Design of High-Current, Low-Voltage DC CB Based on Fast Mechanical LC Topology

Dragan Jovcic
School of Engineering
University of Aberdeen
Aberdeen, AB24 3UE, UK
d.jovcic@abdn.ac.uk

Ibrahim A. Shehu
School of Engineering
University of Aberdeen
Aberdeen, AB24 3UE, UK
ibrahim.shehu@abdn.ac.uk

***Abstract*—This paper presents the application and scaling of a fast LC mechanical DC circuit breaker for high-current applications, like DC railways. The test case of 0.75 kV railways, assumes up to 70 kA peak commutating current for the worst-case f-type fault with 165 kA peak prospective fault current according to EU railway standard. The selection of all key components is discussed, and assumptions are quantified to illustrate design feasibility. The main advantage of the LC DC CB is the short operating time (around 2-3 ms), resulting in lower peak current and reduced stress on all components in the protected circuit. In addition, the LC DC CB has no arcing, implying less wear on the mechanical ultrafast disconnector. A detailed PSCAD model is developed, including the fault test circuit and LC DC CB, and simulations illustrate the expected performance. The total energy dissipation is around 110 kJ, which is absorbed by a bank of commercial surge arresters.**

Keywords—DC Circuit Breakers, Low Voltage DC systems, DC distribution, Railway Circuit Breakers

I. INTRODUCTION

DC Circuit breakers have been used in DC railway traction systems at voltages of 0.75 kV – 3.6 kV for many years [1][2]. Railway standards stipulate quite high steady-state fault currents of up to 125 kA [1]. As low and medium voltage DC systems are expected to develop further in other industries [3], the demand for DC CBs will increase. In some applications, like with electric guns, accelerators, DC collection [3], superconducting systems [4] or large DC storage the fault current magnitude can also reach very high values.

Commercial railway DC CBs are have quite long breaking time, often even longer than 100 ms [2]. There are 3 classes of commercial railway DC CB (H, V, S) according to [2], but even the fastest category (also called limiting breakers) has quite long breaking time of around 20 ms [5][6]. A faster DC CB in these high-current applications would bring many benefits such as lower equipment stresses and less intrusive faults, but shortening breaking time has been very challenging with the commercial DC CB technologies [5][6].

Since 2010 there has been rapid development of DC CB technologies for medium and high voltages [7][8][9] and multiple DC CBs have been installed, including 525 kV units at Chinese Zhangbei DC grid [10]. These DC CBs generally operate in 2-5 ms, although the breaking current capability is 16-20 kA. The most commonly used technology is the hybrid DC CB, which has breaking time of around 2 ms [11].

A recent study focused on the application of hybrid DC CBs to railway applications [12], and the possible benefits are clearly described. However, hybrid DC CB will require continuous cooling system for the semiconductors in the main branch (implying reliability concerns) and the costs will be high. Also, the peak interrupting current of semiconductors is limited, and this study considers around 90 kA prospective fault current which is lower than worst-case in [1] (125 kA).

LC DC CB topology has been proposed for medium and high voltage applications [13], and a 5 kV, 2 kA prototype was developed in university laboratory recently [9]. This is essentially a mechanical DC circuit breaker, but it has been demonstrated that the opening speed is below 2 ms and therefore comparable with fastest hybrid topologies.

In this study, LC DC CB technology is examined for applications with low DC voltage but very high currents, especially the 0.75 kV DC railway market. The aim is to complete the initial design and evaluate the feasibility and sizing of key components through detailed simulation. A detailed PSCAD simulation model is developed to evaluate components stresses and validate performance. Furthermore, a comparative analysis highlights the operational advantages over conventional DC CBs.

II. LC DC CB FOR HIGH-CURRENT AND LOW VOLTAGE

A. LC DC CB topology

Fig. 1 shows the LC DC CB topology considered for high-current applications. It is a mechanical DC CB but there is no arcing while breaking current. The key components are [13]:

- Ultrafast disconnector S_1, with no arcing capability,
- Large capacitor C_s, to limit voltage gradient,
- Energy absorber (arrester bank SA),
- Charging circuit (diode bridge, T_c and R_c),
- Discharge switch (T_t, D_t).

Switch S_1 is commanded to open immediately on receiving trip signal, but it will take some time (around 0.5-1 ms) for contacts to separate. At separation T_t is fired and current commutates to C_s [13]. The commutation therefore occurs at the initial stages of the stroke thus reducing operating time.

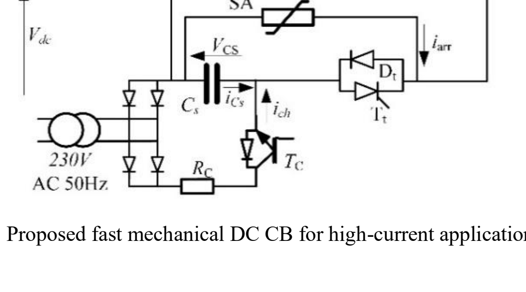


Fig. 1. Proposed fast mechanical DC CB for high-current application.

XXX-X-XXXX-XXXX-X/XX/$XX.00 ©20XX IEEE
979-8-3315-8138-1

B. LC DC CB design assumptions

Conservative assumptions are adopted in this initial design. The assumptions for the fast mechanical switch S_1 are shown in TABLE I. This is based on the assumption that commercial design for 12 kV disconnector in the ongoing MISSION project in [14] can be downscaled to 0.75 kV.

The protection system plays an important role in the overall speed of fault interruption, and the assumed basic structure is shown in Fig. 2a). Considering typical 3 kA load current, a double trip criterion is used: DC current $I_{dc}>D_{th1}$ and voltage derivative $dV_{dc}/dt_c>D_{th2}$. A further conservative relay processing delay of T_{d1}=0.5 ms is adopted.

The controller model for DC CB is shown in Fig. 2b). A delay of T_{d2}=0.5 ms represents the time to contact separation [9]. The delay for discharge activation is small (T_{d3}=0.01 ms) to consider commutation to capacitor, while T_{d4}=10 ms represents the time for operating residual breaker S_2 (it serves to interrupt leakage arrester current and provide isolation).

TABLE I. DISCONNECTOR SWICTH S_1 ASSUMPTIONS

Dielectric	Air (d_{air}=2 kV/mm)
Safety margin	4 ($d_{S1}=d_{air}/4$)
Contact separation velocity	2- 4 m/s
Number of break points	4
Total contact distance in open state	4 mm, (2/0.5)
Total opening time	1-2 ms
Time to contact separation	0.5 mm

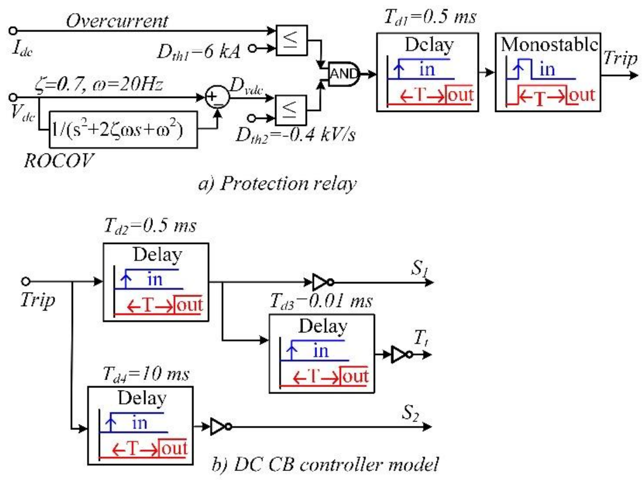


Fig. 2. Protection model and DC CB control.

C. Capacitor Cs calcualtion

Capacitor C_s is the main component in terms of cost/size. The capacitance is determined using a design equation that considers: commutating current, contact velocity and dielectric strength as analysed in [13]. It is initially assumed that the worst-case commutating current is up to 70 kA, as discussed in Section III. With the above assumptions for switch S_1, Fig. 3 shows the design range for capacitance C_s. A value of C_s=8.7 mF is adopted for further study, considering the slowest (conservative) expected contact velocity of 2 m/s.

III. DC CB TEST CIRCUIT ACCORDING TO RAILWAY STANDARD

The railway DC CB standard recommends the test circuit topology and a range of fault current profiles, but parameters and performance details are not specified [1]. Fig. 4 shows the PSCAD test circuit model with all parameter values, which resembles the model in SIMULINK proposed in [12] and [15].

Only duty designated as "f" [2] is studied, since this is fault with highest current typically representing rectifier DC breaker with minimum-impedance fault. The simulation of f-duty DC fault is shown in Fig. 5, which gives much higher current and a steeper slope than faults in [12] and [15]. The prospective steady-state fault current is I_{ss}=125 kA, and the peak value of $\widehat{I_{ss}}$=165 kA is close to the recommended 1.42×I_{ss}, (largest I_{ss}=125 kA) in [1]. The average current derivative is around 16 kA/ms, which is significantly larger than the minimum value of 5 kA/ms given in [1]. Using this response, and assuming 2-3 ms total time to commutation (as described in II.B) we can conservatively extrapolate that the commutating current in LC DC CB will be below 70 kA, as shown in Fig. 5. Therefore DC fault current will be interrupted (or limited) by LC DC CB before it reaches prospective value.

It is noted that in most practical applications fault current profile will be less onerous than this and also an additional inductor can be placed as it is practice in HV applications [8], to reduce current derivate and current at commutation. Lower commutating current will have impact on reduced size/cost of DC CB components (Cs, SA and T_t).

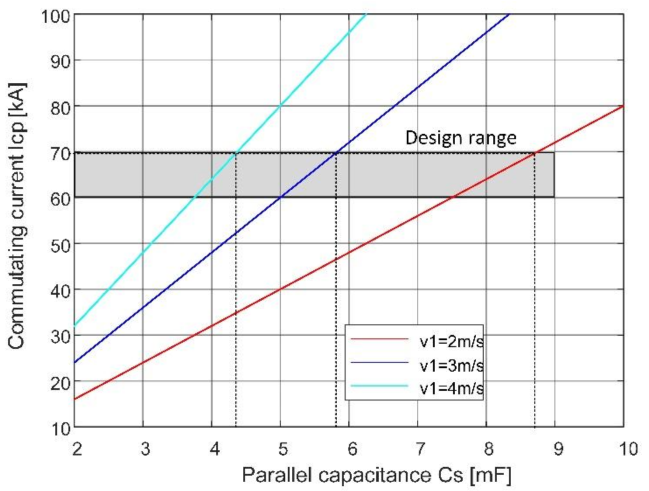


Fig. 3. Capacitor Cs versus interrupting current for given contact velocity.

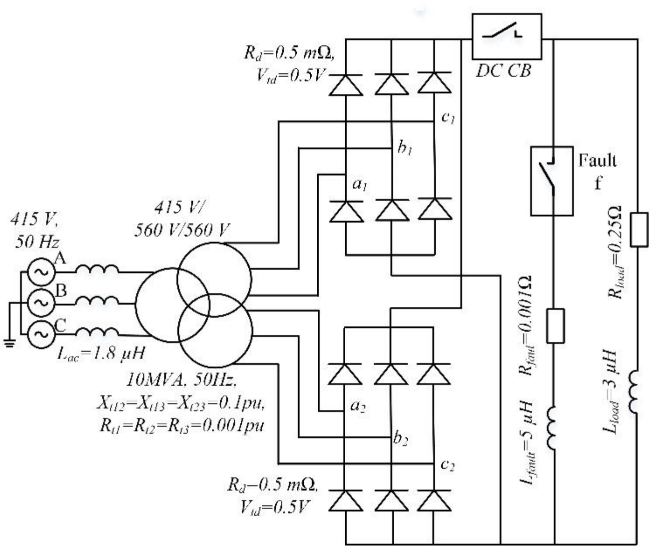
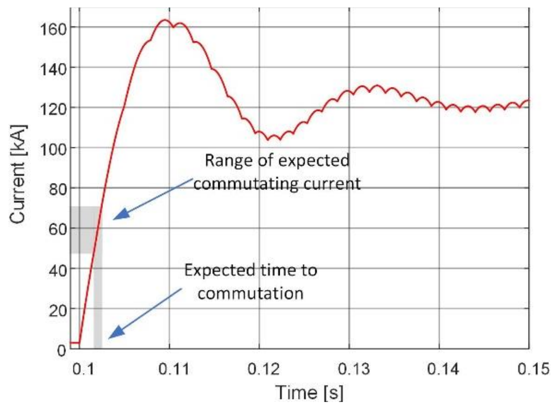
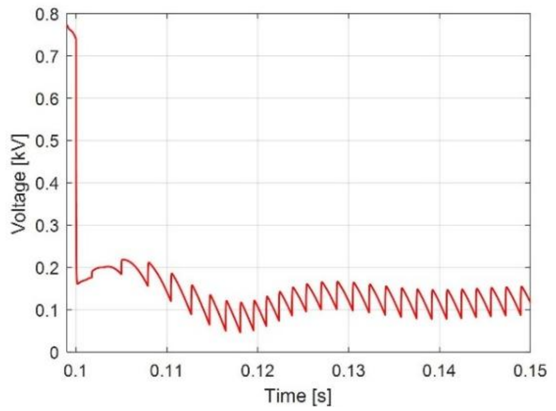


Fig. 4. Test circuit for railway DC CB according to BS/EN 50123-1, 2003.



a) Current



b) Voltage

Fig. 5. Test circuit response with DC CB closed.

IV. Simulation Results and Stress Analysis

A. Simulation model

A detailed DC CB model is developed in PSCAD as shown in Fig. 6. The fast disconnector is modelled using 2 switches (S_{1a} and S_{1b}) with an arc model (R_{arc}) in parallel with S_{1a}, and the arc voltage is represented using a look-up table based on the Pauckert model [16]. Switch S_{1a} opens at any current, and current is then commutated into the arc resistor (or equivalent voltage source). However, switch S_{1b} is configured to open only if the current is below a small chopping value (I_{ch} = 2A) to represent realistic arc interruption and dielectric recovery conditions.

The values for all DC CB parasitics ($R_{p1\text{-}2}$ and $L_{p1\text{-}3}$) are shown in TABLE II. which are conservative values obtained based on studies in [17], and from component datasheets.

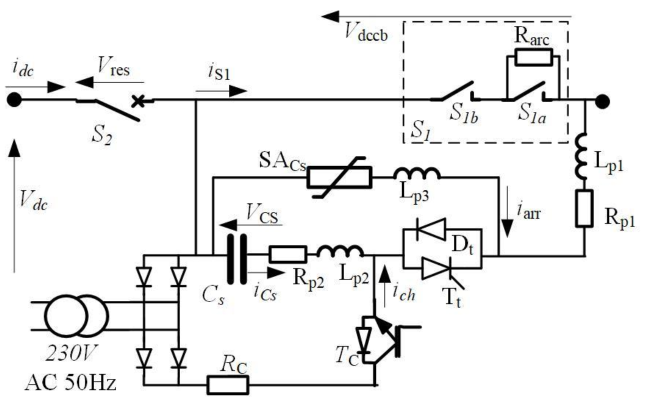


Fig. 6. Model of DC CB developed in PSCAD.

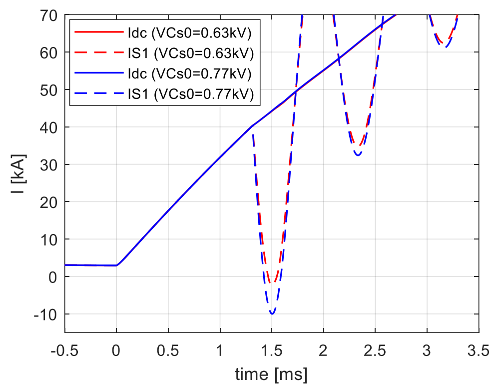
TABLE II. Values for parasitics

Parameter	R_{p1} [mΩ]	L_{p1} [μH]	R_{p2} [mΩ]	L_{p2} [μH]	L_{p3} [μH]
Value	0.5	2	0.17	0.01	0.5

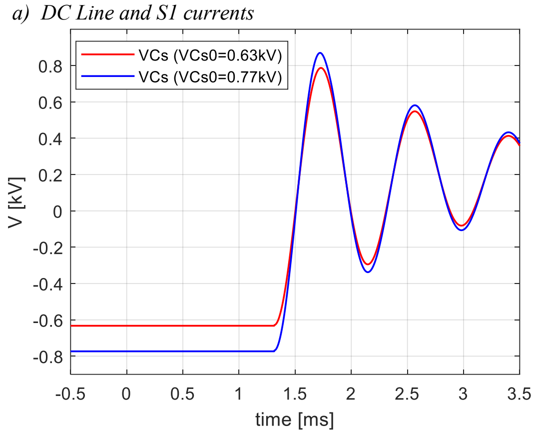
B. Commutation and zero crossing simulation study

The capacitor C_s capacitance in Fig. 3 is adequate for current commutation (from S_1 to C_s) and for safe contact separation if there were no parasitics. Because of parasitics, it is necessary to insert a voltage source in the commutation path at the commutation instant. In previous studies for high-voltage applications [9], another low-voltage pre-charged capacitor is employed. For low-voltage applications, it is more cost effective to pre-charge the existing capacitor C_s to a negative voltage, as shown in Fig. 6.

Fig. 7 shows the study of commutation for various values of the initial C_s voltage V_{Cs0}, which is executed by keeping switch S_1 closed. It is seen that with V_{Cs0}=0.63 kV, commutation would be successful (S_1 current drops to zero) but with minimal margin. The initial voltage of V_{Cs0}=0.77 kV is adopted as it gives adequate commutation margin (approximately 10 kA).



a) DC Line and S1 currents



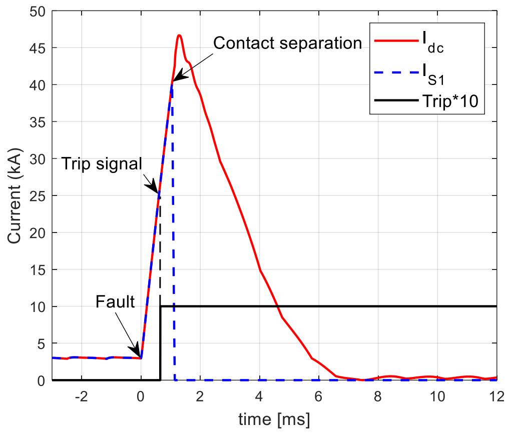
b) Capacitor C_s voltage

Fig. 7. Analysis of commutation for different values of V_{Cs0}.

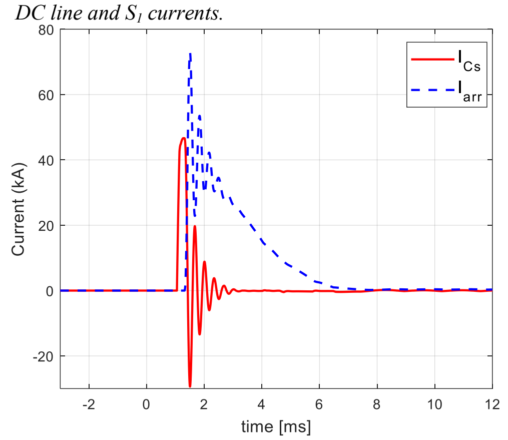
C. Current interruption simulation responses

Fig. 8 shows the simulation of fault current interruption with the selected design, and with variables defined in Fig. 6.

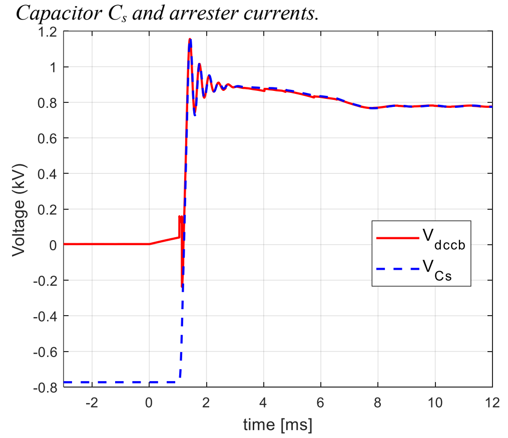
In Fig. 8a), it is seen that the trip signal is sent to the DC CB when the fault current is around 25 kA, and because of the contact sliding time of 0.5 ms, the commutating current at contact separation (I_{S1}) is around 40 kA. This is lower than the assumed design point in Fig. 3, and therefore provides adequate margin. Once current is commutated to capacitor C_s, it continues to rise for a short time and reaches 47 kA peak.



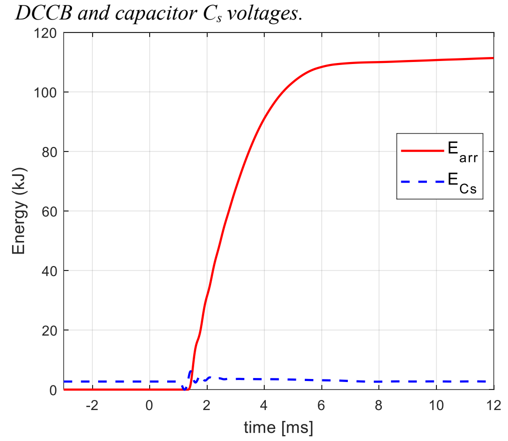
a) *DC line and S_1 currents.*



b) *Capacitor C_s and arrester currents.*



c) *DCCB and capacitor C_s voltages.*



d) *Arrester and capacitor C_s energies.*

Fig. 8. Simulation of DC CB operation.

Fig. 8b) shows the capacitor current (I_{Cs}), which equals line current after successful commutation. The arrester current (I_{arr}), reaches line current when capacitor voltage rises beyond the clipping value (around 1.5 pu).

In Fig. 8c), it is seen that the DC CB voltage (V_{dccb}) reaches peak value of 1.15 kV, which is an important value for minimising cost of the large C_s capacitor bank.

The energy absorbed in the arrester SA (E_{arr}) is around 110 kJ, while C_s energy (E_{Cs}) is much lower as shown in Fig. 8d).

V. Component Selection

A. *Thyristor T_t and Diode D_t stresses*

The discharge switch (T_t and D_t) will take the full fault current after commutation, which peaks at 47 kA and therefore careful stress analysis is required. TABLE III. shows the summary of I^2t and peak voltage stress for the semiconductors obtained from the simulation responses.

TABLE III. Semiconductor stress

Component	Thyristor T_t	Diode D_t
I^2t [A^2s]	731×10^3	108×10^3
Peak voltage [kV]	1.2	1.2

B. *Component list*

TABLE IV. shows the list of selected key LC DC CB components, based on the design and simulation results discussed above.

The selected thyristor provides adequate I^2t capacity but has a relatively low continuous current rating (1.2 kA), which keeps its cost modest. A similar conclusion applies to diode D_t.

The required capacitance C_s can be readily achieved using 6 commercial 1.5 kV, 1.45 mF film capacitors connected in parallel.

A commercial railway arrester rated at 0.44 kV will provide the required clipping voltage, and the required energy capacity can be achieved with 10 units in parallel.

TABLE IV. LC DC CB Key Components

Component	Description	No. Required
Thyristor Tt	Infineon T880N18TOF 1.8 kV, 1.2 kA, 1200×10^3 A^2s (£110)	1
Diode D_t	Vishay VSKE320-20PBF, 2 kV, 320A, 330×10^3 A^2s (£113)	1
Capacitor C_s	KEMET C44USGT7145M34K, 1.5 kV, 1.45 mF, Φ136 mm × 350 mm (£161)	6 in parallel (8.7 mF total).
Arrester SA	ABB POLIM-R 0.44-2 N, 105 mm × 106 mm × 65 mm, rated voltage U_c=0.44 kV, residual voltage for 30/60 µs wave 1.17 kV, energy 24 kJ/kV (Uc)	10 in parallel.

VI. Comparisons

Although no detailed test case comparisons are performed, the following list provides a brief summary of expected benefits:

1.) Fault Interruption Speed. Peak fault current (also DC voltage recovery) is reached in 2-3 ms compared to 20-100 ms with commercial DC CBs. This faster interruption will lower stress on all circuit components and improve load recovery.

2.) Minimal Arcing. Commercial DC CBs have long arcing time (20-100 ms), which causes component wearing and has detrimental visual/audio impact on railway users. The LC DCCB significantly reduces arcing.

3.) Reduced energy dissipation. With LC DCCB, energy is dissipated in arresters, which have less intrusive impact compared with arc-based dissipation.

4.) Maintenance and Operations. Conventional DC CBs require frequent maintenance due to high temperatures and contact erosion in the arcing chamber. The LC DCCB requires less maintenance and allows for a higher number of operations.

VII. Conclusions

The railway DC circuit breakers are required to break very high currents, and while several technologies exist, they all have relatively long breaking times, typically in the range of 20-100 ms.

LC DC CB technology has been developed for medium and high voltage applications, and this study demonstrates that it can be developed for low-voltage, high-current applications (specifically 0.75 kV railways). The design concludes that all key components are commercially available and that operation is feasible within 2 ms with ultrafast disconnector which can be adopted and redesigned from 12 kV application. Simulations performed with a detailed PSCAD model and operating conditions consistent with EU railway standards illustrate feasibility and performance much better than existing commercial DC CBs.

Simulation results show that the LC DC CB can interrupt DC fault current within 3 ms, and that the peak fault current may not exceed 50 kA, for worst case f-fault with prospective peak fault current of 165 kA (steady-state current of 125 kA). In practical terms, the benefits of the LC DC CB are in lower stresses on system components, absence of arcing (eliminating mechanical wearing) and less intrusive fault behaviour.

Acknowledgment

This project has received funding from Horizon Europe under the grant agreement no 101135484 (MISSION project), and UK partner from UKRI grant agreement 10070225.

References

[1] EN 50123-1:2003. Railway applications. Fixed installations. D.C. switchgear. Part 1: General.

[2] EN 50123-2:2003. Railway applications. Fixed installations. D.C. switchgear. Part 2: D.C. circuit breakers.

[3] CIGRE Brochure 875, Medium Volateg DC distribution systems" CIGRE WG C6/B4.37, July 2022,

[4] Hajiri, Ghazi, Kévin Berger, Frederic Trillaud, Jean Lévêque, and Hervé Caron. 2023. "Impact of Superconducting Cables on a DC Railway Network" *Energies* 16, no. 2: 776.

[5] Artur Rojek "Parameters of DC high-speed circuit-breakers" 13th International Conference Modern Electrified Transport – MET'2017, July 2018.

[6] Artur Rojek and Marek Skrzyniarz "Contact arc time – important parameter of DC high-speed circuit-breakers" 2nd International Scientific and Practical Conference "Energy-Optimal Technologies, Logistic and Safety on Transport" (EOT-2019), October 2019.

[7] D. Jovcic, G. Tang and H. Pang, "Adopting Circuit Breakers for High-Voltage dc Networks: Appropriating the Vast Advantages of dc Transmission Grids," in IEEE Power and Energy Magazine, vol. 17, no. 3, pp. 82-93, May-June 2019

[8] CIGRE WG A3/B4.80 "Design, test and application of HVDC circuit breakers" CIGRE technical brochure 873, Paris, July 2022

[9] Dragan Jovcic, "LC DC Circuit Breaker based on Pre-charged Capacitor Commutation", Electric Power Systems Research, Volume 208, 2022, 107896, ISSN 0378-7796.

[10] Rene P. P. Smeets, Nadew A. Belda "High-voltage direct current fault current interruption: A technology review" IET High Voltage 6 (2), December 2020, pp. 171-192

[11] Häfner, J., Jacobson, B.: 'Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids'. Proc. CIGRE 2011 Bologna Symp., Bologna, Italy, Sep 2012, pp. 1-7

[12] M. Xia, Y. Zhou, Y. Huang, H. Yang and Y. Tai, "Research on Short-Circuit Characteristics of Subway DC Traction Power Supply System," *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, Singapore, 2020, pp. 3456-3460, doi: 10.1109/IECON43393.2020.9254651.

[13] D.Jovcic "Fast Commutation of DC Current into a Capacitor Using Moving Contacts" IEEE transactions on power delivery, V35, Iss 2, April 2020, pp 639-646, DOI: 10.1109/TPWRD.2019.2919725

[14] D. Jovcic, "Feasibility Study of a Medium Voltage 12 kV, 1 kA, LC DC Circuit Breaker," *2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE)*, Dubrovnik, Croatia, 2024, pp. 1-5, doi: 10.1109/ISGTEUROPE62998.2024.10863252.

[15] M. X. Li, J. H. He, Z. Q. Bo, H. T. Yip, L. Yu and A. Klimek, "Simulation and algorithm development of protection scheme in DC traction system," *2009 IEEE Bucharest PowerTech*, Bucharest, Romania, 2009, pp. 1-6, doi: 10.1109/PTC.2009.5282111.

[16] Mario Zaja, Ali Asghar Razi-Kazemi, Dragan Jovcic,"Detailed electro-dynamic model of an ultra-fast disconnector including the failure mode" IET High Voltage, Vol 5, Iss 5, October 2020, Pp 549-555

[17] I Shehu, D Jovcic and R Osborne, "Feasibility of DC current commutation in capacitive circuit with 12kV DC CB" EE2025 International Symposium on Power Electronics, Belgrade, 2025.

979-8-3315-8138-1