

Scaled 500A, 900V, Hardware Model Demonstrator of Mechanical DC CB with Current Injection

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Abstract—This paper reports on the development of laboratory-scale mechanical DC Circuit Breaker (DC CB) demonstrator of current injection type. A 500A, 900V DC CB is developed with around 4ms operating time. We have used 3 series connected commercially-available mechanical contactors, with appropriate grading circuits, as the main switch. The resonant circuit has been designed with 3kHz resonance frequency. The experimental tests show successful interruption of 500A current at 1000V DC voltage in both positive and negative direction. Further tests with high impedance faults show successful interruption of low fault current at 65 A. Some further analysis of impact of timing of current injection is shown.

Index Terms—HVDC transmission, Power System Protection, Circuit Breakers.

I. INTRODUCTION

In the recent years there has been significant interest in developing DC transmission networks because of the need to interconnect multiple HVDC systems (on DC side) in order to increase operating flexibility, reliability and to optimise investment in new transmission assets [1][2].

DC Circuit breakers are key enabling technology, and several manufacturers have demonstrated 70-80kV prototypes recently [3]-[5]. The semiconductor (hybrid) topology [5] has very fast opening speed (2-3ms) but costs will be around 1/3 of the VSC HVDC converter costs. The mechanical designs [3],[4] are particularly attractive since operating time is reasonable (5-10ms) while costs are expected to amount to no more than few percent of the VSC converter costs. These DC CBs can be used with Full Bridge MMC converters [6] or with some protection methods with half bridge MMC [2].

The basic operating principle of the current injection DC CBs [3] is well understood, but there has been very little publically reported research on the technology. In particular, there are no experimental results reported by independent research centres.

The goal of this research project is to analyse: design, operation, component stresses, power scaling and failure modes on a laboratory-scale DC CB demonstrator with ratings of around 500A and 900V. This paper reports on the first stage

of the project, describing the developed DC CB demonstrator, design choices, and it presents successful tests on interrupting both rated DC current and lower fault current.

II. MECHANICAL DC CB DESIGN

A. Performance requirements

The main goals of the demonstrator have been specified:

- Current injection topology as in [3],
- Operating time of the order of 5-8ms,
- Rated fault current of 500A with 900V nominal DC voltage. The transient recovery voltage (TRV) will be much higher.
- The main interrupter should be based on the commercially available mechanical units.
- The resonant frequency should be similar as in high-power units (i.e. around 3kHz).

B. Topology of current injection DC CB

As shown in Fig. 1 the considered DC CB consists of:

- Main interrupter S1. This switch takes full fault current and it should be capable of sustaining arcing. The switch should have fast operating mechanism.

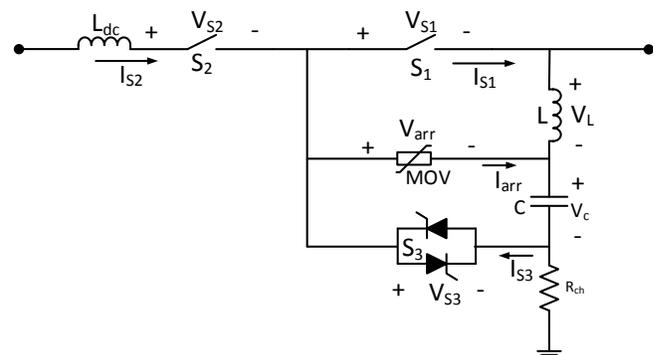


Fig. 1. Current injection mechanical DC CB.

- Residual breaker S2. This is a standard interrupter which only breaks leakage current from energy absorbers.
- Current injection switch S3. This switch can assume different technologies, while a similar design as S1 is used in [3]. It is important that the closing speed should be high, and comparable to the opening speed of S1. It takes fault current for a very short period.
- Energy absorber. This is a bank of surge arresters which dissipates full fault energy (estimated at around 600J).

C. Resonant circuit design

The basic dynamic equation of the resonant circuit is:

$$\frac{V_{C0}}{s} = \frac{I_{S3}}{Cs} + R_{eq}I_{S3} + LI_{S3}s \quad (1)$$

Where R_{eq} is the total resistance in the current path, and V_{co} is the initial voltage on capacitor C. All the other variable and parameters are shown in Fig. 1. Equation (1) can be solved in time domain as:

$$I_{S3} = V_{c0} \frac{\sin(\alpha t) e^{-\frac{R_{eq}t}{2L}}}{\alpha L}, \quad \alpha = \frac{\sqrt{4L - CR_{eq}^2}}{2\sqrt{C}L} \quad (2)$$

In the above equation two terms are crucial for DCCB design:

- Initial current magnitude $V_{co}/(\alpha L)$. This term should be substantially larger than peak current (500A) to ensure current zero crossing.
- Damping term $R_{eq}/(2L)$. This terms should be small to ensure that multiple zero crossings exist.

Firstly equivalent resistance in the circuit R_{eq} is determined. Fig. 2 shows the measured resonant current (S_1 is kept closed). It is seen that the damping is quite large, and probably much larger than it would be expected in the high-power circuit. This is consequence of internal resistance of S_3 and L. This response is used to estimate the value for resistance ($R_{eq}=0.05\Omega$) which is then used to tune PSCAD model of DC CB and to determine L and C from (2).

Because of the substantial damping, the magnitude of the initial injected current is increased to around 1000A to provide adequate margin. It is seen in Fig. 2 that even if DC current exceeds 500A, we should still be able to achieve several zero crossings.

Fig. 3 shows the initial current magnitude versus L for various values of C from (2), while Fig. 3 shows the damping term. Clearly there is a tradeoff since a small L is required for high initial current but larger L is needed for low damping. Capacitance C should be sufficiently large. The selected

values are $C=60\mu F$, $L=46\mu H$, and all parameters are shown in the Appendix.

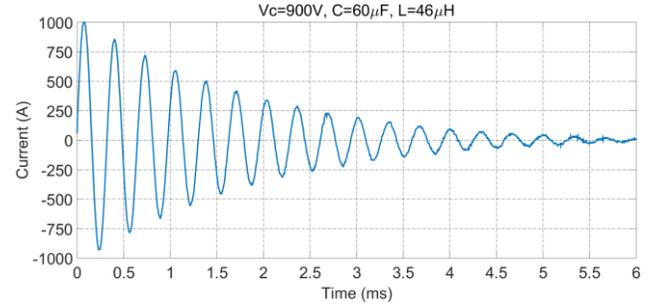


Fig. 2. Measured resonant current.

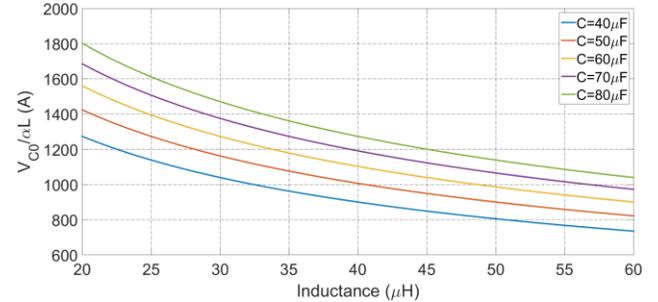


Fig. 3. Magnitude of initial current for different L and C.

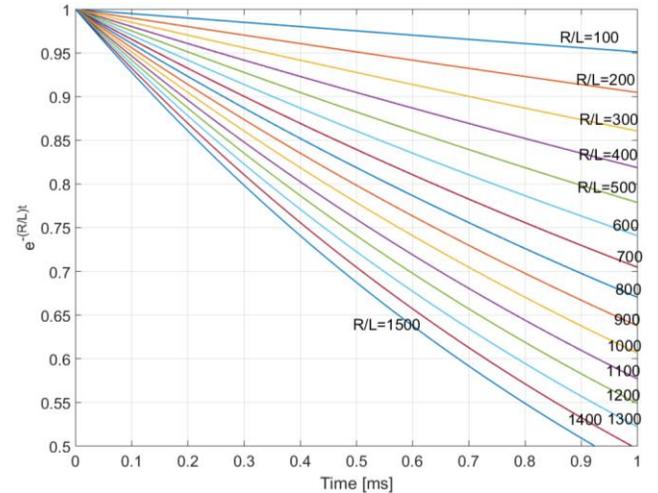


Fig. 4. Damping term for different L and C.

D. Main breaker S_1 design

It has been quite challenging to select a switch with required operating time and ratings. We have finally selected Kilovac, 900V, 500A, EV200HAANA sealed-air switch. Note that in [3] vacuum interrupter is used and therefore some difference in responses is expected. The tests in laboratory demonstrated opening speed (time for contacts to begin separation) of around 3.2ms. The travel time for the contacts has not been determined. At the rated voltage of 900V this contactor is capable of interrupting only around 70A DC current with 300μH inductive load (manufacturer data), or much lower current with our highly inductive load, after a prolonged arcing.

It was necessary to connect 3 contactors in series (S_{1a} , S_{1b} and S_{1c}) in order to provide required voltage rating. We have found that characteristics of operating mechanism could vary notably with these mechanical switches, and this results in an unequal sharing of the voltage across 3 units. Consequently, we have connected grading resistors R_g and capacitors C_g in parallel with each unit, according to methodology in [7], and all the final parameters are given in the Appendix.

E. Injection switch S_3 design

The injection switch S_3 should have fast closing time, but it can be realized in many different ways. We have been unable to find sufficiently fast mechanical device (Kilovac contactors have much longer closing time of around 16ms), and therefore we have used two anti-parallel thyristors. Also, thyristors enable precise control of injection timing, which is important for further research studies.

F. Residual switch S_2 design

The residual switch is a single Kilovac switch (same as S_1)

G. Charging circuit

A very simple charging circuit is used, consisting of permanently connected high-impedance resistor R_{ch} . In order to reduce charging current and heat dissipation a large charging time constant (10s) is used.

III. TEST RESULTS

A. Demonstrator circuit

Fig. 5 shows the schematic of the experimental set-up. The test circuit supplies 500A peak current from a large capacitor bank and uses step-down chopper to control applied voltage, as discussed in [8]. The initial DC voltage is 1000V, but the post fault voltage is controlled to 900V. The load bank enables adjustment of the initial current. The fault is applied by closing a high-current IGBT. A simple fault detection circuit is developed which sends the trip signal when current exceeds 50A.

Fig. 6 shows photograph of the experimental set-up, where the labels correspond to the circuit diagram. This photograph enables estimation of the relative size of the components.

B. Positive current interruption

Fig. 7 shows the interruption of rated current 500A, in positive direction. In Fig. 7 a) it is seen that fault current reaches 500A just before interruption, while TRV reaches 1300V. The arc voltage (just before interruption) is quite large which is common for air-breakers. Fig. 7 b) shows that resonant current reaches 500A and the interruption occurs in the first zero-crossing.

The timing of current injection is found to be critical for successful interruption. We have found that sufficient time must be allowed for contacts to separate before current is injected, in order to enable voltage withstand when current crosses zero. Many tests with too early current injection (just after contacts begin to separate) have led to unsuccessful interruption. The optimal timing for this DC CB is found to be around 4.7ms after the trip signal to S_1 .

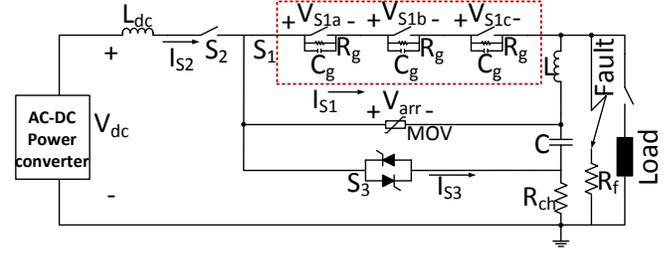


Fig. 5. Schematic of the experimental set up.

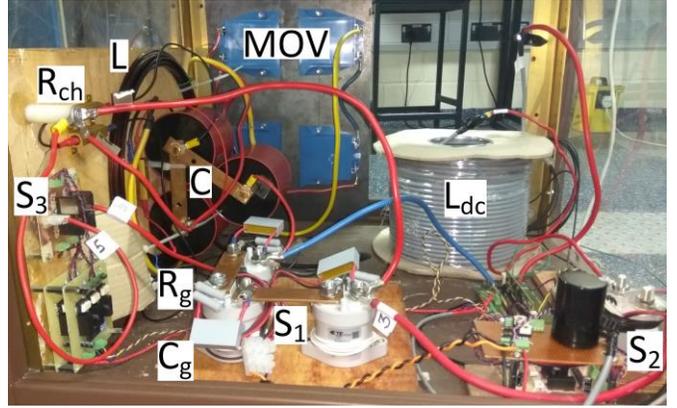
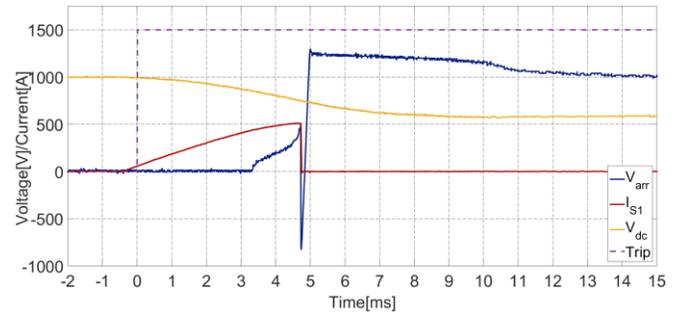


Fig. 6. Photograph of the experimental set up.

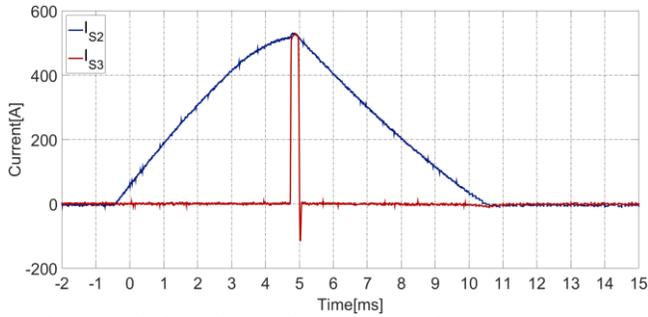
Fig. 7 c) indicates that the voltages across 3 series-connected switches are different, which is the consequence of different operating time of S_{1a} , S_{1b} and S_{1c} . The use of grading resistors and capacitors helps balancing the 3 voltages. The most pronounced unbalance occurs in the arcing phase. It is seen that all three contactors are arcing but one contactor has longer arc because of faster opening speed. Since contactors are in series, a zero crossing will interrupt current in all 3 devices which implies simpler voltage sharing after the interruption.

C. Negative Current interruption

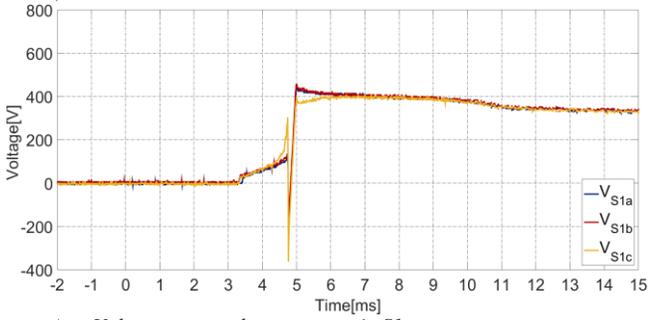
Fig. 8 shows the interruption of rated current 500A in negative direction. In this case the first oscillating half-cycle is superimposed on DC current and zero crossing occurs on the second half-cycle, approximately 170 μ s later (1/2 of 3kHz cycle) than in case of positive current.



a) DC voltage, S_1 current and arrester voltage.

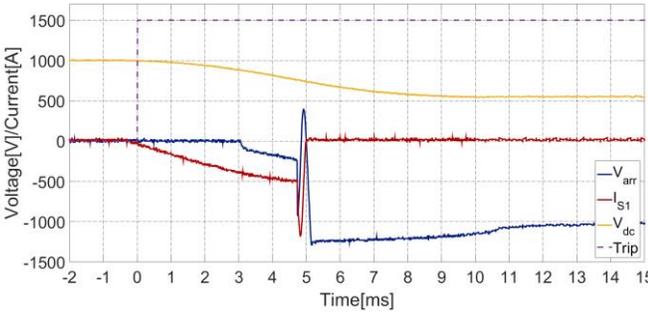


b) Residual switch S_2 , and resonance switch S_3 current.

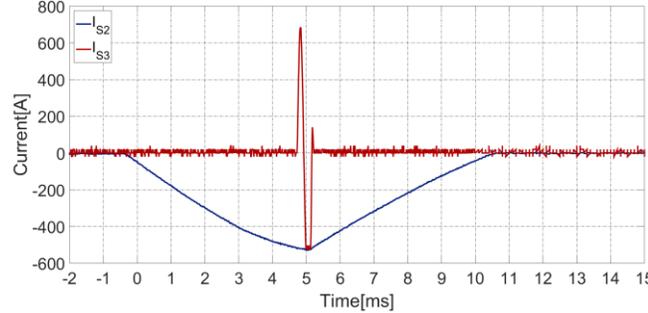


c) Voltages across the contactors in S_1

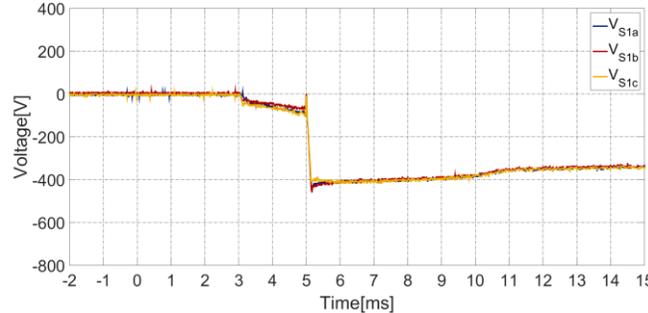
Fig. 7. DC CB interrupting 500A positive fault current.



a) DC voltage, S_1 current and arrester voltage.



b) Residual switch S_2 , and resonance switch S_3 current.

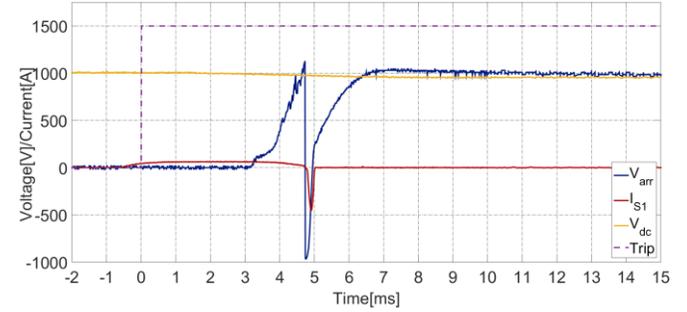


c) Voltages across the contactors in S_1 .

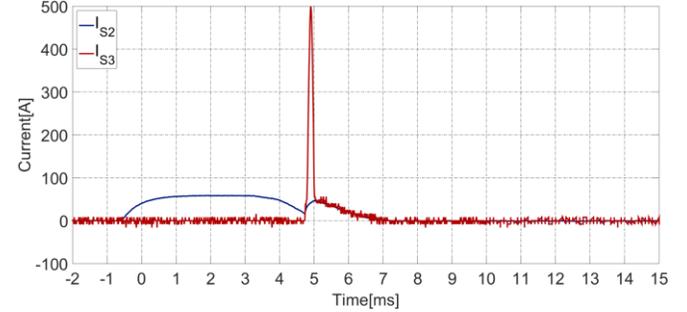
Fig. 8. DC CB interrupting 500A negative fault current.

D. Low current interruption

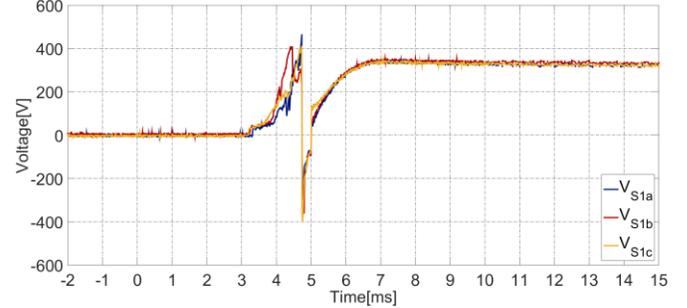
Fig. 9 shows the tests with high-impedance DC fault. It is known that low current interruption may be more challenging with mechanical DC CBs, since current derivative at zero crossing is larger when DC current is low [3]. The arc voltage is significantly larger at low current and it is seen that the current is almost interrupted before the injection circuit is activated. It is noted that the shape of observed arc voltage is characteristic for air-interrupters, while in vacuum interrupters the arc will be much smaller.



a) DC voltage, S_1 current and arrester voltage.



b) Residual switch S_2 , and resonance switch S_3 current



c) Voltages across the contactors in S_1

Fig. 9. DC CB interrupting 65A positive fault current.

IV. CONCLUSIONS

The paper shows the detailed design of a laboratory-scale 500A, 900V mechanical DC Circuit breaker, operating in around 4ms. It is concluded that damping in the resonant circuit is quite large and therefore the initial value of resonant current is conservatively selected as 2 times the rated DC fault current. The design demonstrates that is feasible to connect 3 mechanical contractors in series and that voltage sharing can be balanced with grading resistors and capacitors.

The hardware test demonstrated successful interruption of rated 500A fault current in both positive and negative

directions. Also, the test with high-impedance faults demonstrated successful interruption of 65A current.

The timing of current injection is found to be critical for successful interruption. Sufficient time must be allowed for contacts to separate before current is injected in order to enable voltage withstand when current crosses zero.

V. ACKNOWLEDGMENTS

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VI. APPENDIX – TEST SYSTEM DATA

Component	Data
S ₁	3 x Kilovac EV200HAANA
S ₂	Kilovac EV200HAANA
S ₃	2 x Thyristor 1600V, 70A VS-70TPS16PBF
C	60μF WIMA film capacitor
L	46μH,
L _{dc}	7mH
R _{ch}	50kΩ
R _g	7.5 kΩ
C _g	50nF
Arresters	4x EPCOS B72260B0131K001 (170 V _{dc})

REFERENCES

- [1] D Jovic and K Ahmed "High-Voltage Direct Current Transmission: Converters Systems and DC Grids", Wiley 2015
- [2] M.Hajian, L.Zhang and D.Jovic "DC Transmission Grid with Low Speed Protection using Mechanical DC Circuit Breakers" IEEE Transaction on Power Delivery, Vol 30, issue 3, June 2015, pp1383-91
- [3] S.Tokoyoda, at all, "DC Circuit Breakers for HVDC Grid Applications HVDC and Power Electronics, technology and developments", CIGRE B4 colloquium, Lund, May 2015.
- [4] Thomas Ericsson, magnus Backman and Stefan Halen, "A low loss mechanical HVDC breaker for HVDC Grid applications" CIGRE Paris 2014, August 2014, Paper B4-303.
- [5] J. Hafner and B. Jacobson, "Proactive hybrid HVDC breakers—A key innovation for reliable HVDC grid," in Proc. Cigre Symp., Bologna, Italy, Sep. 13–15, 2011.
- [6] Jovic, W. Lin, S. Nguefeu and H. Saad "Low Energy Protection System for DC Grids Based on Full Bridge MMC Converters" IEEE Transactions on Power Del., vol 33, iss 4, August 2018, pp 1934-1943.
- [7] Sho Tokoyoda at all "Breaking Test for High Voltage DC Circuit Breaker", CIGRE B4 colloquium, Winnipeg, Oct 2017
- [8] D Jovic and M.H. Hedayati "DC Chopper based test circuit for high voltage DC circuit breakers" IET ACDC Power transmission, Manchester, February 2017.