional inductor in the commutation branch which limits the current derivative [7]. The maximum current derivative for vacuum breakers is  $100\text{-}2500\text{ A}/\mu\text{s}$  [16], while it is much lower in air breakers. It is known that the maximum current derivative for successful recovery is highly dependent on the plasma conditions [17] which are important for mechanical DC breakers since commutation occurs at the end of the stroke after  $3\text{-}10\text{ ms}$  arcing. It is postulated in this study that such inductor is not required with LC DC CBs since there is practically no arcing (it lasts less than  $50\ \mu\text{s}$ ) [11] and therefore thermal phenomena play no role. LC DC CB commutates at the beginning of the stroke, there is minimal arcing and dielectric strength on recovery is unaffected. Another downside of using a series

inductor is that the peak current reduces, and then much higher pre-charge voltage is required implying higher costs for the charging circuit and the injection switch.

## B. Calculation of pre-charged capacitor ratings

When Thyristor  $T_t$  closes  $C_h$  discharges connecting  $C_h$  in series with  $C_s$  across the switch. This means that their voltage share is inversely proportional to their capacitance. In order to reduce voltage  $V_{ch}$ , a high  $C_h$  capacitance will be required.

Fig. 2. shows the model for the commutating circuit just before closing the Thyristor  $T_t$ . Parameters  $L_p$  and  $R_p$  represent total parasitic inductance and resistance in the commutation circuit (two capacitors, switch  $S_1$ , thyristor and cables). The analytical model for the circuit ( $S_1$  closed) gives the following expressions for the circuit variable  $I_{cs}$  and  $V_{cs}$ :

$$I_{cs} = \frac{V_{cho}}{L_p \omega_p} \frac{1}{\sqrt{(1-\zeta^2)}} e^{-\zeta \omega_p t} \sin \omega_p t \sqrt{(1-\zeta^2)} \quad (2)$$

$$V_{cs} = \frac{V_{cho}}{L_p C_h \omega_p} \left[ 1 - \frac{1}{\sqrt{(1-\zeta^2)}} e^{-\zeta \omega_p t} \sin \left( \omega_p t \sqrt{(1-\zeta^2)} + \phi \right) \right] \quad (3)$$

$$\zeta = \frac{R_p}{2L_p \omega_p}, \quad \omega_p = \frac{1}{\sqrt{L_p C_e}}, \quad C_e = \frac{C_s C_h}{C_s + C_h}, \quad \phi = \tan^{-1} \frac{\sqrt{(1-\zeta^2)}}{\zeta} \quad (4)$$

Using (2), (3) and (4), the following variables of special interest are determined:

$$I_{csp} = \frac{V_{cho}}{L_p \omega_p} \frac{1}{\sqrt{(1-\zeta^2)}} e^{-\zeta \pi / 2} \quad (5)$$



$$(dI_{CS}/dt)_p = V_{ch0} \omega_p \sqrt{\frac{C_e}{L_p}} (1 - \zeta^2), \quad (6)$$

$$V_{CS\_ss} = \frac{V_{ch0}}{L_p C_h \omega_p} \quad (7)$$

- $I_{Csp}$  is the peak value of current. This variable determines maximum commutating current and should be  $I_{Csp} > I_o$ . It requires high  $V_{ch0}$ , high  $C_h$  and low  $L_p, R_p$ .
- $(dI_{CS}/dt)_p$  is the peak value of current derivative. It should be as low as possible to avoid reignition. It requires low  $V_{ch0}$  and high  $L_p$ .
- The steady state voltage  $V_{CS\_ss} \approx V_{ch\_ss}$ . This voltage equals the recovery voltage on contacts just after interruption. It should be low for better probability of successful recovery. It requires low  $V_{ch0}$ , high  $C_h$  and  $L_p$ . Depending when  $S_1$  opens during this transient the arc voltage further reduces  $V_{CS\_ss}$ .

This analysis shows that high  $C_h$  with low parasitics is preferred. An iterative process is needed, which involves assumed  $V_{ch0}$  and evaluation of all variables in the above equations. The selected design is  $V_{ch0} = 264$  V which gives  $C_h = 4200$   $\mu F$ , and all parameter values are shown in Table I. The total capacitance across the switch becomes  $C_e = 365$   $\mu F$ . The maximum voltage stress on  $C_h$  during interruption is  $V_{ch} = 300$  V, but this voltage can be limited with  $SA_{ch}$ . The obtained variables in (5)-(7) are:  $I_{Csp} = 2765$  A,  $V_{CS\_ss} = 224$  V, and  $(dI_{CS}/dt)_p = 153$  A/ $\mu s$ . The obtained frequency  $f_p = \omega_p / (2\pi) = 6.5$  kHz, is much higher than frequencies used with vacuum DC circuit breakers (around 2 kHz) [6][7].

The values for  $L_p = 1.6$   $\mu H$  and  $R_p = 36$   $m\Omega$  are obtained by tuning the analytical model parameters to match the experimental responses. Fig. 3 shows comparison of the analytical model and experimental results which confirms validity of the model in (2)-(4). The inaccuracy is caused by the uncertainty with parameters  $L_p$  and  $R_p$ , which are non-linear and depend on the operating conditions.

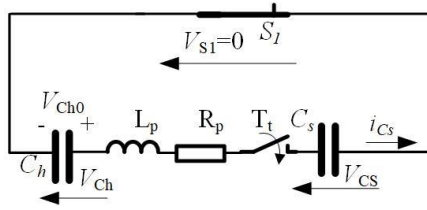


Fig. 2 Model of the commutation circuit with pre-charged capacitor.

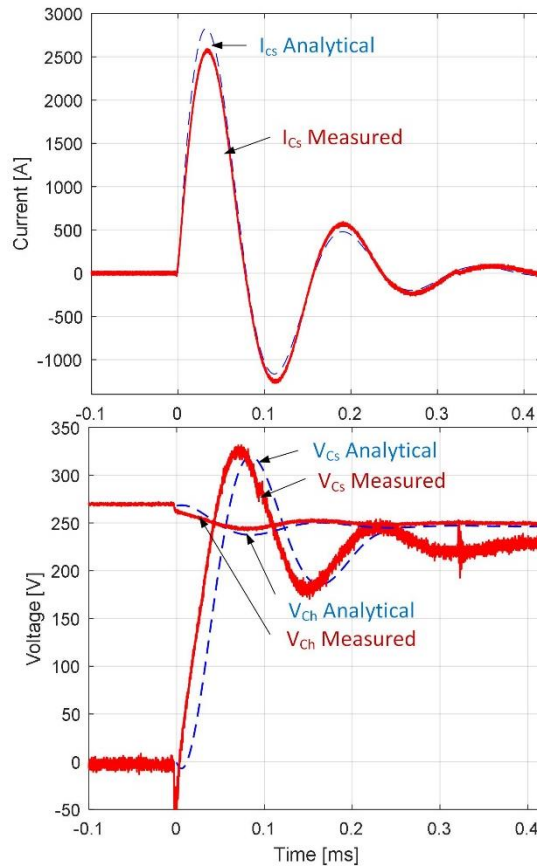


Fig. 3 Commutation circuit response with  $S_I$  closed and with  $V_{ch0}=264V$ .

## IV. Experimental Testing

### A. Hardware set up

The University laboratory is equipped with 5 kV, 2 kA test circuit based on capacitor bank that gives maximum energy of 10 kJ. It also enables adjustment of fault current through a delay and test voltage. Fig. 4 shows photograph of the developed LC DC CB with pre-charged capacitor. It is seen that the pre-charged circuit does not significantly increase size of the breaker. The charging circuit for  $C_h$  consists

of a 400 V diode rectifier with a Variac, which is located on an insulating platform (not shown in Fig. 4).

Fig. 5 shows the photograph of the 2-break UFD contact assembly. In the closed state there is 2 mm overlap, while in open state the distance between contacts is 3 mm, and the opening time is 1.5 ms. The details on the test circuit and UFD are given in [15].

There are two options for the implementation of  $C_h$ :

- Using film capacitor. The advantages are: faster transients are allowed, there is less risk of explosion, and higher voltage ratings are available.
- Using electrolytic capacitor. The advantage is that energy density is higher (smaller size).

Both the above options are tested, but the installed electrolytic capacitor is slightly larger  $C_h = 4700 \mu F$ , because of the component availability. Fig. 6 shows the circuit diagram with the electrolytic capacitor  $C_h$ . It is necessary to use bypass diode  $D_{ch}$  to prevent negative voltage on the electrolytic capacitor during opening.

The impact of two critical design variables is studied during the tests to evaluate robustness:

- The initial voltage is varied  $180 V < V_{ch0} < 350 V$ , and
- The timing instant  $T_{ch}$  for discharging  $C_h$  is varied  $335 \mu s < T_{ch} < 420 \mu s$ .

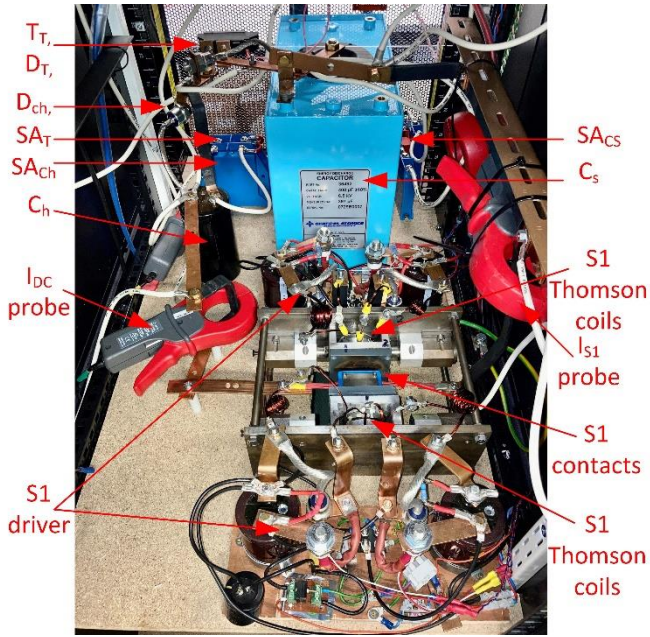


Fig. 4 Photograph of 5 kV, 2kA LC DC CB prototype (electrolytic capacitor).

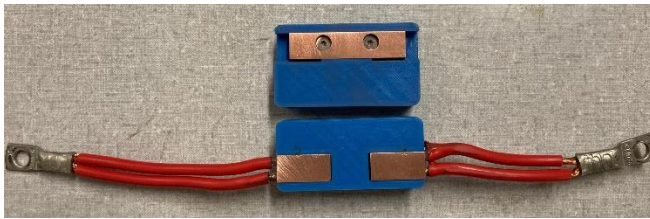


Fig. 5 Photograph of the contact assembly (2 break points).

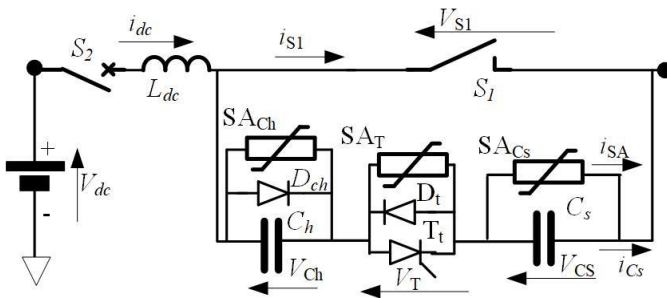


Fig. 6 LC DC Circuit Breaker with electrolytic pre-charged capacitor.

**B. Pre-charged film capacitor**

Fig. 7 Shows the successful commutation of 2.2 kA using film capacitor. This is the current value close to the peak capability of the test circuit, while in a practical application with firm DC voltage, the current would somewhat rise further following commutation as studied in [10]. The gap voltage  $V_{s1}$  is measured with two different instruments to provide high-resolution arc transient (right axis) and

system voltage (left axis). The pre-charge voltage of  $V_{ch0} = 185 \text{ V}$  is used which is the minimal value that supported successful commutation. In this test the commutation occurs around  $400 \mu\text{s}$  after the trip signal, and there is  $80 \mu\text{s}$  arcing (commutation interval).

Fig. 8 shows the impact of different timing of  $T_{ch}$  using zoomed curve for the gap voltage. The separation of contact occurs  $T_o = 320 \mu\text{s}$  after the trip signal as seen by the gap voltage rise to around  $30 \text{ V}$ . This arc voltage is in broad agreement with the previous research [18]. Such arc voltage is adequate to commutate currents up to around  $300\text{-}400 \text{ A}$  with arc-only commutation [11]. The discharge of  $C_h$  should occur around the contact separation instant, and the exact timing is a design parameter. If the discharge occurs too early, then contacts may not have sufficiently separated to withstand the recovery voltage. The red curve represents the case of early closing of  $T_t$ , just before contacts separate leading to zero crossing around the time of contact separation.



by blue and green curves, then arcing is longer, and this leads to high plasma temperature and lower dielectric strength. In case of longer delays, the arc voltage plays the damping role in the commutation circuit and therefore the recovery voltage becomes lower. The results in Fig. 8 demonstrate that this topology is quite robust to  $T_{ch}$  variation, since commutation is successful for 3  $T_{ch}$  values differing by  $85 \mu s$ . In this figure it is also seen that the recovery voltage is well defined and stable which is caused by a large capacitance across contacts and which helps preventing reignition and restrike.

### C. Pre-charged electrolytic capacitor

Fig. 9 shows 2 kA commutation using pre-charged electrolytic capacitor. The response is similar as with film capacitor except that  $V_{ch}$  is restricted to negative values by the bypass diode. Also, when the bypass diode conducts the total capacitance is  $C_s$  (instead of  $C_e$ ) and therefore the slope of  $V_{ch}$  is marginally lower. In this figure, the pre-charged voltage is higher  $V_{ch0} = 260 V$ , to illustrate robustness to this variable.

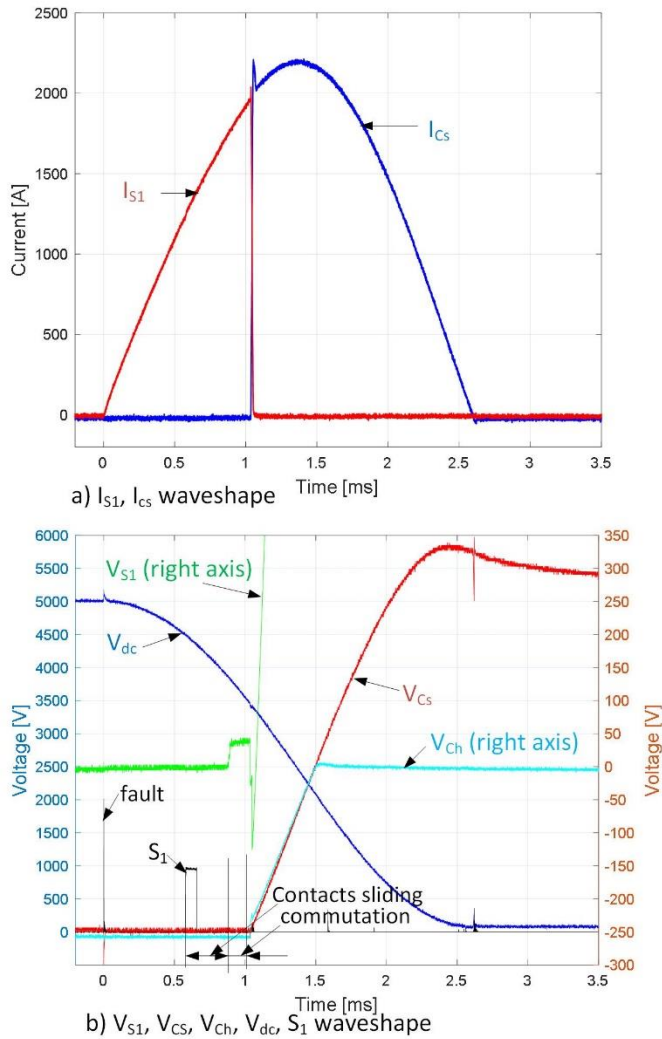


Fig. 9 DC fault response with 2 kA commutation (electrolytic capacitor).

#### D. Negative DC fault current

Most DC CBs will have unidirectional requirement, but some will be required to break DC fault currents in both directions. In the case of negative DC fault current, the pre-charged voltage  $V_{ch0}$  remains the same polarity and this means that the injected current is added to the fault current in the first half-cycle. The first opportunity for zero crossing in the main switch occurs at the second (negative) peak of the injected current, as it is seen in the test in Fig. 10. The second peak will always be of lower magnitude but in the studied test circuit it is significantly lower because of high damping as shown in Fig. 3. This is attributed to high parasitics ( $L_p$  and  $R_p$ ) caused by the experimental nature of this prototype and should be improved with professional manufacturing. In these laboratory tests it was



possible to commute up to  $1.6 \text{ kA}$  negative current as seen in Fig. 10. It is further noticed that the voltage  $V_{ch}$  now increases in magnitude when the current is injected. Further tests with electrolytic capacitor and negative current have also confirmed successful commutation.

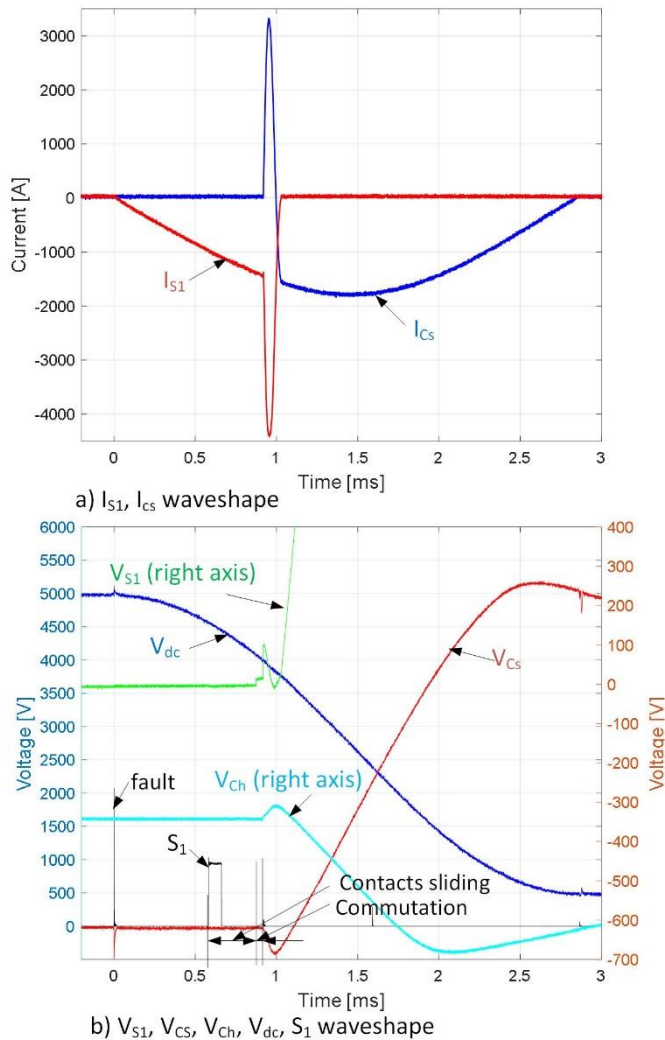


Fig. 10 DC fault response with negative fault current and  $1.6 \text{ kA}$  commutation.

### E. Low DC fault current

The LC DC CB operation at very low current is of particular interest since it corresponds to the highest current derivative at zero crossing, which is critical case for successful gap recovery. Considering experience with numerous tests below  $60 \text{ A}$ , it is reported that the commutation was always successful. In most cases the commutation was successful in the first zero crossing, as shown

in Fig. 11 for the case of  $I_0=60\text{ A}$  and  $V_{ch0}=264\text{ V}$ . It is seen that the low current causes slow rise of the recovery voltage, but the fault current is interrupted well before recovery voltage reaches the arrester clipping voltage.

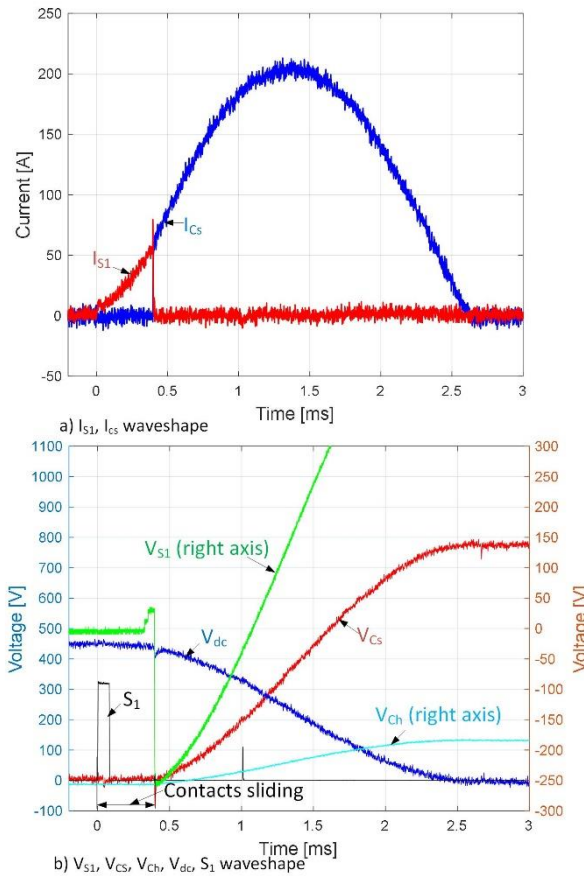


Fig. 11 DC fault response with 60 A commutation.

However, in some cases commutation was unsuccessful in the first but successful in the second zero-crossing. Fig. 12 illustrates a case with 300 A current interruption with successful commutation on the second zero crossing. In this test, a larger pre-charge voltage is used  $V_{ch0} = 280\text{ V}$  leading to higher peak current, and current derivative  $(dI_{CS}/dt)_p=163\text{ A}/\mu\text{s}$ . A good property for all topologies with current injection is that multiple zero crossing opportunities exist, and this enhances probability of successful breaking. Furthermore, as the DC current is lower the number of available zero crossings

will increase. At all subsequent zero crossings the gap distance becomes larger, and the current derivative is lower which progressively increases probability for successful recovery.

It is also seen that the  $V_{CS}$  voltage rise is very slow in this case, and it only increases to positive values before the fault current is interrupted.

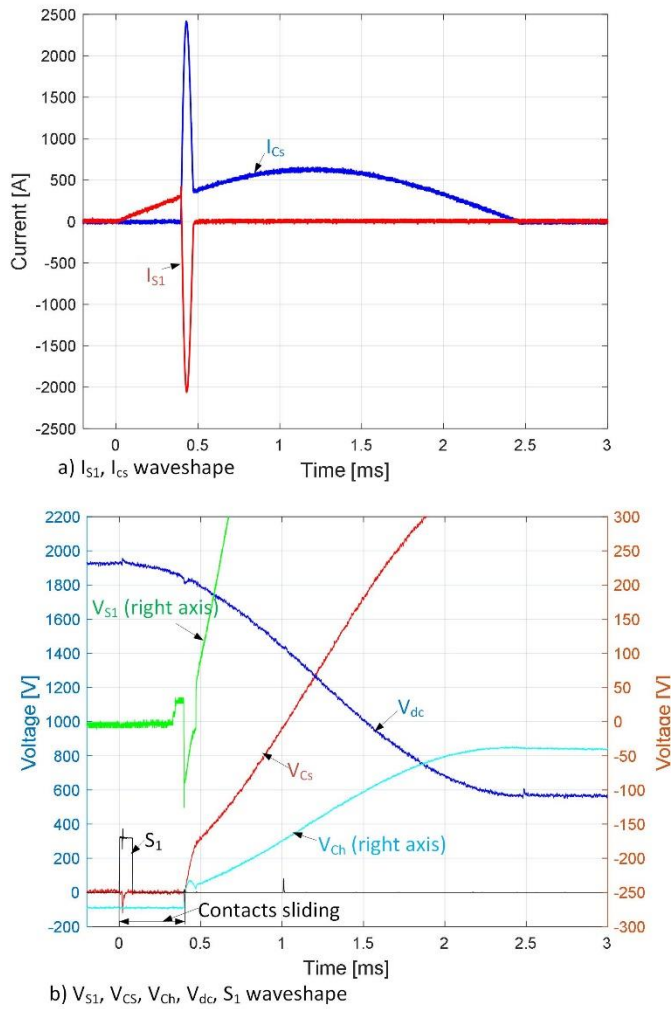


Fig. 12 DC fault response with 300 A commutation,  $V_{cho} = 280$  V and interruption on 2<sup>nd</sup> zero crossing.

## V. Conclusion

The article presents study of a LC DC Circuit Breaker topology with a pre-charged capacitor. The analysis of the theoretical model concludes that the pre-charged capacitance should be high, voltage should be low and the parasitics should be minimised for the optimal design. The design for the practical test case of 5 kV, 2 kA LC DC Circuit Breaker recommends that the pre-charged capacitor has capacitance around 10 times the main capacitor and the voltage requirement is around 10% of the DC CB rating. Further detailed cost studies of the additional pre-charged circuit will be needed if this technology is considered for higher voltages. The experimental tests demonstrate successful DC current commutation of 2 kA at 5 kV, using either film capacitor or electrolytic capacitor. Successful breaking is also demonstrated on hardware for negative DC fault current and for very low currents. In case of low currents, the current derivative is the highest and occasionally leads to failed interruption on the first zero-crossing which may need further detailed analysis. The robustness to the timing of injection and the pre-charged capacitor voltage is generally good, although future optimisation may lead to better performance and lower costs.

With these high-current experimental demonstrations, and because of the high operating speed, mechanical LC DC CB shows great potential for applications with medium voltage DC systems.

## VI. Acknowledgment

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