Multibreak LC DC Circuit Breaker

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***Abstract*— LC DC Circuit breaker has previously demonstrated great potential for applications with DC grids at high or medium voltage, and this paper presents further technology improvements based on an experimental study. The increase in the arc voltage is analysed as the number of break points increases, since arc voltage critically determines magnitude of DC current that can be commutated. The paper describes the design of a 4-break contact assembly which provides total air gap of around *6 mm*. It is concluded that it is feasible to build a 4-break disconnector with a *5 m/s* gap velocity and with around *30-40 µs* tolerance in the opening time of the four breaks. The experiments show that each break point increases the gap voltage and the commutating current almost proportionally to the number of break points. The measurements confirm that 4-break LC DC Circuit Breaker using *800 µF* capacitor can commutate *930 A* DC current with around *4.2 kV* recovery voltage. It is measured that the commutation occurs *290 µs* after the trip signal, which also denotes the time when DC CB begins inserting increasing counter voltage, and which is faster than most commercial DC breakers.**

***Index Terms*— DC switchgear, HVDC protection, DC Circuit Breakers.**

I. INTRODUCTION

DC CB (Circuit Breakers), are seen as key components in DC grids, at transmission and distribution levels and have been in rapid development in the past 10 years [1][2].

Hybrid DC CBs represent state of the art technology [3]. They operate fast, within 2-3 ms, but they include a high-voltage semiconductor valve which significantly increases breaker cost. They have been commercialized to high voltages and implemented in the Chinese Zhangbei DC grid and in the multiterminal Zhoushan HVDC [2].

Mechanical DC CBs use solely electromechanical components in the interrupting branch, but generally have slower opening speed, of around *8-10 ms*. They too have been implemented in the Zhangbei DC grid and in the previous multiterminal NanAo HVDC [4].

The cost of the DC CB is significantly higher than AC CBs of comparable ratings, and is one of the impediments for further DC grid development. Also, it is highly desired to improve the operating speed of the DC CBs, to reduce the peak DC fault current and passive inductors, but also to improve DC grid reliability.

The internal DC current commutation is the key challenge with DC CB design, and many options exist [5]. In all the commercialized DC CB technologies it occurs at the end of the stroke of the mechanical switch. With mechanical DC breakers commutation occurs after prolonged (*8-10ms*) arcing while contacts are moving. Multiple recent research projects have investigated commutation at the beginning of the switch stroke [6], and researchers in [7] have experimentally demonstrated this concept at low voltages. Commutation at the instant of contact separation results in faster DC CB opening speed and lowering both: peak current and energy dissipation.

The recently proposed LC DC Circuit breaker achieves commutation at the beginning of switch stroke while using only mechanical components, and has been demonstrated on hardware at *130A*, *1.3kV* in [8]. In this design, the DC current commutation occurs in around *300-500 µs*, which also denotes the time when DC CB begins insertion of counter voltage. Therefore, this topology brings significant advantage in DC CB operating speed. The key novelties of LC DC breaker are:

- Contact assembly with lateral overlap enables non-zero contact velocity at separation,
- Parallel capacitor limits the voltage rise across the gap while contacts are moving.

The commutation in LC DC CB happens because of the arc voltage, which however lasts for only a short period of time, in the order of *20-70 µs*. Such short arcing will not cause significant thermal phenomena in the contact chamber. The commutation in LC DC CB has been further analysed in some depth with the realistic parasitic parameters in [9], and successful commutation is demonstrated on a *400A*, *1.3kV* LC DC CB device. Reference [9] concludes that one of the methods to further increase LC DC CB rating is to increase the arc voltage. LC DC CB utilizes UFD (Ultra-fast disconnector) as the switch, which has been commercialized for high voltage [10], and similar design is used in many commercial DC CBs.

This article reports on the studies to advance LC DC CB concept to higher current and voltage levels. A possible increase in the short-duration disconnector arc voltage with multiple break points is analysed. The arc voltage and parasitics are very difficult for theoretical studies and always require experimental studies to confirm conclusions. A hardware prototype at 5 kV test voltage is developed, employing multiple break points, and this paper reports on the experimental results in the University laboratory.

II. LC DC CB WITH 4 BREAK POINTS

Fig. 1 shows the schematic of LC DC CB with 4 break points. The main components include [8]:

- S is UFD, since fast opening is desired. The previous studies consider only one break point, while this study evaluates benefits of employing multiple breaks.
- SA is energy absorber (bank of arresters) similar as with all DC CBs. It is rated for somewhat higher nominal DC voltage.
- C_s is parallel capacitor which is rated similarly as SA.
- S_{res} is residual switch.
- L_{dc} is required to limit the slope of current.

Assuming that there are no parasitics in the circuit, the current is commutated to the capacitor C_s when the switch S opens if the following is satisfied [8]:

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$$v_0 d_{air} > I_0 / C_s \tag{1}$$

where I_0 is the comutating current, v_0, is contact velocity at separation and d_{air} is the dielectric strength for air.

The commutating circuit (shown in red) will have some parasitics denoted by the total inductance L_p, and resistance R_p. The current that can be commutated in the presence of parasitics can be calculated as the function of the arc voltage V_{gap}, as shown in [9]:

$$I_{cp} = \frac{V_{gap0}}{Z_p} \frac{1}{\sqrt{(1-\zeta^2)}} e^{-\zeta \omega_p T_p / 4} \tag{2}$$

$$Z_p = \sqrt{\frac{L_p}{C_s}}, \quad \zeta = \frac{R_p}{2Z_p} \quad \omega_p = \frac{1}{\sqrt{L_p C_s}}, T_p = \frac{2\pi}{\omega_p} \tag{3}$$

The gap arc voltage is usually small $10\ V < V_{gap} < 15\ V$, and this limits the current that can be commutated. Also, in the attempt to increase the DC CB rated voltage, the components will have larger parasitics and this makes commutation more difficult.

Multiple break points are not commonly used with switching devices, as it is easier to break a single, long arc in the arcing chamber. In this study it is postulated that multiple break points will increase V_{gap} and it is expected that this will enable commutating larger currents as seen in (2).

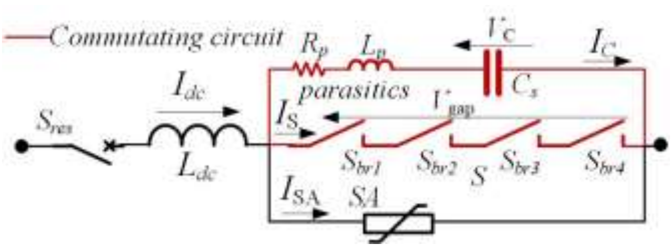

Fig. 1. LC DC CB using disconnector S with 4 break points.

III. Hardware prototype

The DC CB test rig and the initial DC CB prototypes in the University laboratory are presented in [7] and [8]. This hardware has been upgraded for *5.2 kV, 2 kA* capability recently. The test circuit consists of a *737.5 µF, 5.2 kV* bank of capacitors which can provide maximum of *10 kJ* of energy. Table 1 gives the key test circuit parameters. A photograph of the DC CB hardware demonstrator is shown in Fig. 2. Two of 6*.5 kV, 400 µF, (23 kg, 360×183×278 mm)* capacitors by General Atomics are connected in parallel as C_s. Bus bars are used where possible in the commutation path to reduce parasitics.

A transistor T_1 shown in Fig. 2 is used only as a back-up switch and it is not active in the test results. It is commanded to open *200 µs* after the expected commutation to prevent long and destructive arc in case that commutation is not successful. It remains closed in these tests and brings some additional parasitic inductance and resistance in the circuit.

Table 1. Table I Parameters of the test LC DC CB.

Label	Description .	value
T_{UFD}	UFD opening time	*1.5 ms*
T_o	Time to contact separation	*290 µs*
z_{max}	Maximum gap distance (1 break point)	*3 mm*
OL	Contact overlap in closed state	*3 mm*
d_{air}	Dielectric constant of air	*3 kV/mm*
v_0	Contact gap velocity at separation	*5 m/s*
V_{dc}	Rated test circuit DC voltage	*5 kV*
L_{dc}	Series inductor	*4.2 mH*
C_s	2x400 µF Capacitor from General Atomic	*800 µF, 6.5 kV*

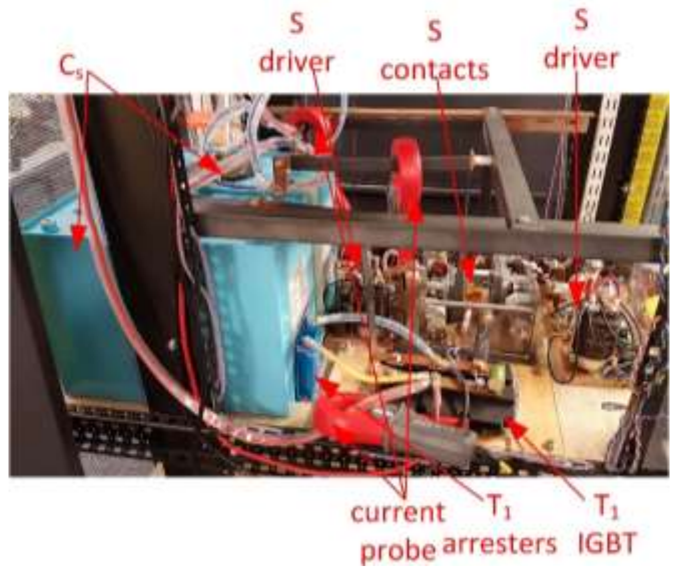

Fig. 2. Photograph of 6.5 kV LC DC Circuit Breaker.

IV. UFD with multiple break points

The practical design challenge has been developing contact assembly that provides simultaneous circuit separation in multiple points. A further constraint is that each break point should provide adequate contact surface to enable low closed-circuit resistance.

Fig. 3a) and b) show the design diagrams of the contact assembly in open and closed state, while Fig. 3c) shows the photograph of the built contact assembly. Both contact holders are moving, and each is driven by two Thomson coils to achieve fastest opening speed [7]. To achieve 4 breaks, one contact holder supports 2 contacts while the other has 3 contacts, all arranged to enable contact leading edge separation perpendicular to the travel direction of the holders. Each rod (and holder) has around *3 mm* stroke. This enables *3 mm* gap between holders in the open state, while the total electrical gap is *6 mm*. In the closed state there is a *3 mm* overlap which gives contact surface of around *25 mm*^{2} (copper blocks are *10×20 mm*) on each break point. This contact surface should not cause excessive heat at *300-500 A* nominal current, assuming *10-15 A/mm*^{2} allowed contact current density. This overlap causes some initial sliding period while contacts conduct current.

One dielectric holder has two contacts firmly attached to the holder, and the top surface has been machined to give level and smooth contact plane. The second dielectric holder has three contacts which are supported on springs and guiding pins to enable consistent force on the contact surface. The spring force reduces contact surface resistance and enables current conduction in the period while contacts are sliding before separation occurs. A *1 mm* groove is added beside contact leading edge to relieve plasma arc pressure. Two other sets of contacts have been made for 2 break points, and also for 1 break point.

V. Experimental results

A wide range of DC current breaking tests has been performed with 1, 2 and 4 break points. The commutating current is progressively increased by changing the test circuit voltage and the DC CB trip instant, until unsuccessful breaking occurs. Tests were stopped after first unsuccessful commutation occurred.

Fig. 4 shows the experimental measurements for the largest obtained successfully commutated current for 1,2 and 4 break points. The left graphs show the test circuit voltage V_{dc}, current I_{dc} and breaker voltage V_C. The breaker trip signal S is shown to enable estimation of the operating time. The right graphs show the internal breaker variables (zoomed): gap voltage V_{gap}, capacitor current I_c and UFD current I_s. The gap voltage represents the arc voltage during the commutation interval. The main conclusions are:

- With 1,2 and 4 break points it is possible to commutate progressively larger current of up to *285 A*, *530 A* and *930 A* respectively.
- The number of break points approximately linearly and almost directly proportionally increases the peak commutating current.
- The arc voltage curve shows that the 4 breaks occur randomly but within *30-40 µs*. This non-simultaneous breaking is the result of inaccuracies in the manufacturing and also some unavoidable free play in the contact assembly.
- Each break point contributes similarly towards increasing both: the gap voltage and the slope of the voltage.
- The commutation interval lasts up to *50 µs* depending on the current magnitude.
- The contact sliding period last around *290 µs* and shows continuous current without significant increase in resistance.

The DC current breaking has been successful at all current magnitudes below the values indicated Fig. 4, without uncertainty. Fig. 5 shows one test measurements when breaking a lower DC current of *740 A* with 4 break points. By comparing with the *930 A* case in Fig. 4c) we can observe different shape in the V_{gap} curve at the end of commutation. The difference between the arc voltage and the circuit voltage (when arc is extinguished) is larger when lower current is commutated, and this difference gives good estimation of the margin for successful commutation.

Fig. 6 shows the measurements with unsuccessful breaking of around *930 A* current, which is shown to facilitate deeper understanding of the commutating process with multi-break contacts. Here, the fourth break occurs quite late, approximately *70 µs* from the first break, which is the result of poor alignment in one of the initial experimental contact assemblies. It is seen that the fourth break occurs after the current I_s reaches minimum value (around *200 A*), and therefore it contributes to develop another I_s minimum. Both of these I_s minimums are not sufficiently low and therefore arc is not extinguished, and commutation is not successful. The experiments show that the current minimum should reach around *100 A* and then current reduction self-perpetuates (chopping value). This is in agreement with the previous studies that have shown that the arc voltage curve (in air) has inflection point at around *50 – 150 A* [11], and at lower currents the *IV* curve has negative slope leading to self-extinguishing property.

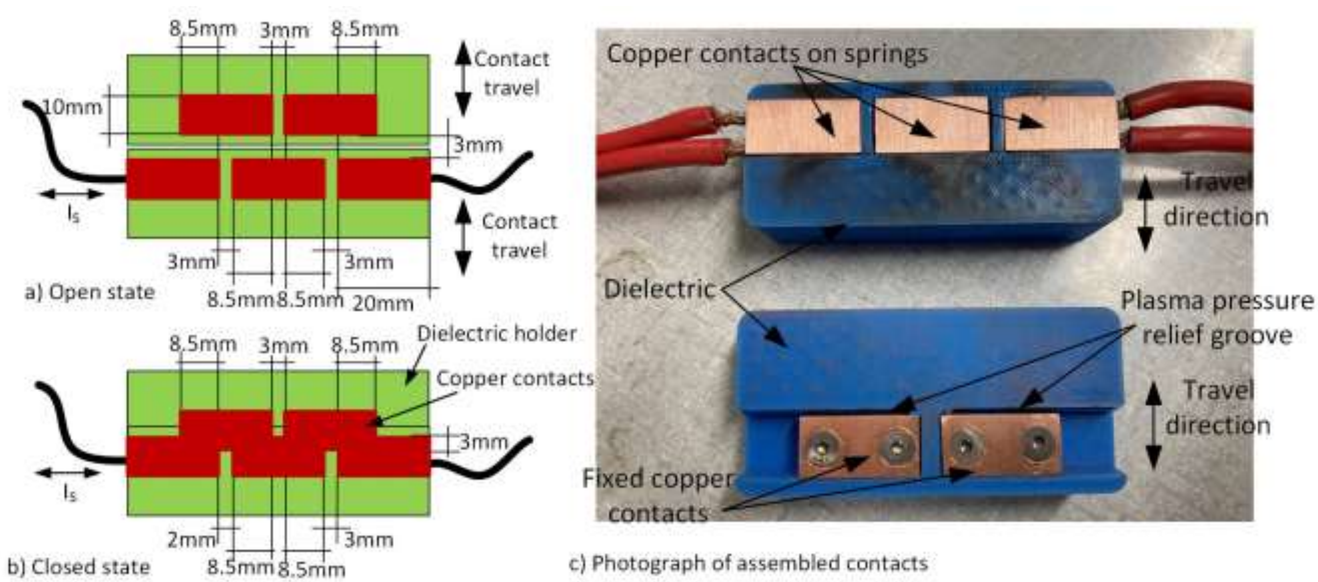

Fig. 3. 4-break point contact assembly, sketch drawings and photograph.

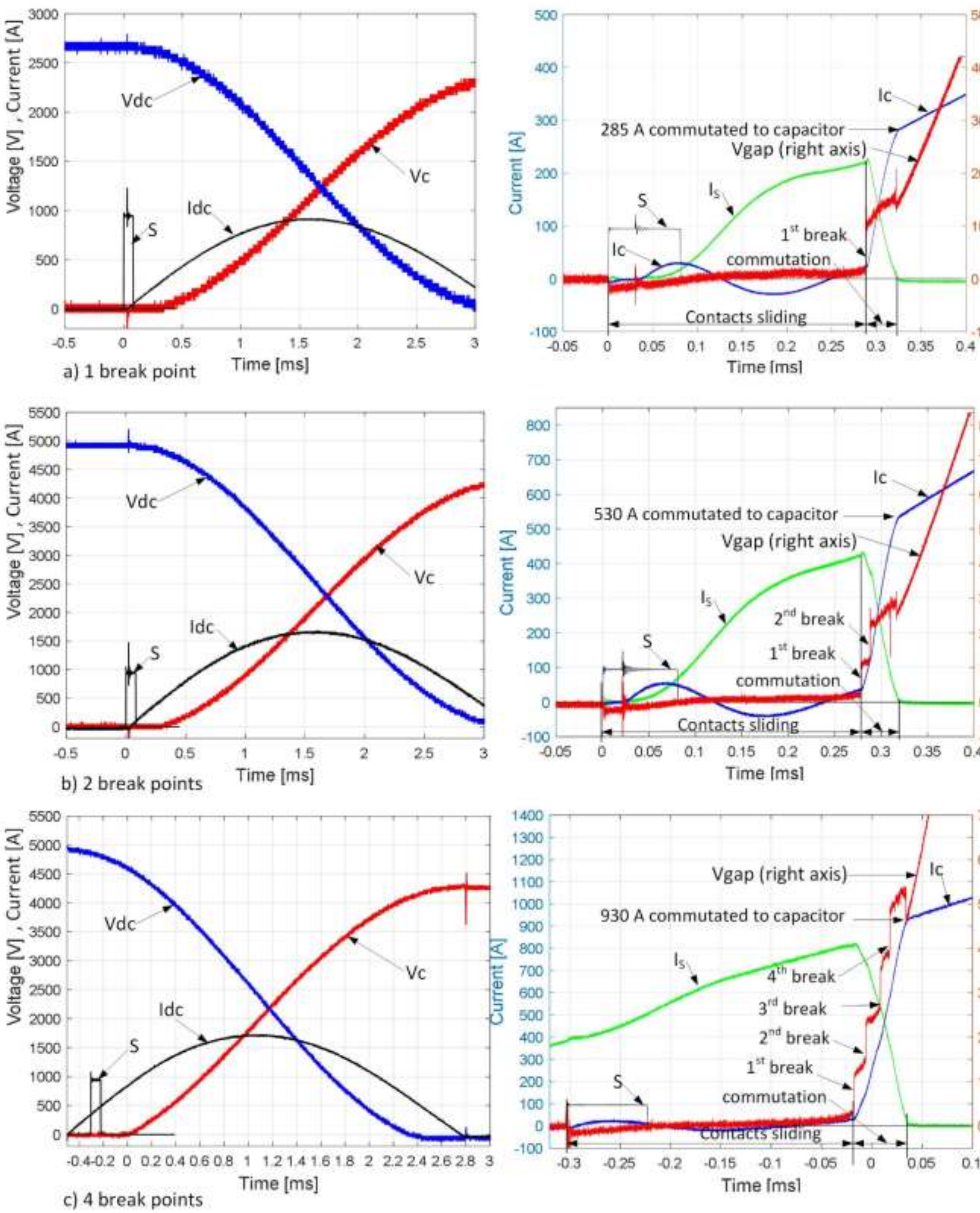

Fig. 4. Largest successful DC fault current breaking with a) 1 break point, b) 2 break points and c) 4 break points.

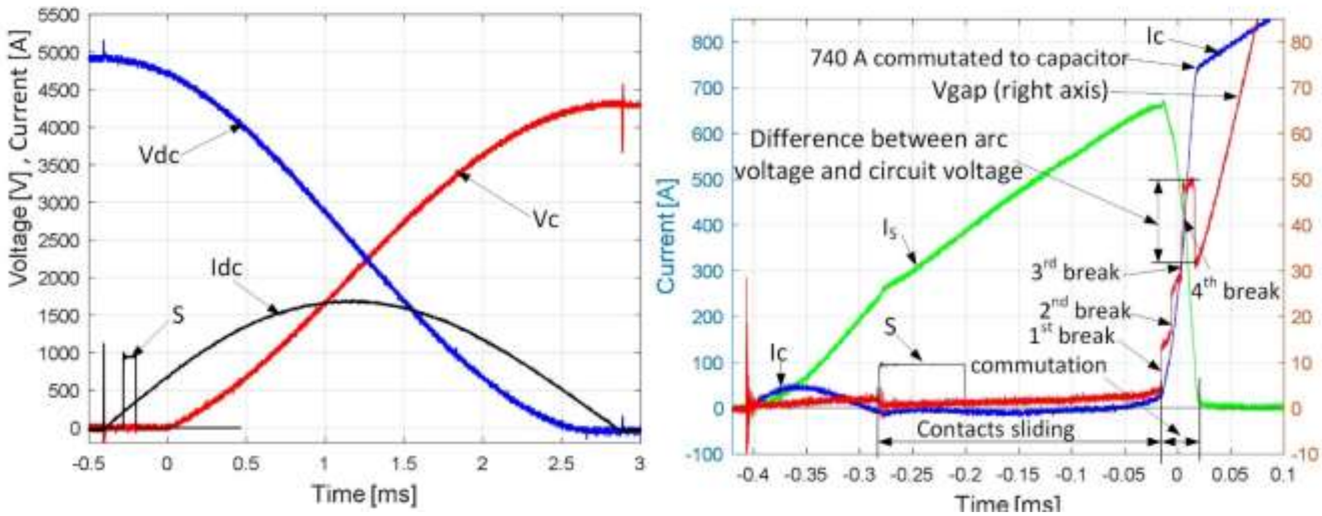

Fig. 5. 740 A DC fault current breaking with 4 break points.

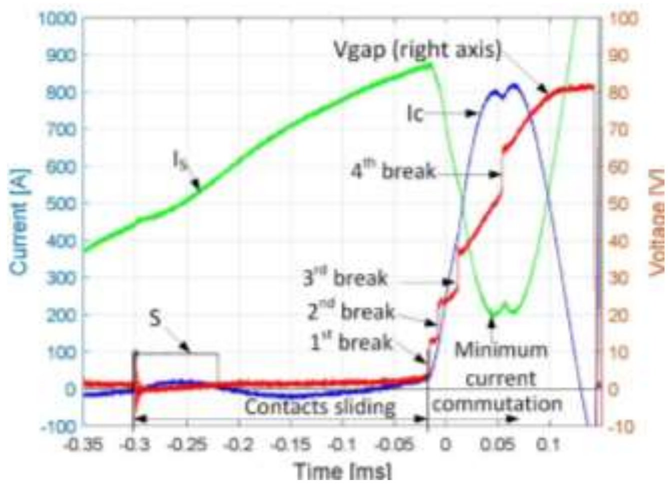

Fig. 6. Unsuccessful DC fault current breaking with 4 break points.

VI. Conclusions

The paper presents experimental study of the use of multibreak disconnector with LC DC Circuit Breaker. It is concluded that it is feasible to build a 4-break disconnector on a *5 m/s* gap velocity with around *30-40 µs* tolerance in the opening time of the four breaks. The experiments show that each break point increases gap voltage and the commutating current almost proportionally to the number of break points.

The measurements confirm that 4-break LC DC Circuit Breaker can commutate *930 A* DC current with around *4.2 kV* recovery voltage. The commutation occurs *290 µs* after the trip signal, which is much faster than with commercial DC Circuit Breakers. Since LC DC CB uses solely mechanical components, this topology shows good promise for developing fast and inexpensive DC Circuit Breaker at transmission/distribution voltages.

VII. Acknowledgment

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