PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

DC Circuit Breakers research trends opportunities and challenges

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PROgress on Meshed HVDC Offshore Transmission Networks

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

CONTENT

1. WP6 overview,
2. WP6 DC CB development research,
3. DC CB demonstartion in China,
4. New DC CB research trends,
5. Conclusions,

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1) Characterisation of DC CBs, WP6 overview

	Tasks	Lead	partners	timeframe
6.1	Develop system-level model for hybrid DC CB	UAbdn	ABB, SGI, DNV-GL	M1-M11
6.2	Develop system-level model for mechanical DC CB	DELFT	MEU, DNV-GL	M1-M11
6.3	Develop component-level and real-time model for hybrid DC CB	UAbdn	DELFT, ABB, DNV-GL	M18-M30
6.4	Develop component-level and real-time model for mechanical DC CB	DELFT	MEU, DNV-GL, UAbdn	M18-M30
6.5	*Develop kW-size hardware prototypes for hybrid and mechanical DC CBs*	*UAbdn*	*ABB, DEFLT, DNV-GL*	*M1-M36*
6.6	Demonstrate DC CB failure modes on kw-size hardware prototypes	UAbdn	DELFT	M31-M48
6.7	Analyse hybrid DC CB integration into EHV DC grid	UAbdn	DELFT, TenneT	M31-M48
6.8	Develop roadmap for VARC DC CB scaling to EHV DC voltage	DELFT	SciBreak, TenneT	M31-M48
6.9	Develop standard DC CB verification plan and RTDS models	UAbdn	ABB, DELFT, MEU, DNV-GL, SGI, SciBreak	M12-M24
6.10	Develop roadmap for mechanical DC CB scaling to EHV DC voltage	MEU	DNV-GL, TenneT, UAbdn	M31-M48

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1) Characterisation of DC CBs, WP6 overview

conferences published:

1. *D Jovcic and M.H. Hedayati "DC Chopper based test circuit for high voltage DC circuit breakers" IET ACDC Power transmission, Manchester, February 2017, DOI: 10.1049/cp.2017.0030*
2. *A. Jamshidifar and D Jovcic "Modelling of Hybrid DC Circuit Breaker Based on Phase-Control Thyristors", IEEE PES GM, Chicago, July 2017.*
3. *F. P. Page at all. "Mechanical Circuit Breaker Modelling for System-level, Real-time Protection System Simulations" CIGRE B4 colloquium, Winnipeg 2017,*
4. *M.H. Hedayati and D Jovcic "Low Voltage Prototype Design and Testing of Ultra-Fast Disconnector (UFD) for Hybrid HV DC CB" CIGRE B4 colloquium, Winnipeg 2017,*
5. *A. Jamshidifar, D Jovcic and A. Hassanpoor "Control methods for fault current limiting using hybrid HV DC Circuit Breakers", CIGRE Paris 2018.*
6. *A. Jamshidifar, D Jovcic. M Popov and S. Liu " Modelling and Comparison of Common Functionalities of HVDC Circuit Breakers" IEEE PES GM 2018.*
7. *M.H. Hedayati and D Jovcic "500A, 900V, Mechanical DC CB Demonstrator for HVDC applications", ISGT, Sarajevo, October 2018*
8. *D Jovcic "1200V, 200A Laboratory prototype for series LC DC Circuit Breaker" CIGRE Alborg, June 2019,*
9. *M. Wang, D. Jovcic, W. Leterme, D. Van Hertem, M. Zaja, I. Jahn "Pre-standardisation of Interfaces between DC Circuit Breaker and Intelligent Electronic Device to Enable Multivendor Interoperability", CIGRE Alborg, June 2019,*

journals published:

1. *A. Jamshidifar and D Jovcic "Design, Modeling and Control of Hybrid DC Circuit Breaker Based on Fast Thyristors", IEEE Transactions on power Delivery, October 2017, DOI: 10.1109/TPWRD.2017.2761022*
2. *M. Hedayati and D Jovcic "Reducing Peak Current and energy in HVDC CB using disconnector voltage control", IEEE Transactions on power Delivery, February 2018, DOI: 10.1109/TPWRD.2018.2812713 ,*
3. *L. Lian, S. Liu, M. Popov: Optimized Algorithm of Active Injection Circuit to Calibrate DC Circuit Breaker, submitted to International Journal of Electric Power And Energy Systems*
4. *S. Liu, M. Popov: Development of HVDC System-level Mechanical Circuit Breaker Model, submitted to International Journal of Electric Power And Energy Systems*
5. *D. Jovcic, M. Zaja and M. Hedayati, "Bidirectional Hybrid HVDC CB with a single HV Valve" IEEE Transactions on Power delivery, early access, 2019,*
6. *D. Jovcic " Series LC DC Circuit Breaker" IET High Voltage, early access, 2019*
7. *Liu, S., Liu, Z., de Jesus Chavez, J., & Popov, M. "Mechanical DC circuit breaker model for real time simulations". International Journal of Electrical Power & Energy Systems, 107, 2019, 110-119.*

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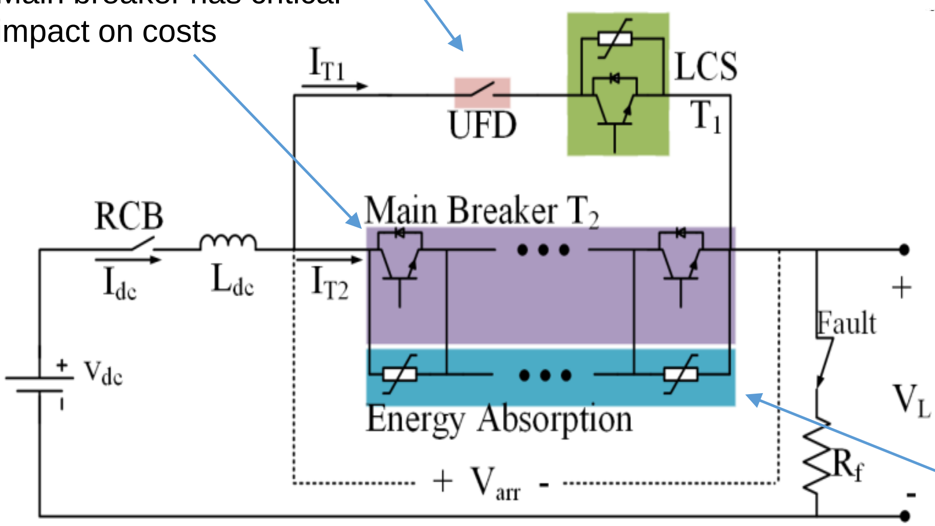
2) DC CB development in WP6

Hybrid DC CB advancement using disconnector voltage control

- Load commutation switch,
- Ultrafast disconnector,
- Main breaker,
- Energy absorber

UFD determines opening time

Main breaker has critical impact on costs



Energy absorber has critical impact on size

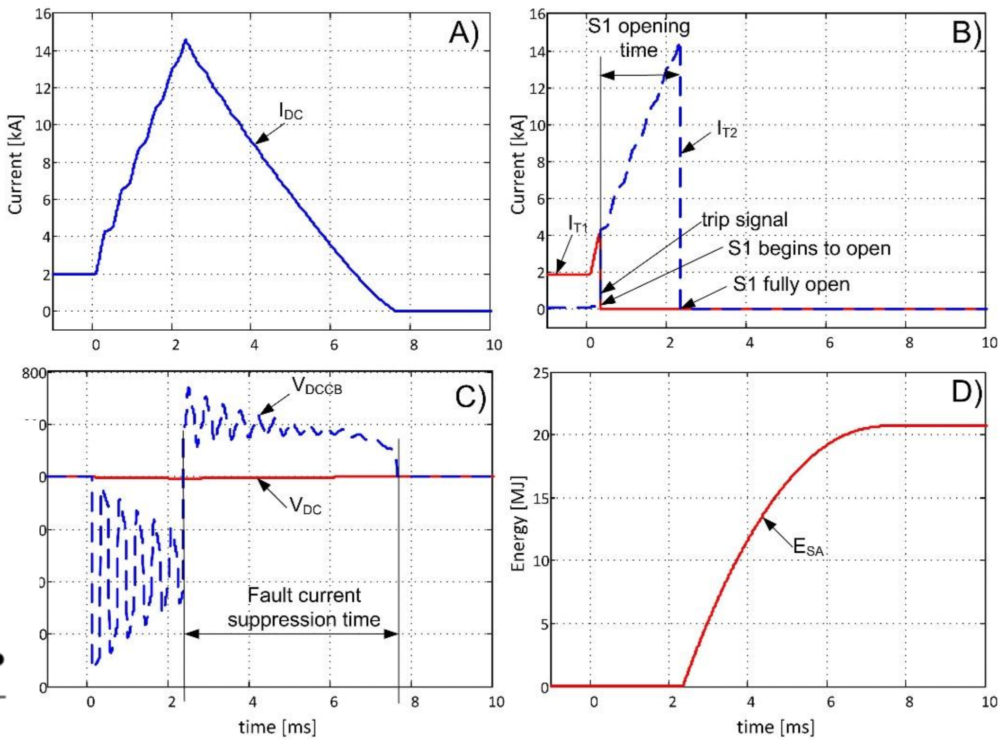


Figure 1– Hybrid DC Circuit Breaker, and typical response of 320kV, 16kA unit.

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2) DC CB development in WP6

Hybrid DC CB advancement using disconnector voltage control

- Contact position is estimated,
- UFD voltage withstand is proportional to the contact distance,
- Arresters are inserted incrementally as contact separation distance is increasing,
- Earlier insertion of arresters leads to faster current reduction,
- Controller is similar to the current limiting controller.

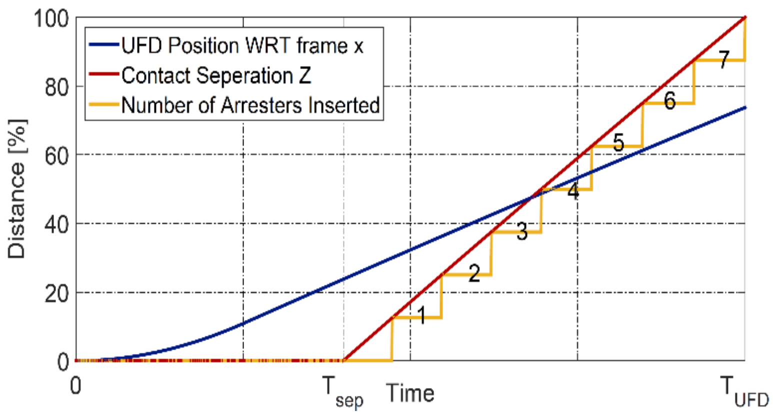

Figure 2– UFD contact position with respect to the fixed frame, UFD contact separation, and number of inserted arresters.

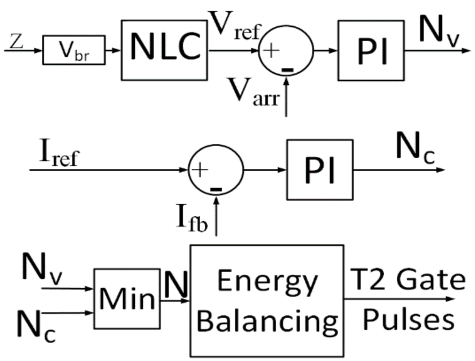

Figure 3 – Voltage controller for opening of HCB

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2) DC CB development in WP6

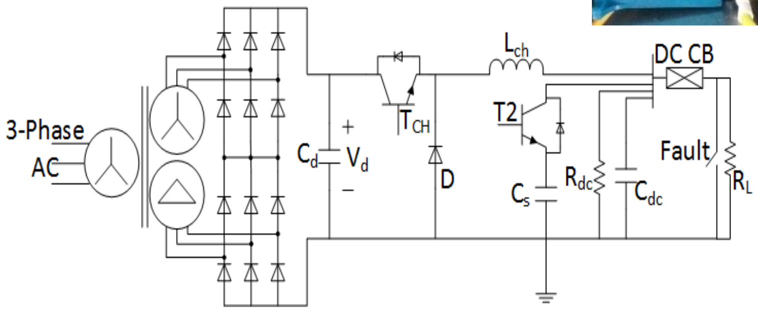
Experimental circuit in Aberdeen laboratory:

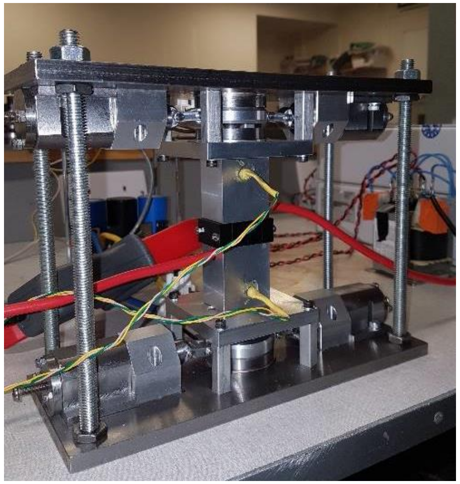
1) 1000V, 500A test system: DC voltage and current control,

2) 900V, 500A, hybrid DC CB: UFD, MB, LCS, RCB,

3) Fast Disconnector: 2ms, 3mm, 2kV, Ich<500mA,

4) Main breaker: 8 cells, 200V each,





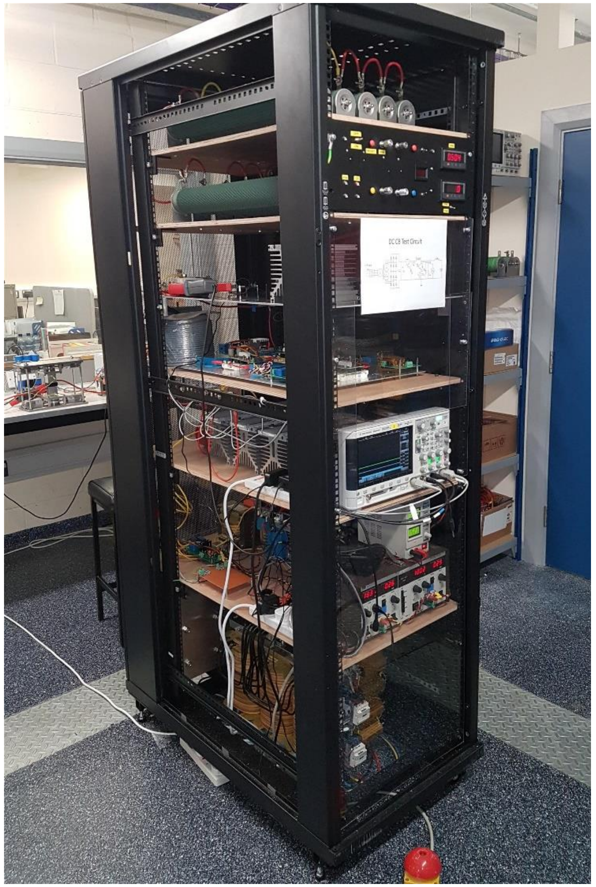


Figure 4– 500A, 1kV test circuit and hybrid DC CB.

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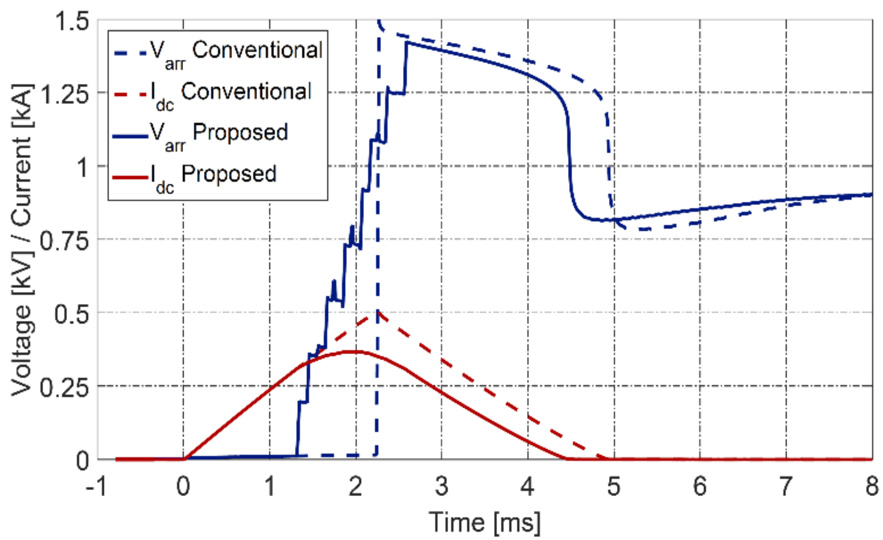
2) DC CB development in WP6

Hybrid DC CB advancement using disconnector voltage control

- Counter voltage is inserted earlier,
- Peak current is 30% lower,
- Energy dissipation is 30% lower,



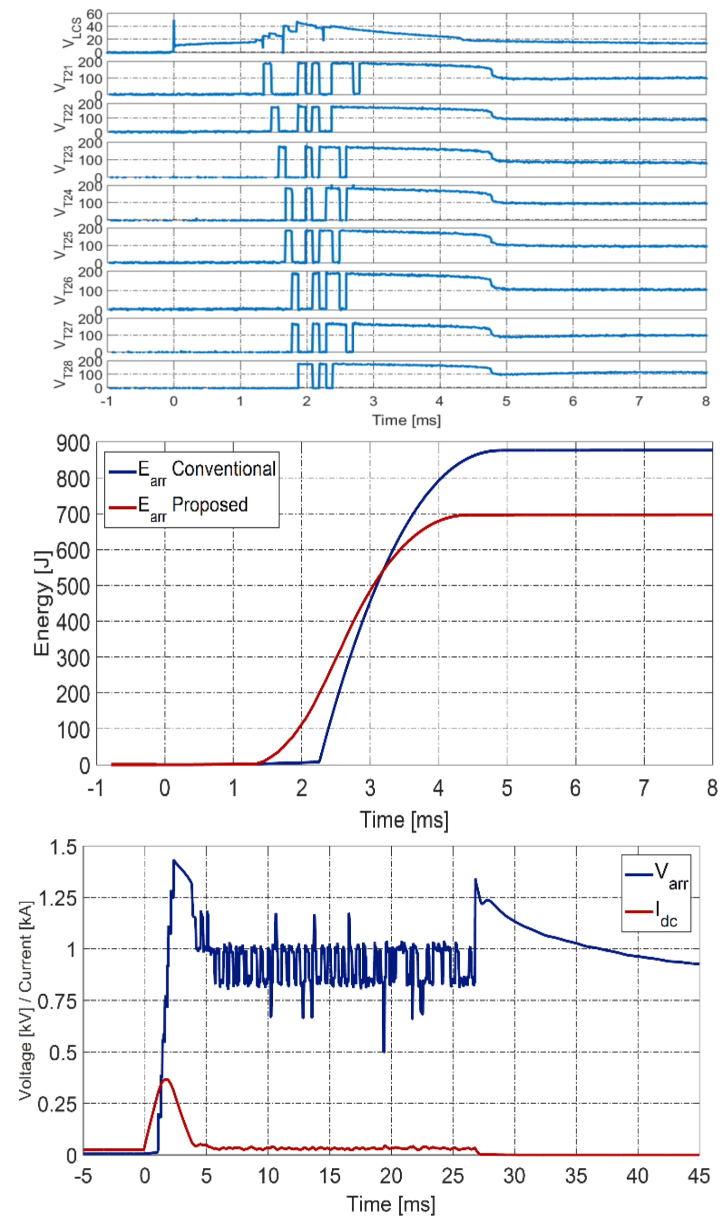


Figure 5– HCB experimental results with conventional and proposed controls.

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2) DC CB development in WP6

Bidirectional Hybrid DC CB with a single HV valve

- Hybrid DC CB is available as unidirectional or bidirectional version,
- Unidirectional DC CB may suffice in some applications,

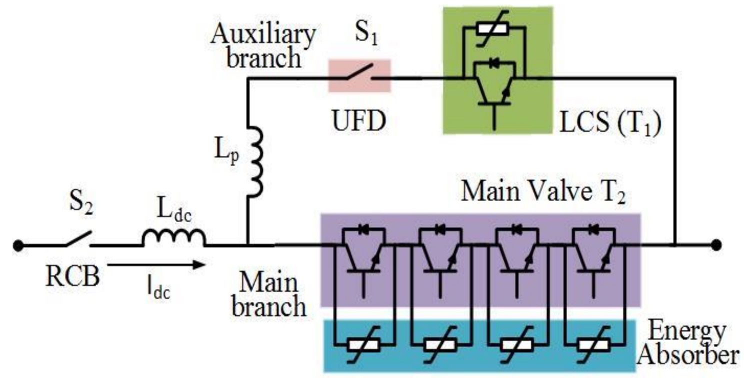

Figure 6– Unidirectional hybrid DC Circuit Breaker

Bidirectional hybrid DC CB:

- Two Load commutation switches,
- Two Main breaker valves,
- Ultrafast disconnector,
- Energy absorber,
- Cost, size and weight will be larger than unidirectional

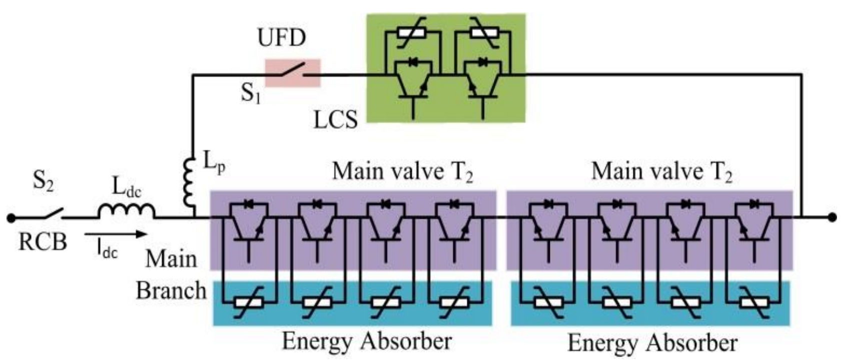

Figure 7 – Bidirectional hybrid DC Circuit Breaker

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2) DC CB development in WP6

Bidirectional Hybrid DC CB with a single HV valve and 2 UFDs

- Similar performance as original bidirectional DC CB (may require 4ms opening time),
- Significant cost reduction because of the use of a single HV valve,

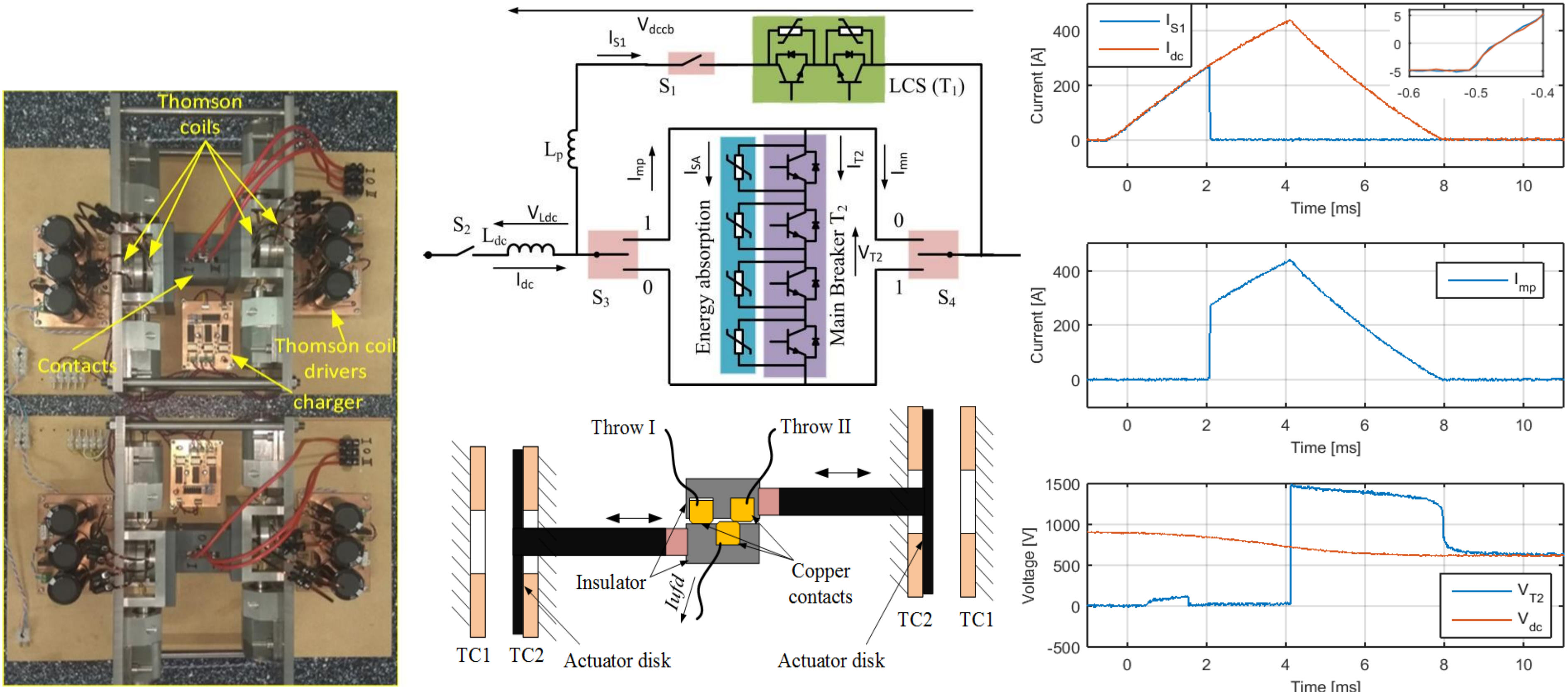

Figure 8– Bidirectional hybrid DC CB with single HV valve and 2 UFDs

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2) DC CB development in WP6

Bidirectional hybrid DC CB with single HV valve, 4 UFDs and 4 low-voltage diodes

- Same performance as original bidirectional DC CB (2ms opening time),
- Significant cost reduction because of the use of a single HV valve,

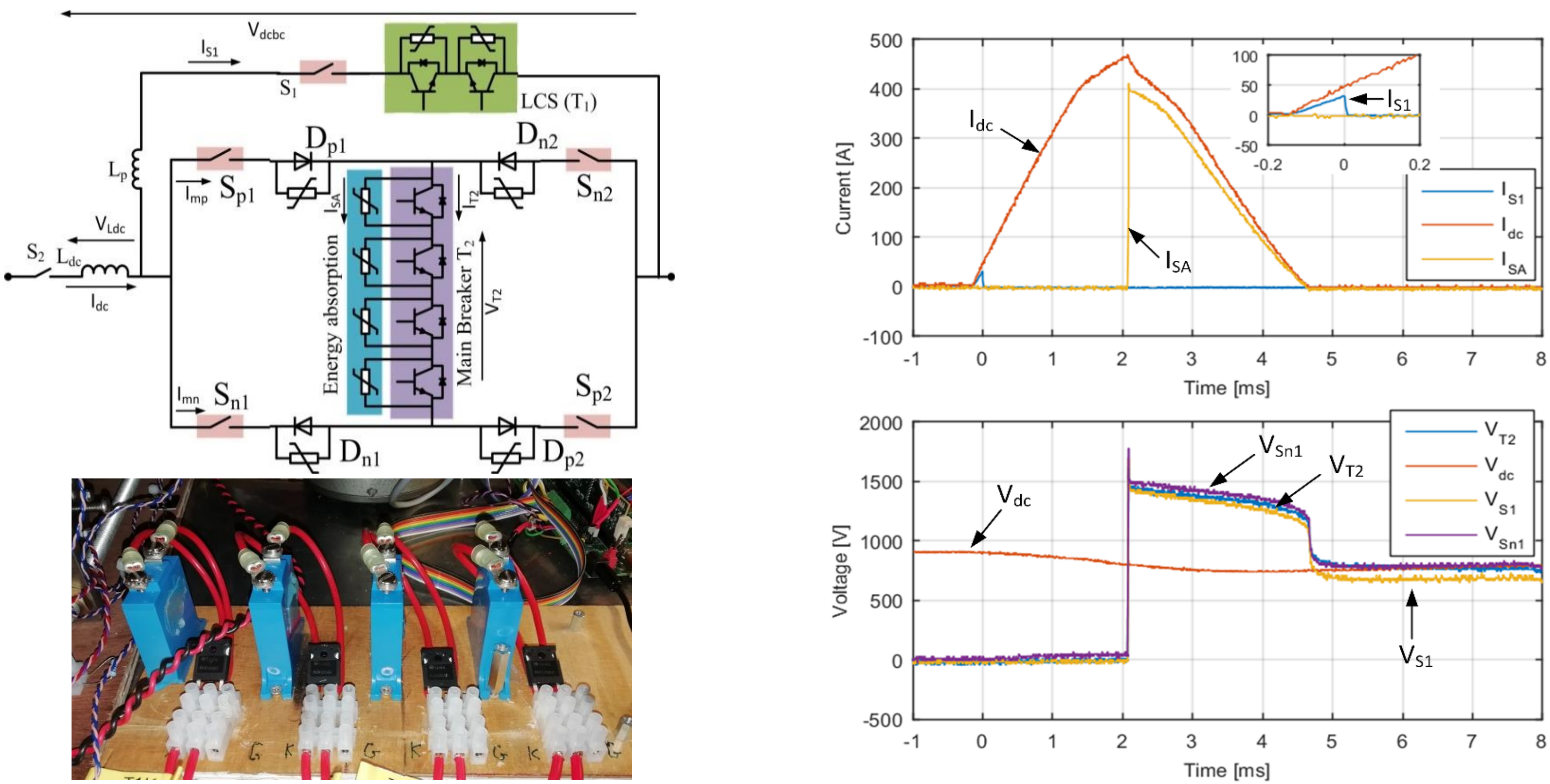

Figure 9– Bidirectional hybrid DC CB with single HV valve, 4 UFDs and 4 LV diodes.

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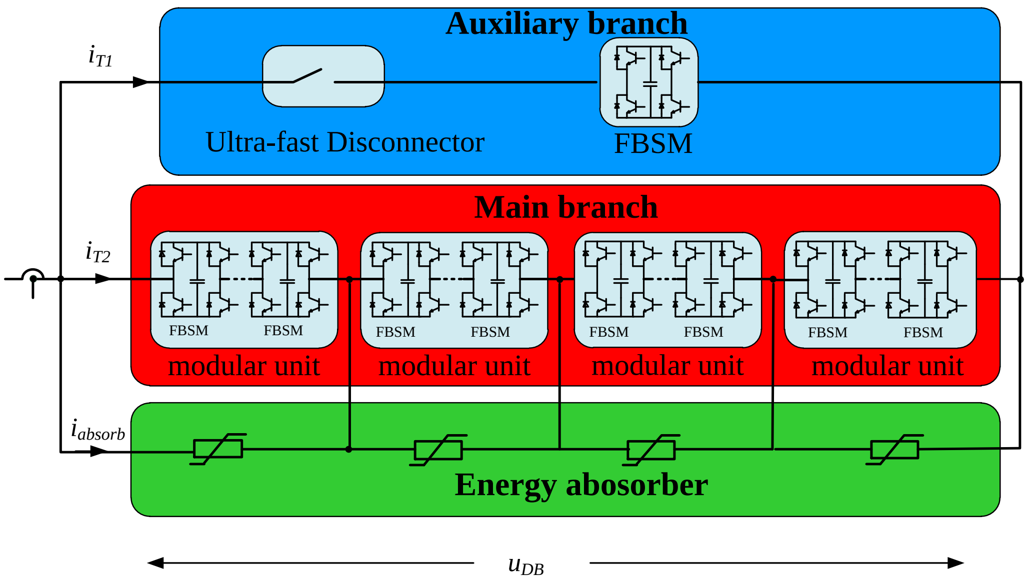
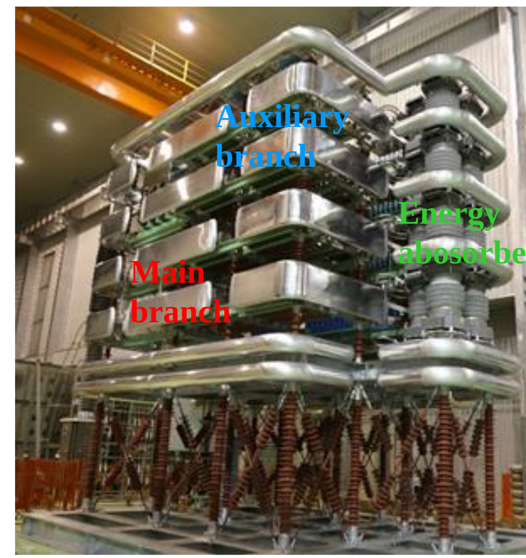
3) DC CBs installed in China

Zhoushan DC Circuit Breaker

- Similar as ABB Hybrid DC CB,
- Rated for 200kV, 15kA, 2ms,
- Uses full bridge cells in the main valve,
- Main valve is modular,
- Inherently bidirectional,
- Topology is suitable for different vendors,
- UFD is based on 6 series-connected vacuum interrupters,



(a)



(b)

Figure 10 – DC CB installed at Zhoushan MTDC [1]

[1] 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.

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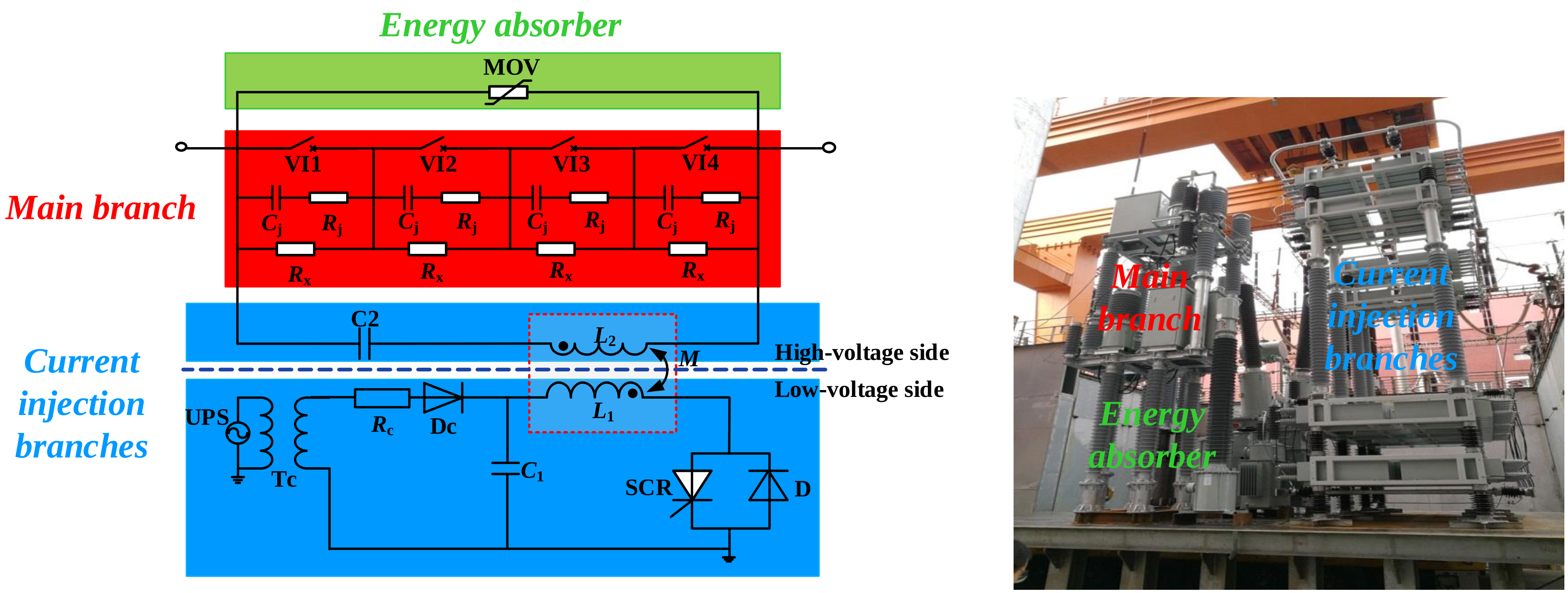
3) DC CBs installed in China

Nan'Ao DC Circuit Breaker

- Similar to MEU current injection DC CB,
- Rated for 160kV, 9.2kA, 3.9ms,
- HV closing switch is not needed,
- Current injection is activated using low-voltage circuit,
- 4 (40kV) vacuum interrupters in series,



(a) (b)

Figure 11 – DC CB installed at Nan'Ao MTDC [1]

[1] 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.

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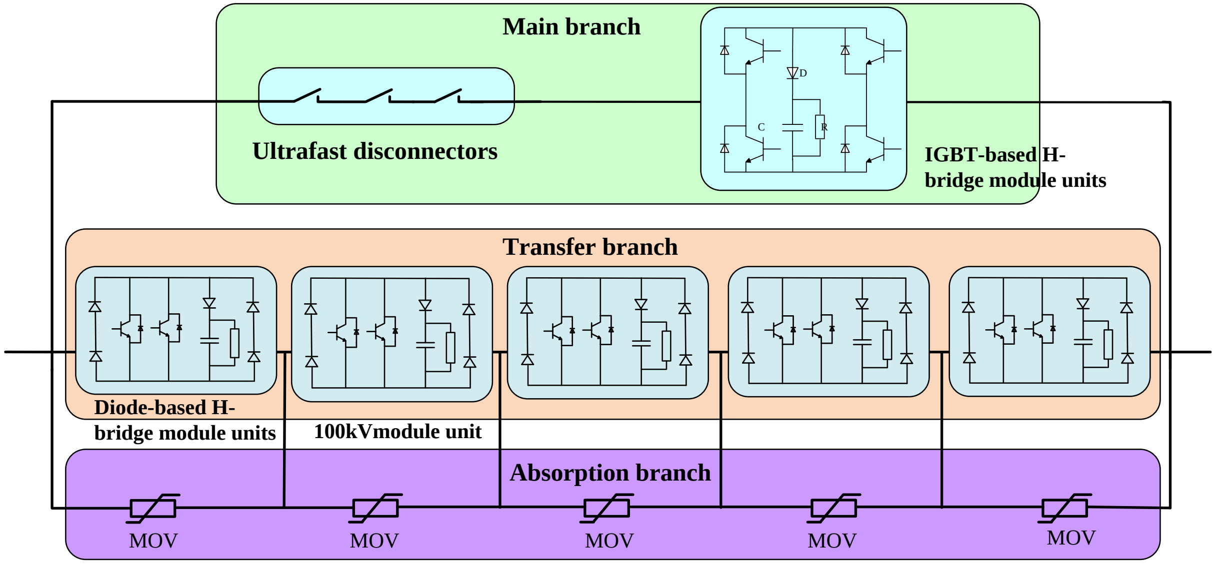
3) DC CBs installed in China

Zhangbei DC Circuit Breaker

- Similar to ABB hybrid DC Circuit Breaker,
- Rated for 500kV, 26kA, 2.6ms,
- 2 HV valves in parallel,
- Unidirectional HV valve with 4 HV diodes,



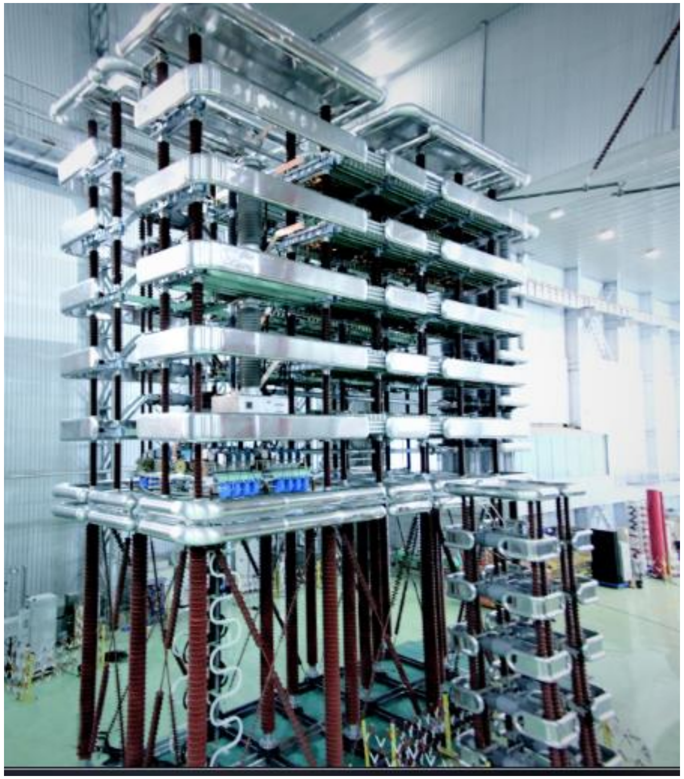


Figure 12 – DC CB developed for Zhangbei DC grid [2].

[2] G. Tang, "Research on key technology and equipment for 500kV DC grid," HVDC forum, KU Leuven, July 2018,

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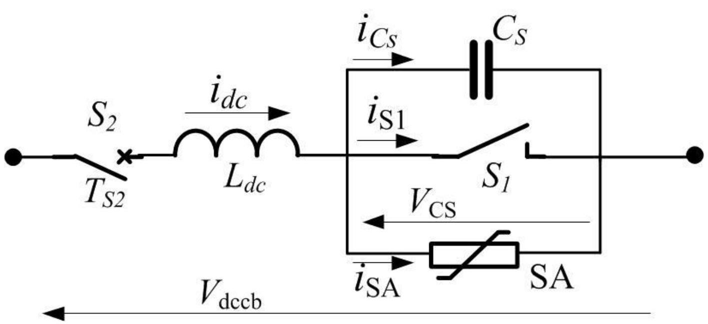
4) New DC CB research trends

Series LC DC circuit breaker components:

1) S1 is disconnector (no arcing),
2) S2 is conventional AC CB,
3) Ldc and Cs are passive components. SA limits voltage (may not be needed).

benefits

1) Control of disconnector voltage without power electronics,
2) Capacitor voltage is quite stable and can be used
to limit voltage between moving contacts,
3) Contact speed at separation determines capacitance.



Contact velocity

Dielectric strength

Commutating current

$$v_0 E_b > \frac{I_0}{C_s}, \quad z = 0, \ t = 0$$

Capacitance

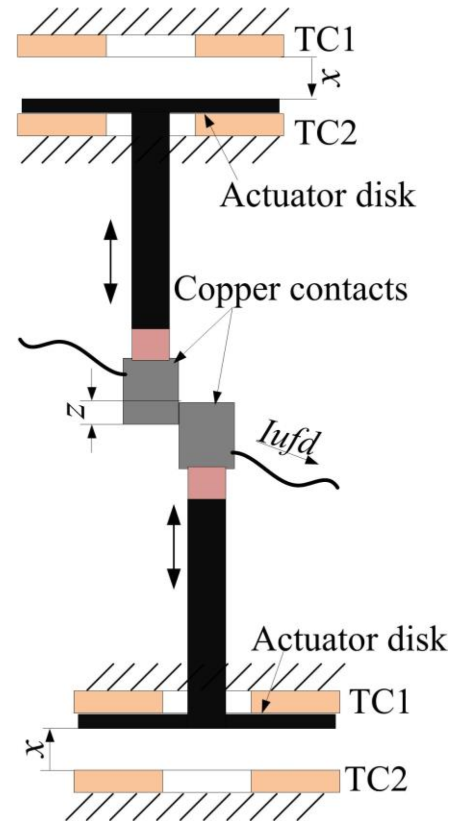


Figure 13– Schematic of series LC DC Circuit Breaker [A].

[A] D.Jovcic “Fast Commutation of DC Current into a Capacitor Using Moving Contacts” IEEE transactions on power delivery, early access 2019, DOI: 10.1109/TPWRD.2019.2919725.

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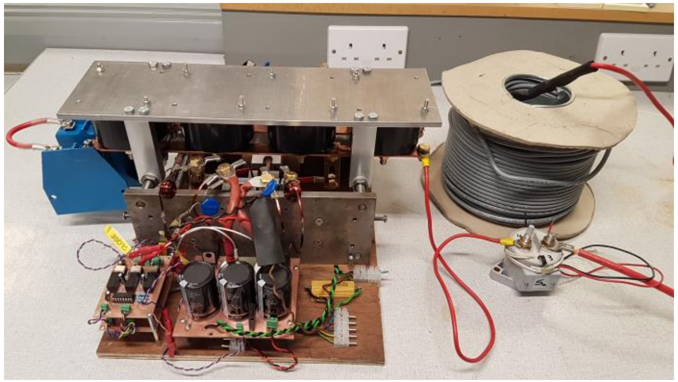
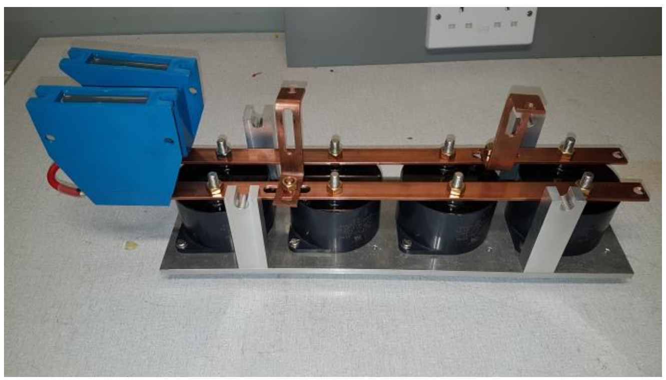
4) New DC CB research trends

Series LC DC Circuit Breaker experimental verification

- Ultrafast disconnector with 1ms opening time,
- Current commutation in 350µs,
- 490A commutation, peak voltage 1300V





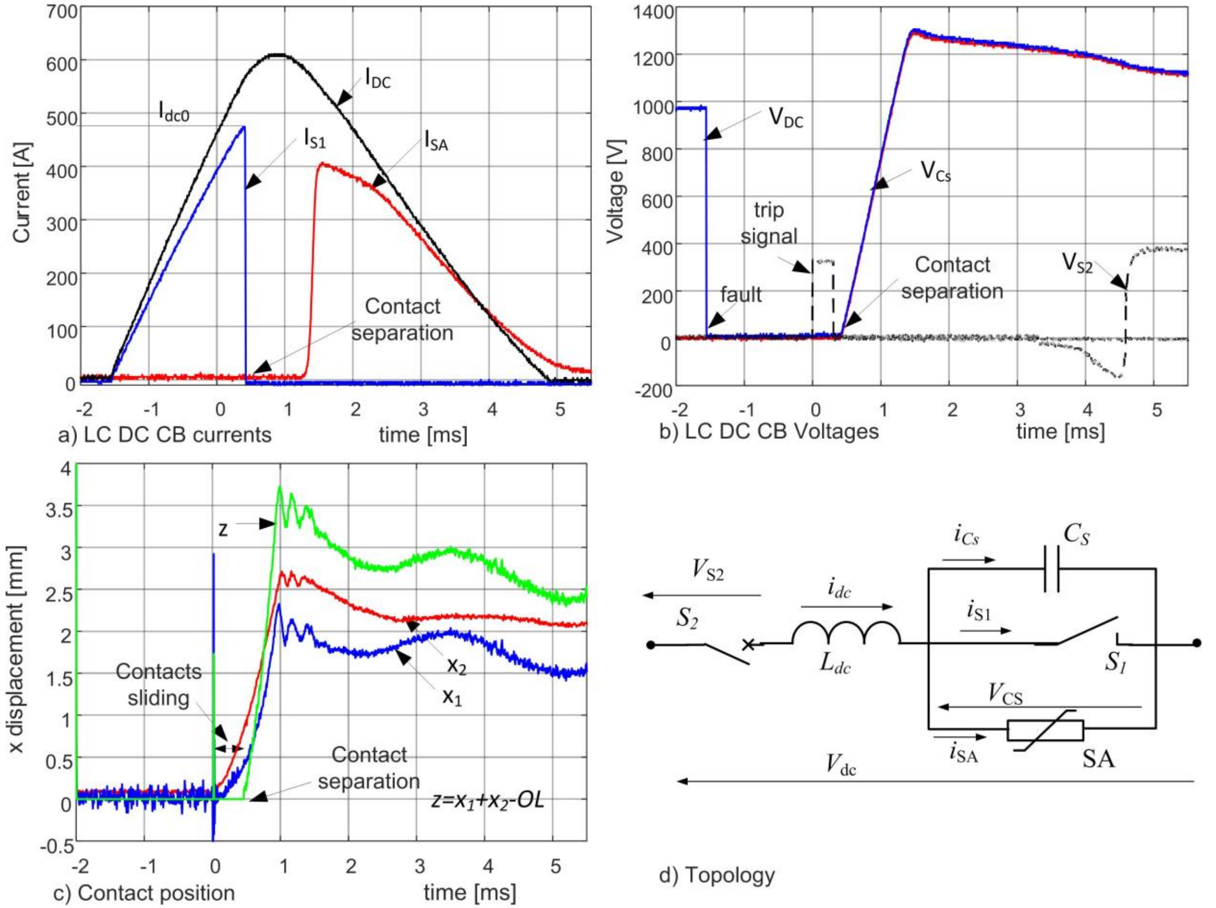


Figure 13– LC DC CB experimental verification: 0.35ms, 490A commutation, 1300V .

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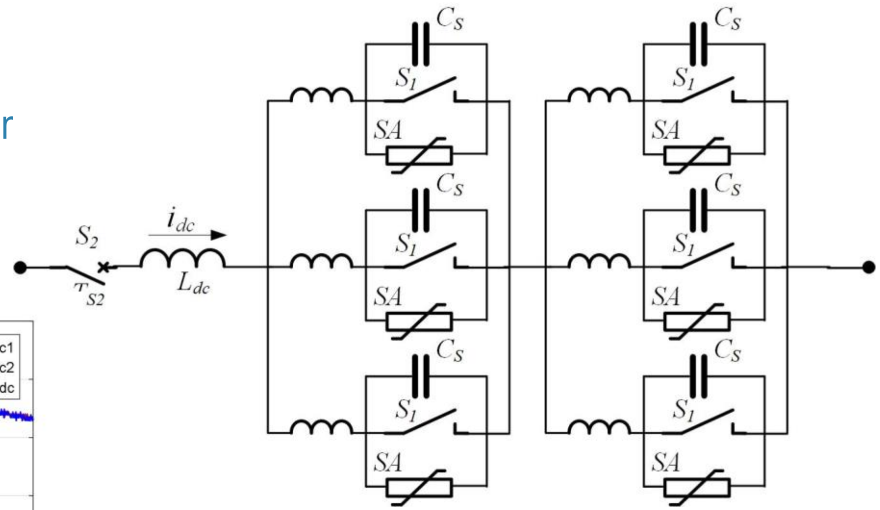
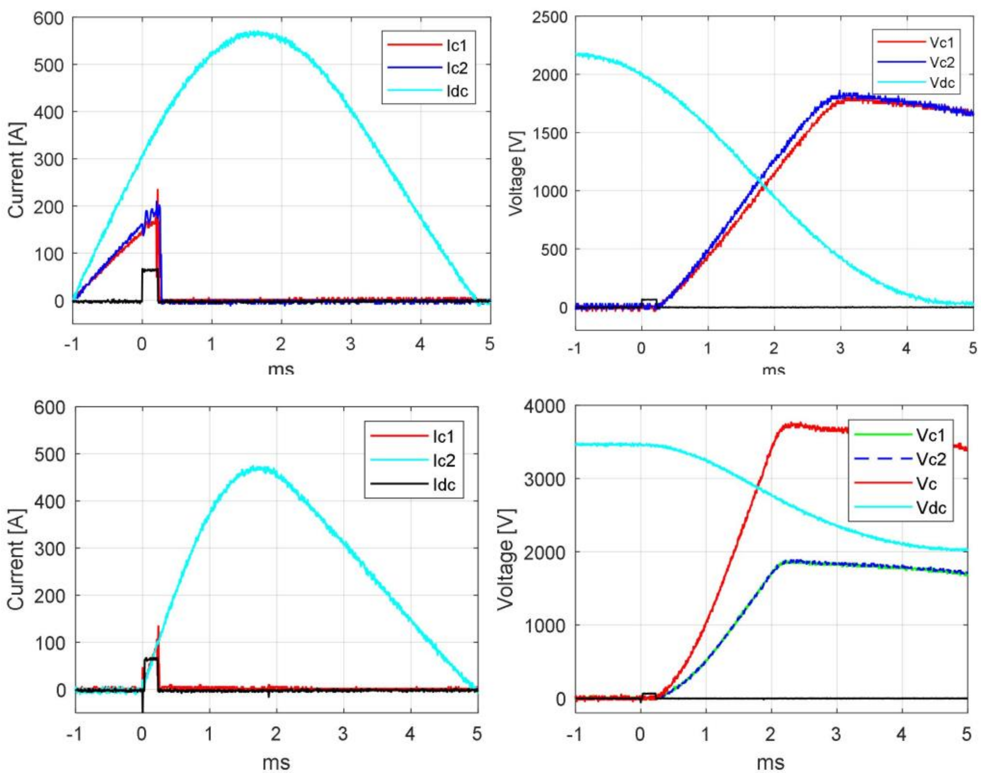
4) New DC CB research trends

Series LC DC Circuit Breaker experimental verification:

- Modular topology enables increase in current and voltage,
- LC Circuit breaker is very convenient for series/parallel conr
- Series connection (voltage sharing) has been verified,
- Parallel connection (current sharing) has been verified,





a) Two in parallel (190A+190A, 1900V)

b) Two in series (1900V+1900V, 130A)

Figure 15– Modular LC DC Circuit Breaker experimental verification.

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Series LC DC Circuit Breaker experimental verification:

- Low voltage IGBT enables commutation with parasitic inductances,
- IGBT voltage rating is very low, 220V for 900V D CB, (2-3kV for 320kV DC CB).
- The topology is similar to hybrid DC CB but capacitors are used instead of the main valve,

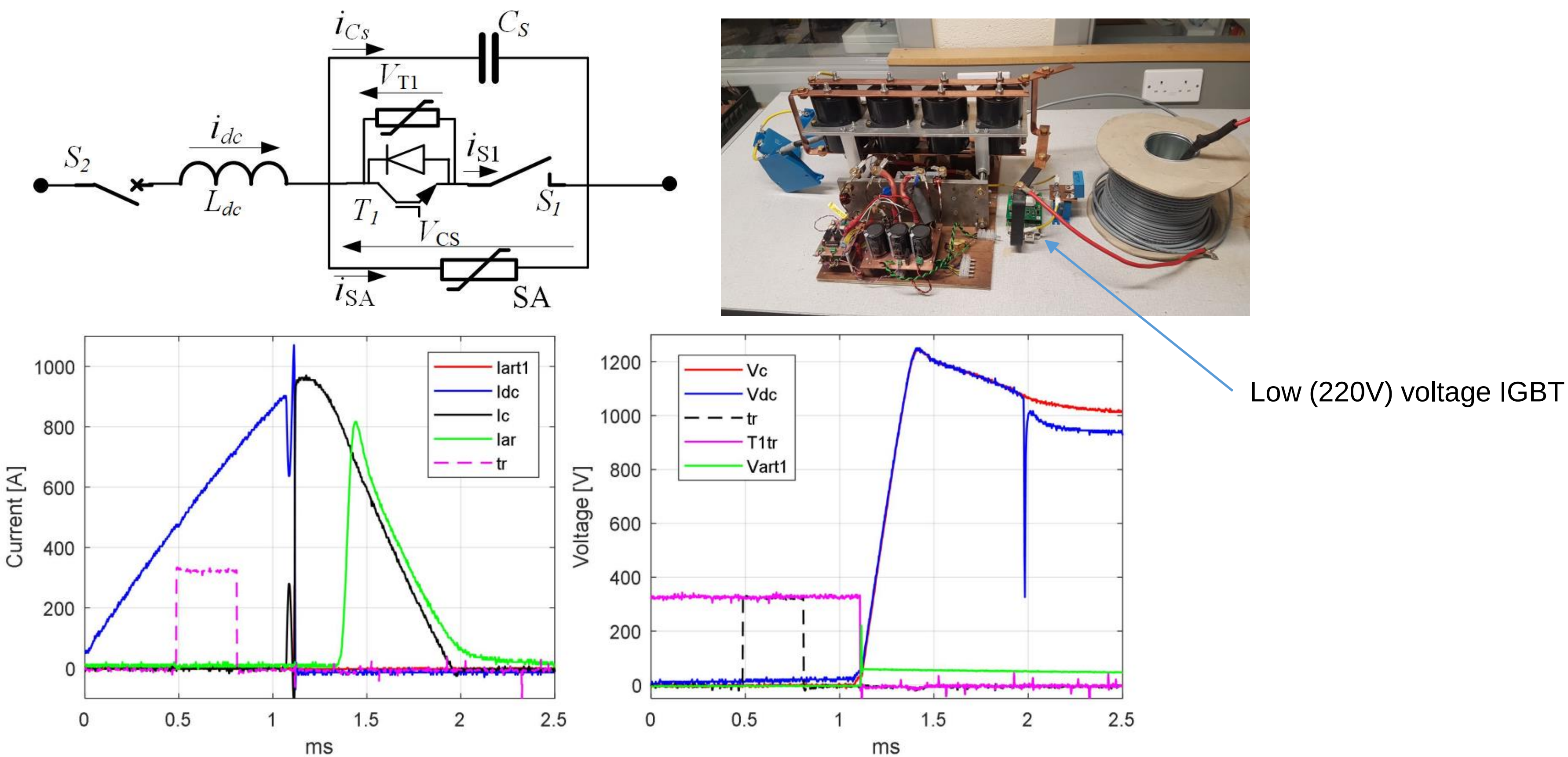

Figure 16– Series LC DC Circuit Breaker with IGBT commutation switch. 1100A,1300V.

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4) New DC CB research trends

Table I Comparison of 320 kV series LC, hybrid and mechanical DC CB for identical initial conditions.

	PARAMETERS	Series LC DC CB	Hybrid DC CB [7]	Mech. DC CB [5]
Initial conditions (identical for all)	V_{dc}	320kV	320kV	320kV
	I_{dcn}	2kA	2kA	2kA
	L_{dc}	200mH	200mH	200mH
	t_f (protection trip)	0.35ms	0.35ms	0.35ms
	I_{dcf} (t=0)	2.6kA	2.6kA	2.6kA
Components	C_s (series capacitor)	13µF	-	-
	C_p (resonant circuit)	-	-	3.3µF
	L_p (resonant circuit)	-	-	1.1mH
	T_2 (HV valve)	-	IGBT valve 480kV, 16kA	-
	LCS (LV valve)	-	IGBT valve 3x3, 10kV, 6kA	-
	S_1	Fast disconnector	Fast disconnector	Fast vacuum switch
	S_2	Fast vacuum switch	Vacuum switch	Vacuum switch
	S_3 (resonant circuit)	-	-	Fast vacuum switch
Performance	V_{dcp}	489 kV	491 kV	507 kV
	t_{max} (V_{dcmax})	2.0 ms	2.0 ms	8.0 ms
	I_{dcp}	4.4 kA	5.8 kA	15.7 kA
	t_{IDCP} (I_{dcpeak})	1.65 ms	2.0 ms	8.0 ms
	E_s	5.7 MJ	9.7 MJ	66 MJ
	t_{S2} (I_{dc}=0)	7.5 ms	9.3 ms	25.5 ms

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4) New DC CB research trends

Siemens DC Circuit Breaker:

- Similar to LC DC Circuit breaker with IGBT commutating switch,
- Employs vacuum arcing switch,
- Fast operation and reduced costs,

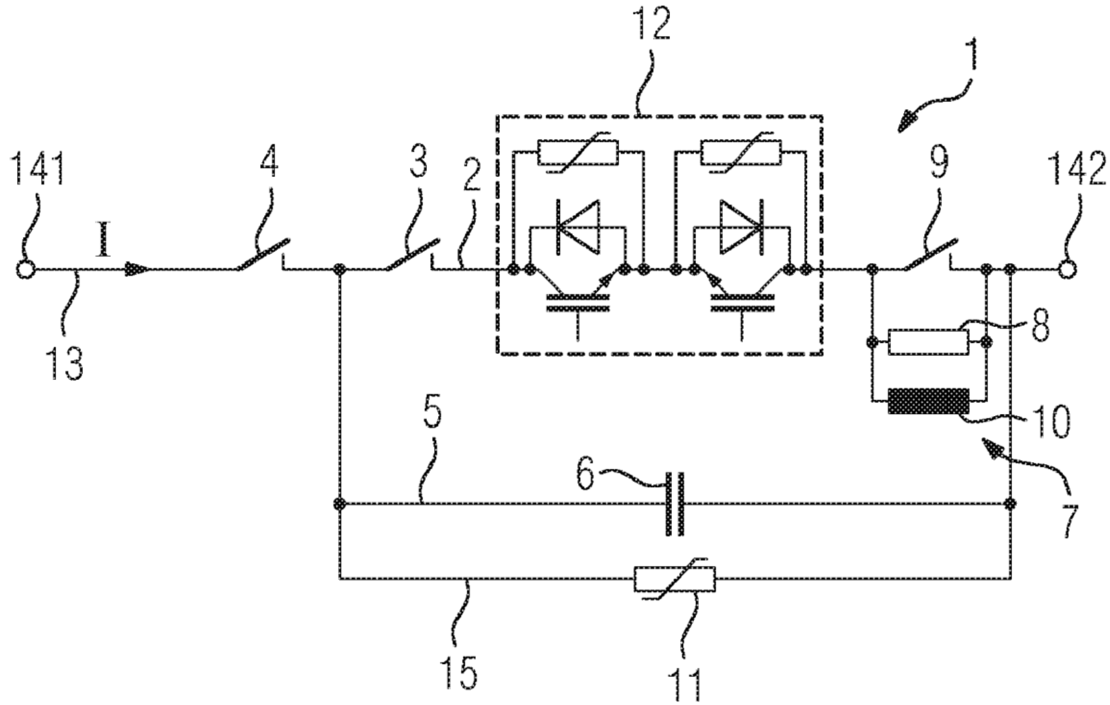

Figure 17 – Siemens DC Circuit Breaker [3].

[3] Siemens, “Device and Method for switching a direct current ," US 2016/0300671, November 2013,

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4) New DC CB research trends

Assembly DC Circuit Breaker:

- Intended for DC bus with multiple DC lines,
- Only one HV valve is used,
- Each DC line has an LV valve and an UFD,
- Significant cost savings are possible,

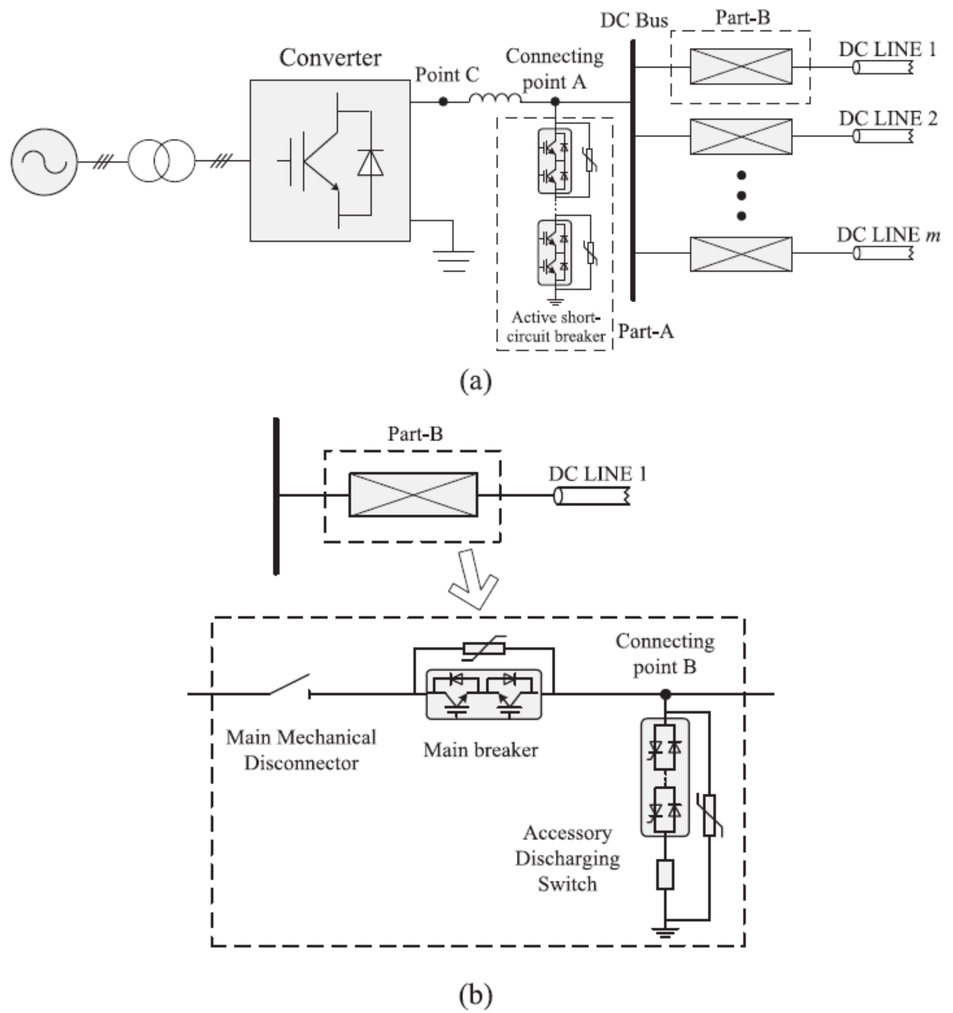

Figure 18 – Assembly DC Circuit Breaker [4].

[4] G. Liu, F. Xu, Z. Xu, Z. Zhang and G. Tang, "Assembly HVDC Breaker for HVDC Grids With Modular Multilevel Converters," in *IEEE Transactions on Power Electronics*, vol. 32, no. 2, pp. 931-941, Feb. 2017.,

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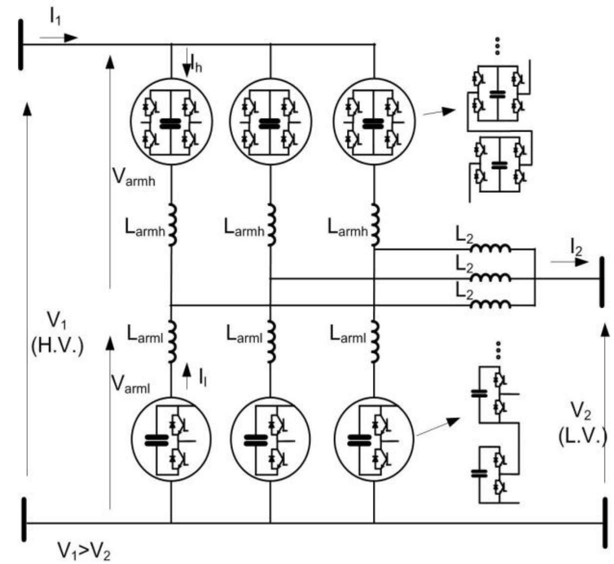
4) New DC CB research trends

DC/DC as a Circuit Breaker:

- Connection between different voltage levels,
- DC fault isolation,
    - Operates similarly as a full bridge MMC AC/DC,
    - No energy dissipation,
    - Response is faster than DC CB,
    - Repeated operation is straightforward,
- Power flow control,
- Integration of different technologies
- Galvanic isolation (depends on topology),



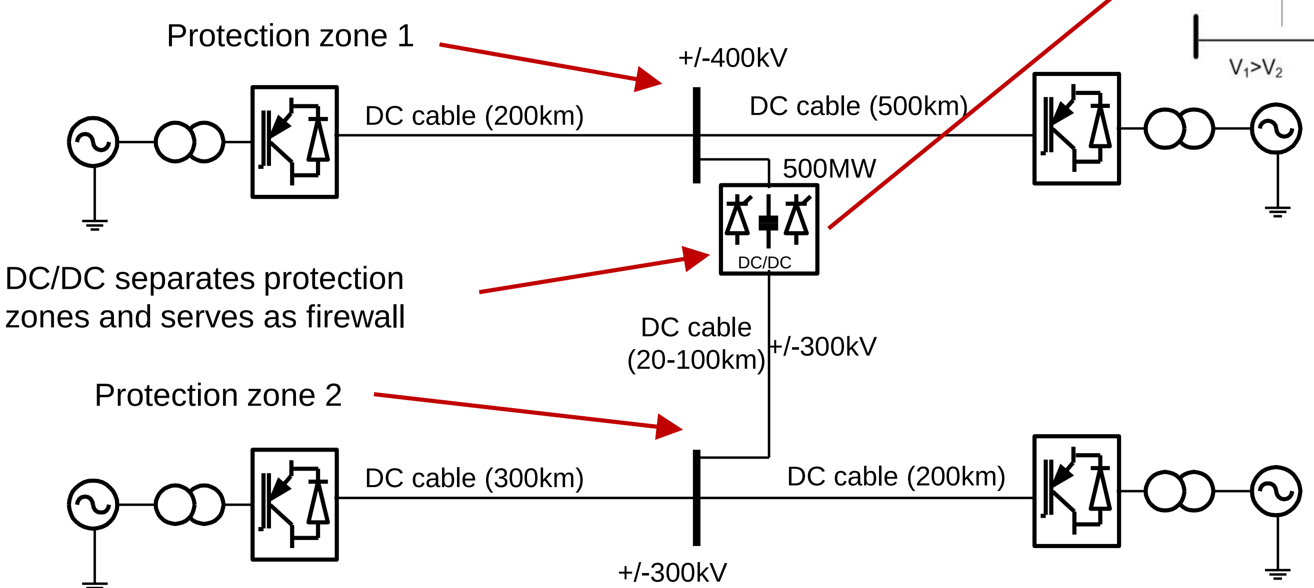


Figure 19 – Interconnection between two dc systems using DC/DC.

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Conclusions

1. WP 6 has made substantial theoretical studies on DC CB enhancements:
   a. UFD voltage control results in 30% lower peak current and energy dissipation,
   b. Bidirectional DC CB can be developed with a single HV valve,
2. In China, 3 different DC CBs have been installed,
   a. Zhoushan hybrid DC CB uses standard FB cells:
   b. Nan'Ao mechanical DC CB employs low voltage injection switch,
   c. Zhangbei project demonstrates 500kV, 26kA DC CBs,
3. Series LC DC CB shows promising results:
   a. Mechanical 1300V unit commutates 490A in 350µs,
   b. IGBT-assisted 1300V unit demonstrates 1100A commutation in 350µs.
4. Substatial DC CB research is ongoing worldwide:
   a. Siemens DC CB resembles series LC DC CB,
   b. Assembly breaker substantially reduces total DC CB costs on a large DC bus,
   c. DC/DC operates as DC Circuit Breaker,
5. DC CB development research is recommended:
   a. Theoretical topology studies,
   b. Low power demonstration,
   c. Topology advancements and HV testing,

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