

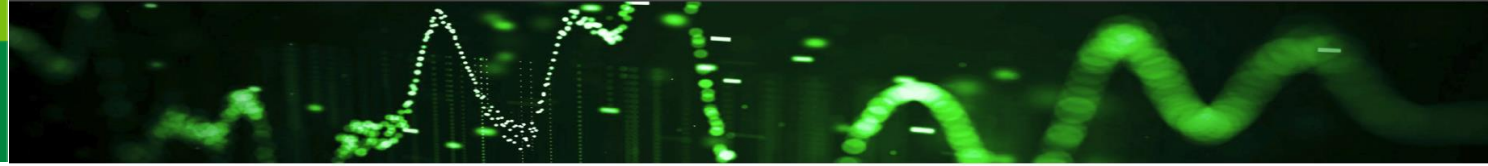


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**ENERGY EFFICIENCY &
RENEWABLE ENERGY**



2024 DIRECT CIRCUIT BREAKER WORKSHOP

HV DC Circuit Breaker –

State-of-the-Art Technologies, Challenges, and Opportunities

Richard Zhang

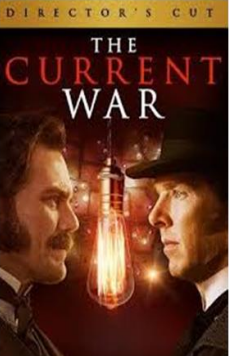
Professor, Hugh P. and Ethel C. Kelly Chair
Center for Power Electronics Systems
Power and Energy Center
Virginia Tech

zhangr@vt.edu

The Real Truth about the “Current War” - DC or AC? LV or HV?

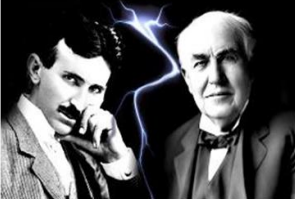


Dec. 31, 1879
Thomas Edison at Menlo Park



DIRECTOR'S CUT
THE CURRENT WAR

Nikola Tesla



Thomas Edison

George Westinghouse



Samuel Insull

Cost



Serve more customers



Safety

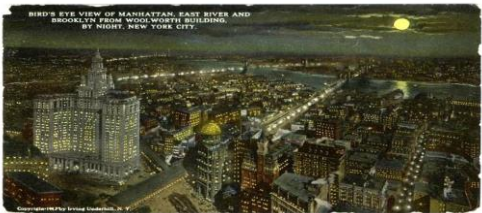
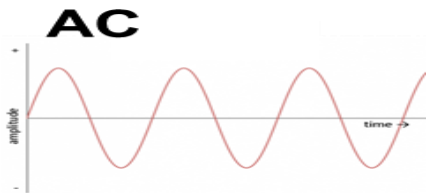


Rise of DC



DC Circuit Breaker ...

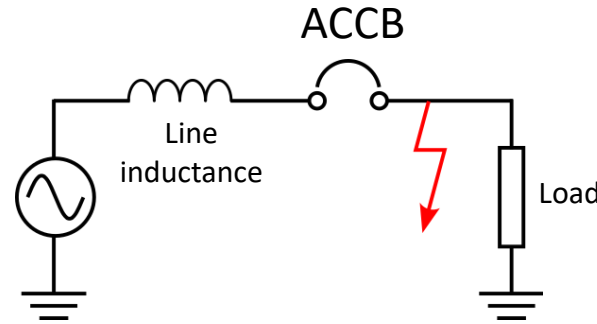
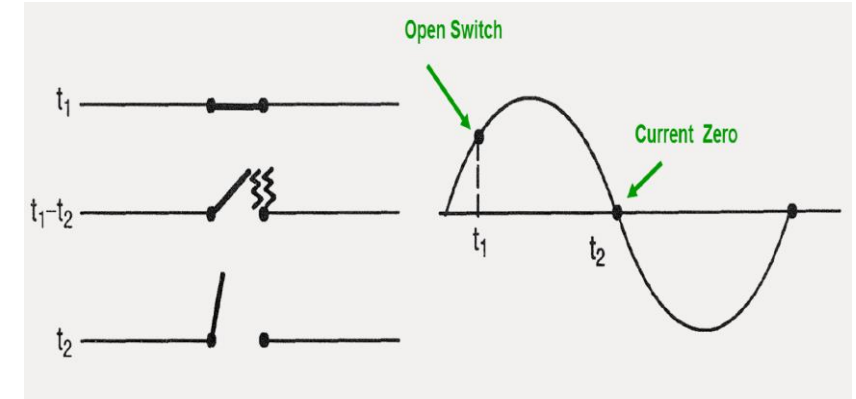
... the last holy grail to create DC grids ...
faster fault clearance & selectivity of fault isolation



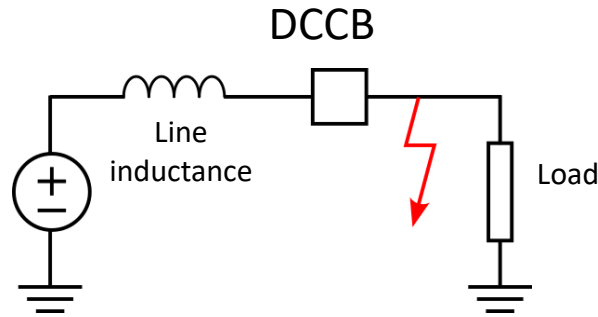
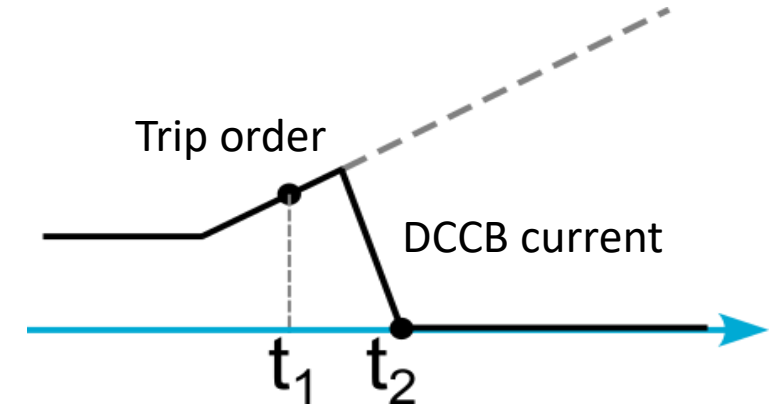
- Not really about DC or AC, but more about LV or HV
- Edison did not know how to do DC/DC converter

AC v.s. DC Circuit Breaker

ACCB

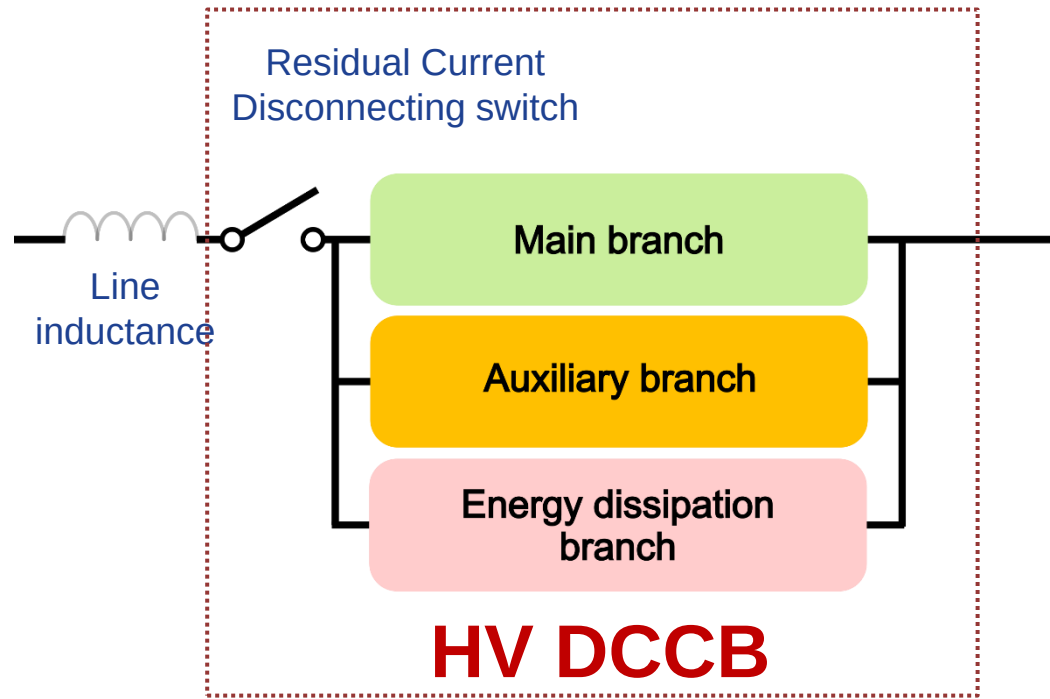


DCCB

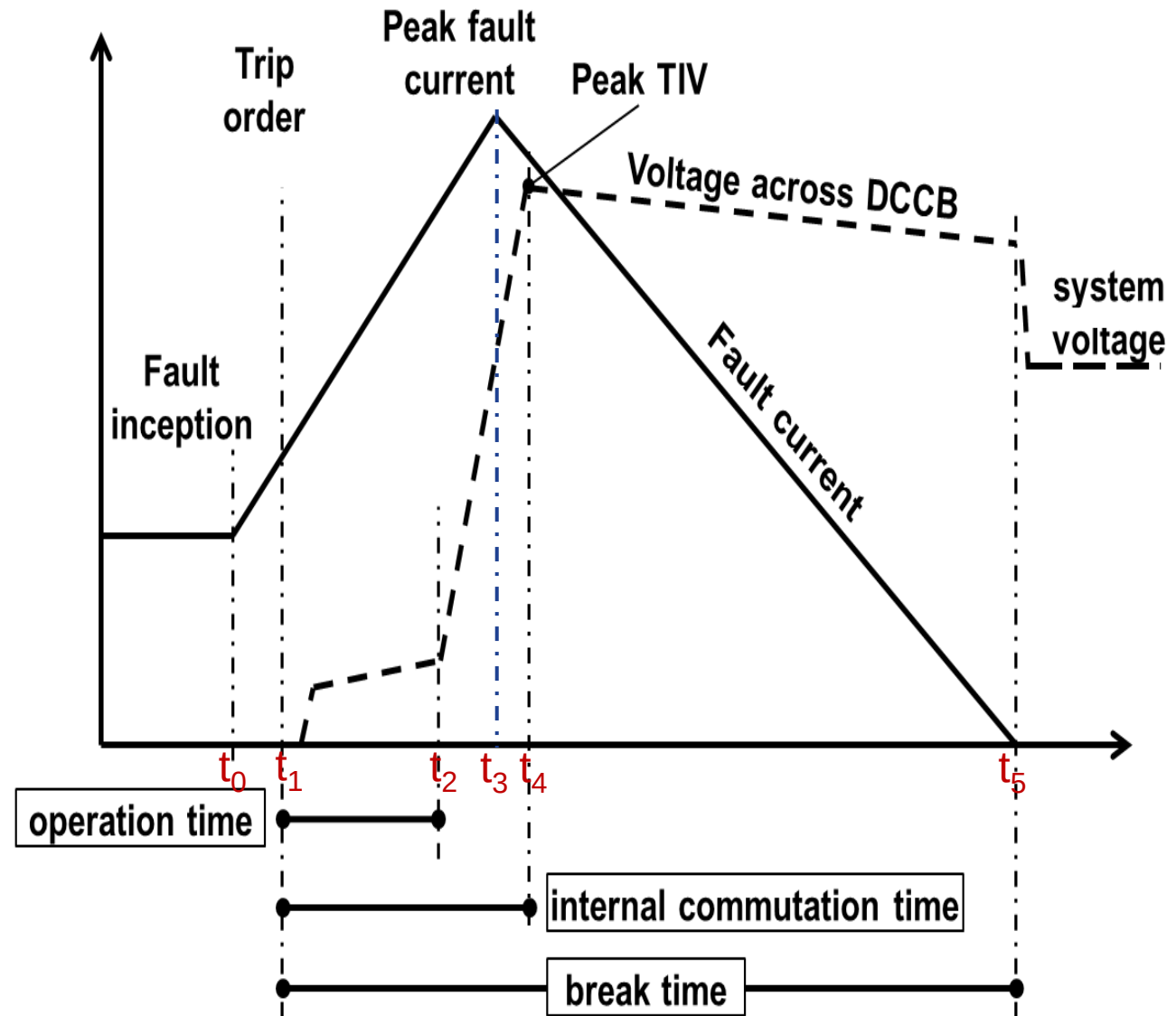


- **DCCB ... challenge to interrupt current without the natural and regular current zero-crossing points as in ACCB**
- **Creating artificial current zero-crossing point is necessary for DCCB ... significant impact on cost, size, complexity**

High Voltage DC Circuit Breaker (HV DCCB) – Generic Principle & Challenges



- Technically ... multi-disciplinary challenges (HV, PS, PE, ME, thermal, control, arc physics, material...)
- High voltage AND high current
- High costs for development, validation, and product
- Niche market with chicken-N-egg situation – market v.s. product readiness

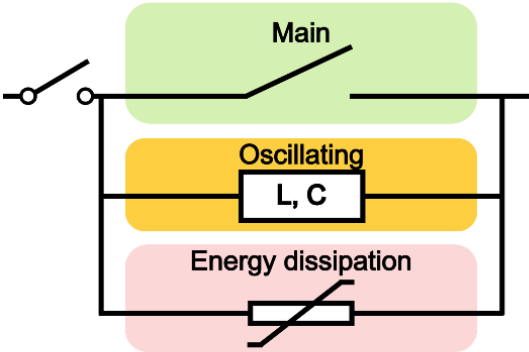


Cigre B4/A3 Technical Brochure 873 "Design, test, and application of HVDC circuit breakers"

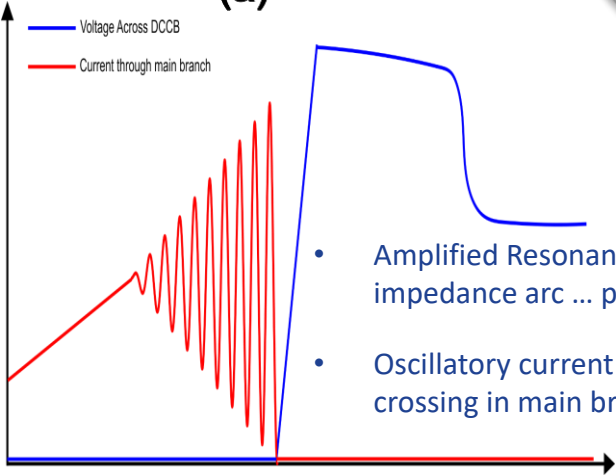
Cannot be treated as a commodity product for its R&D, design, validation, and deployment

Two Simplest Types of HV DCCB

Passive Oscillation Mechanical Breaker



(a)



- Amplified Resonance among L, C and negative impedance arc ... positive feedback loop
- Oscillatory current leads to current zero-crossing in main branch



• Simple and Low cost



• Too slow!

Residual Current
Disconnecting switch

Line
inductance

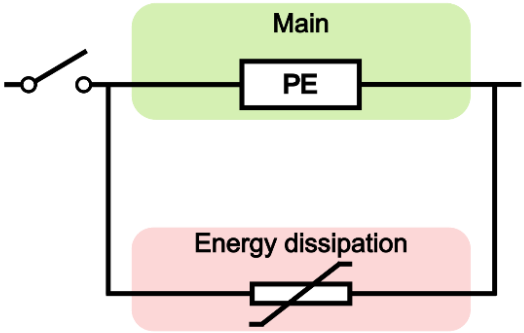
Main branch

Auxiliary branch

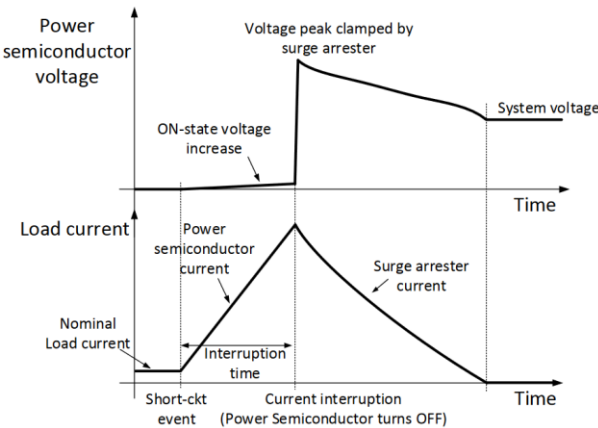
Energy dissipation
branch

HV DCCB

Power Electronics Breaker



(e)



R. Rodrigues, et al, "Solid state circuit breakers for shipboard distribution systems", IEEE Electric Ship Technologies Symposium, 2017



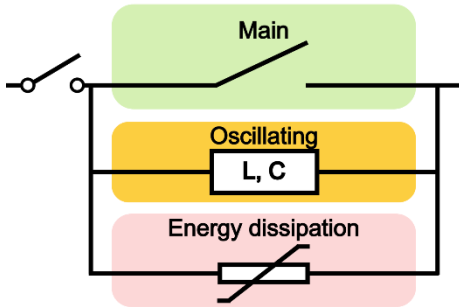
• Very fast



• Lossy & high cost

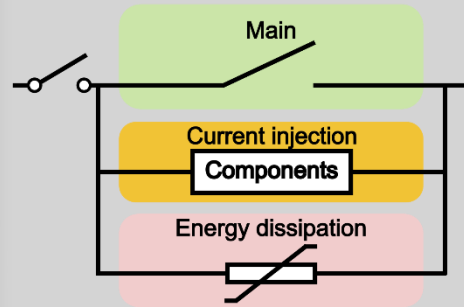
Fundamental Types of HV DCCB & Characteristics

**Passive Oscillation
Mechanical Breaker**



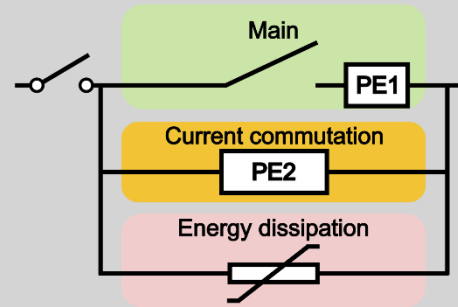
(a)

**Active Current Injection
(ACI) Mechanical Breaker**



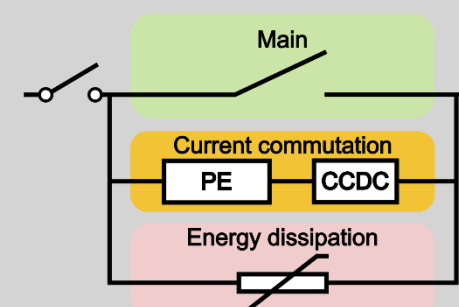
(b)

**Mechanical-Power
Electronics Hybrid Breaker**



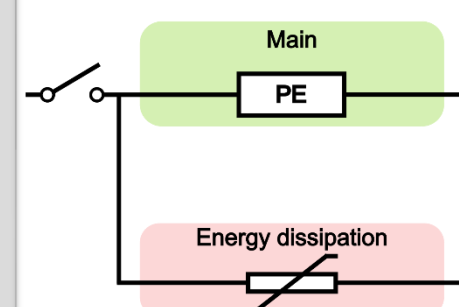
(c)

**Coupled Negative Voltage
Injection Hybrid Breaker**



(d)

**Power Electronics
Breaker**

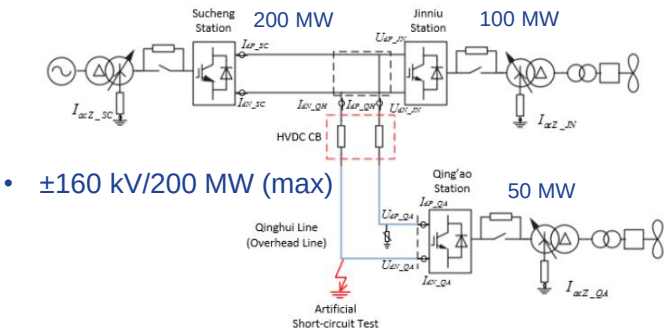


(e)

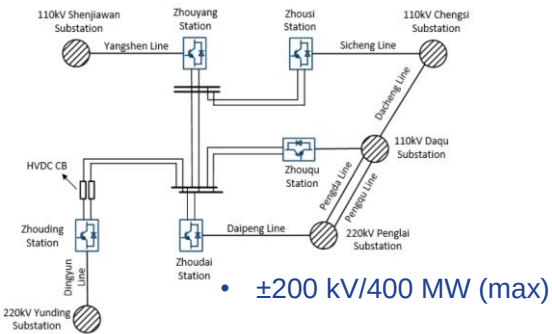
	Passive Oscillation Mechanical (a)	Active Current Injection Mechanical (b)	Hybrid (c)	Coupled Negative Voltage Injection Hybrid (d)	Power Electronics (e)
Main Branch	Mechanical interrupter	Mechanical interrupter	Mechanical disconnecter in series with a PE switch (PE1)	Mechanical interrupter	Power electronics switch
Auxiliary Branch	Passive oscillation circuit, e.g., L, C	Active current injection	Power electronics (PE2)	Power electronics switch in series with active current injection circuit	N/A
Energy Dissipation Branch	Surge Arrestor/Metal Oxide Varistor (MOV)				
Mechanism to Commutate Current Out of Main Branch	Arc induced oscillating current	Triggered oscillating current injection	Turn-off of PE switch (PE1)	Triggered oscillating current injection	Turn-off of PE switch
Mechanism to Commutate Current out of Auxiliary Branch (if exists)	Self-commutated by LC oscillation charging capacitor	Self-commutated by LC oscillation charging capacitor	Turn-off of PE switch (PE2)	Turn-off of PE switch (PE)	N/A

HV DCCB in Pilot/Demonstration Projects

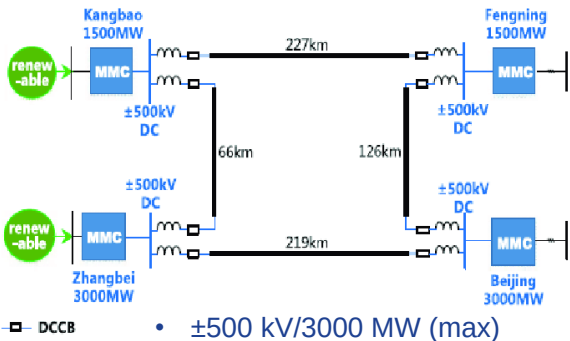
Nan'ao 3-terminal MTDC



Zhoushan 5-terminal MTDC



Zhangbei 4-terminal MTDC



Year	Project	HV DCCB Technology	HV DCCB Capability (rated voltage/interrupted current/operation time)
2013	TWENTIES	Hybrid	120 kV/5.2 kA/2ms
2016	Zhoushan Flexible DC Grid	Hybrid	200 kV/ 15 kA/ 3ms
2017	<u>Nan'ao</u>	Active current injection	160 kV/ 9 kA/ 5ms
2019	<u>Zhangbei</u>	Active current injection (2 units installed)	535 kV/25 kA/3ms
		Coupled negative voltage <u>injection</u> (2 units installed)	
		Hybrid (12 units installed)	
2020	<u>PROMOTioN</u> Demonstration	Active current injection	200 kV/ 16 kA/ 8ms
		Active current injection - VARC	80 kV/ 15 kA/ 2ms
		Hybrid	350 kV/ 20 kA/ 3ms



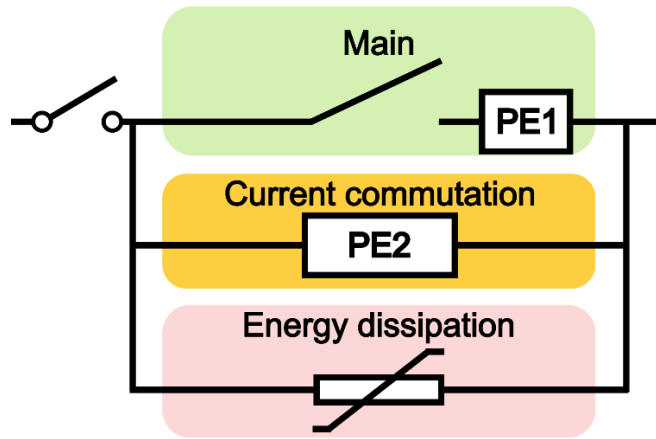
- Proven capability
- Validated feasibility in projects



- **High cost ... ~\$8-10 M/unit**
- Limited operation experience & robustness track record

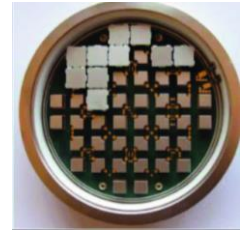
A Quick Probe in High Cost of HV DCCB

Hybrid HV DCCB Example



PP-IGBT

IGCT

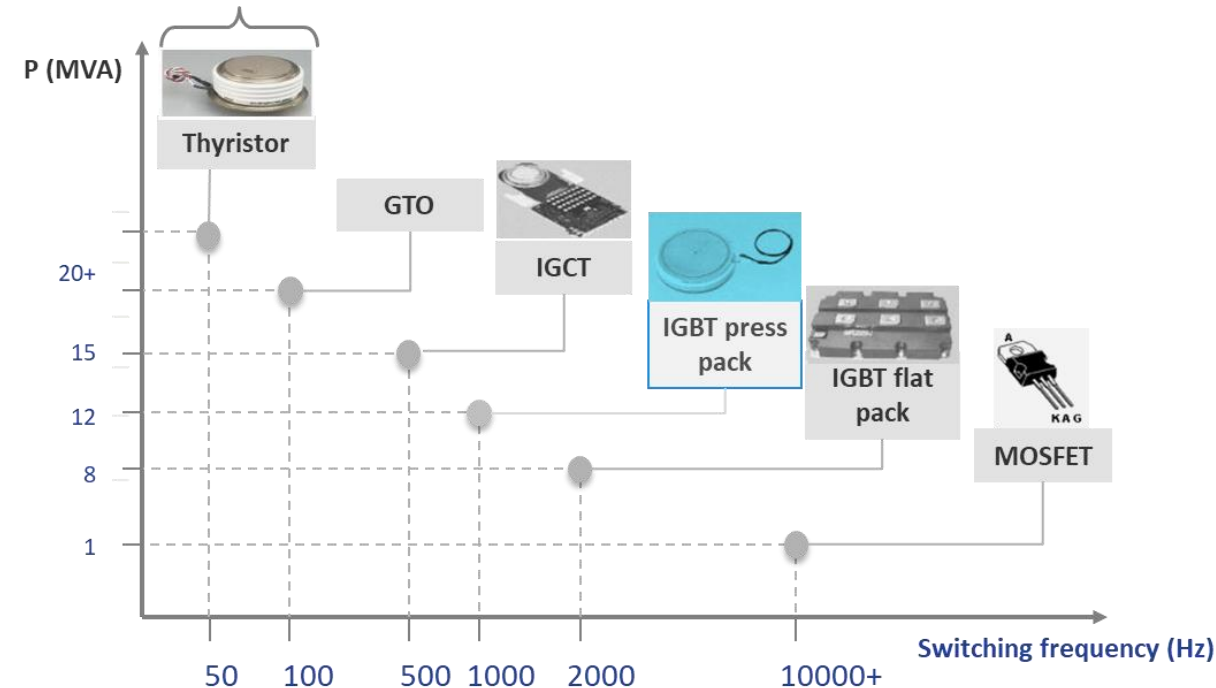


1) High-cost components with design duties that are overkill for DCCB

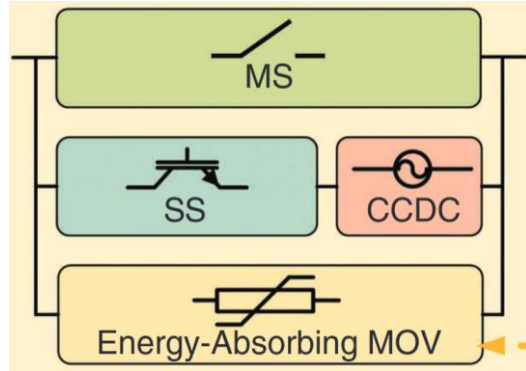
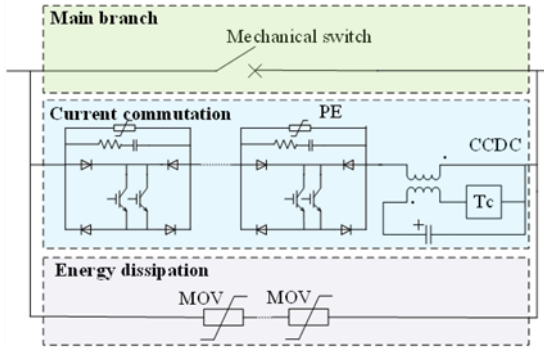
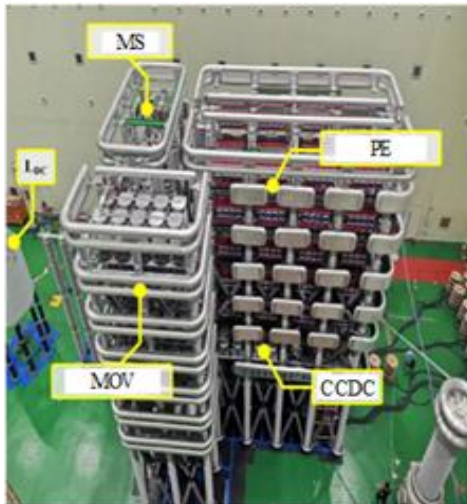
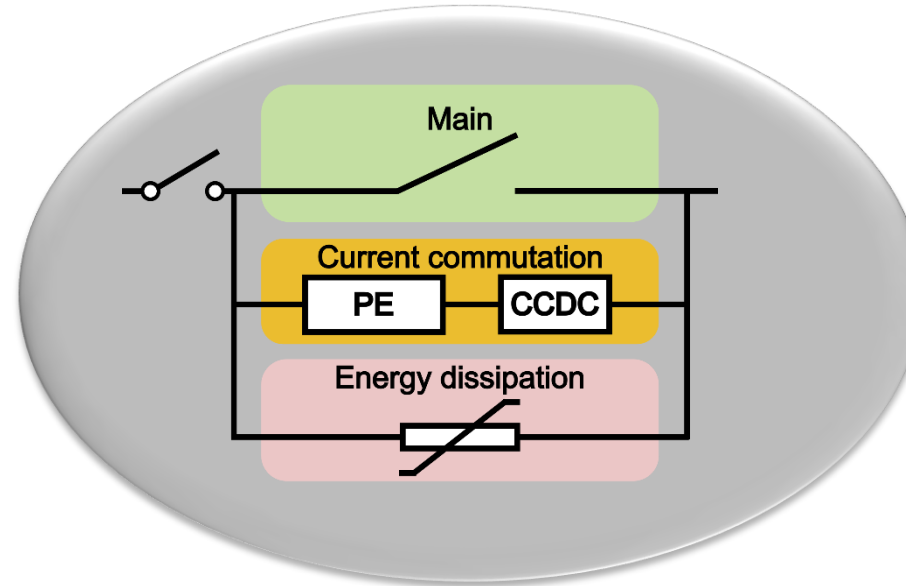
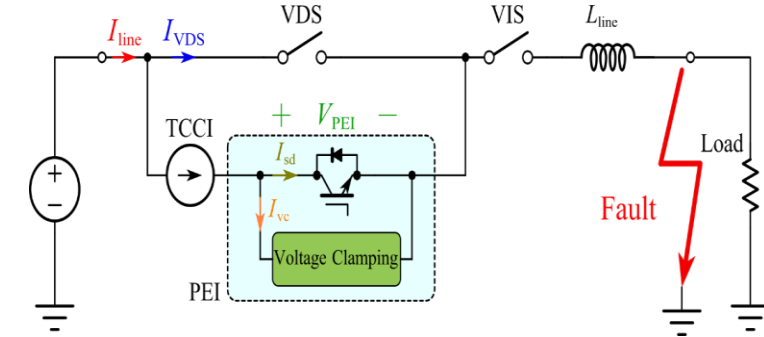
- Low-cost design favors use of COTS components whose characteristics unfit as low cost for DCCB e.g. PE switches are design for **150~300+ billions switchings**, while DCCB in **1,000s switchings**, over life time.

2) Blindly pursue higher interrupting current capability without system trade-off leads to high cost

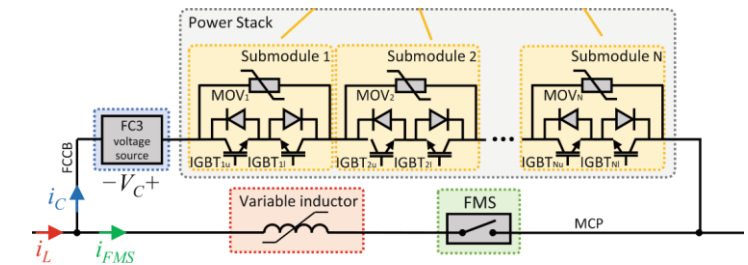
3) Components with non-ideal characteristics leads to high-cost design compromise



Coupled Negative Voltage Injection Hybrid DCCB



MV DCCB with similar concept by Eaton (ARPA-E BREAKERS project)

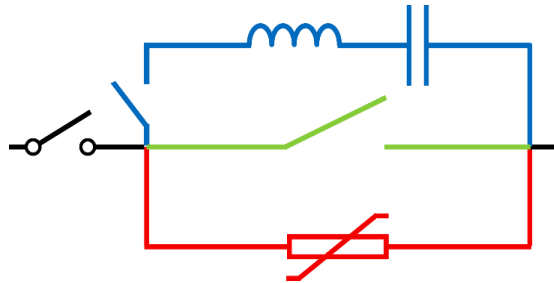
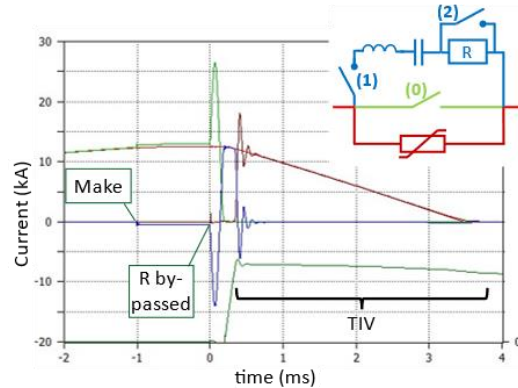


MV DCCB with similar concept by Georgia Tech (ARPA-E BREAKERS project) with saturable inductor in Main Branch

Originally proposed Coupled Negative Voltage Injection Hybrid HV DCCB by Tsinghua Univ

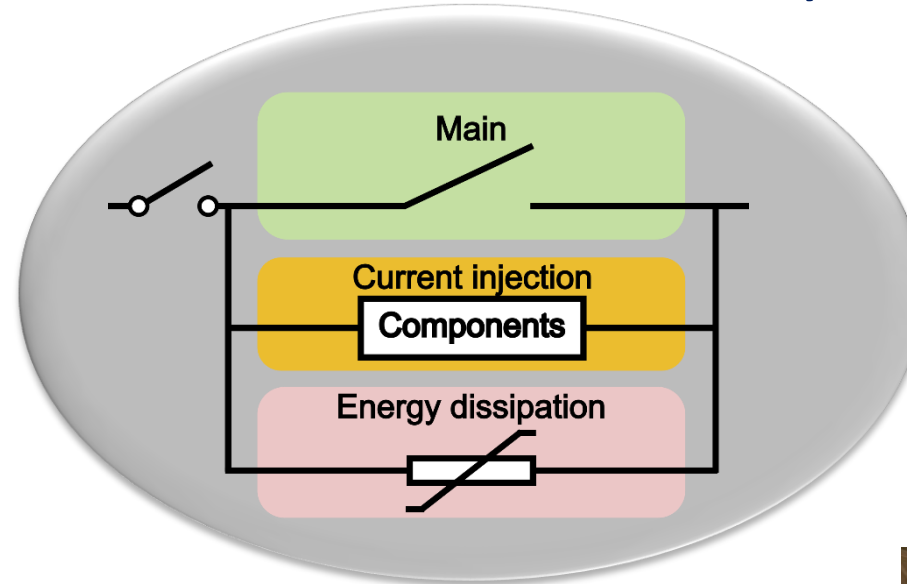
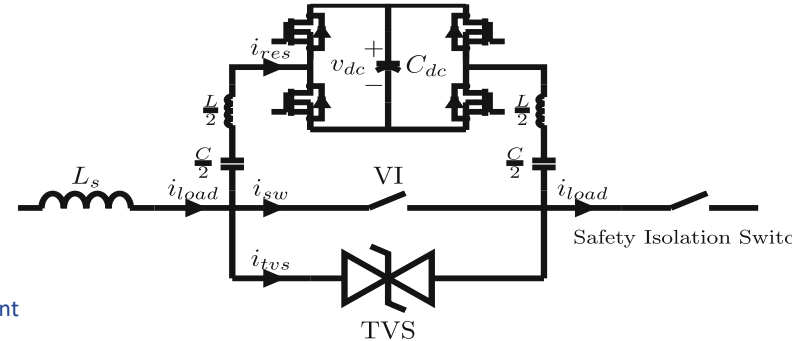
- Share common traits with ACI and hybrid DCCB

ACI DCCB - Innovations to Drive Robustness, Low Cost and High Density



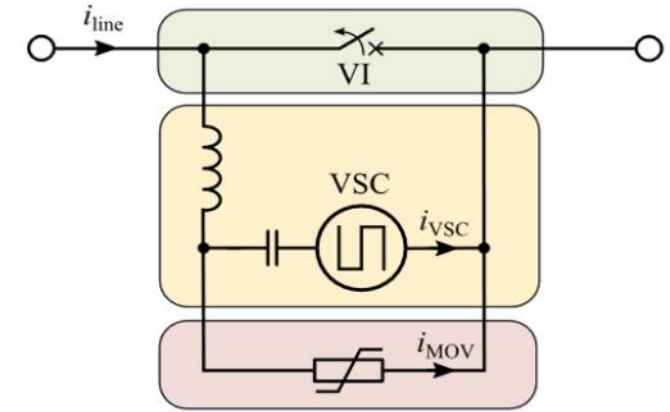
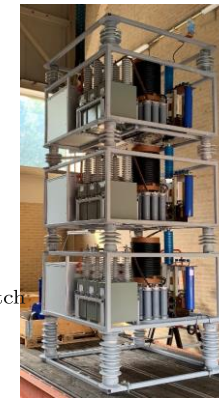
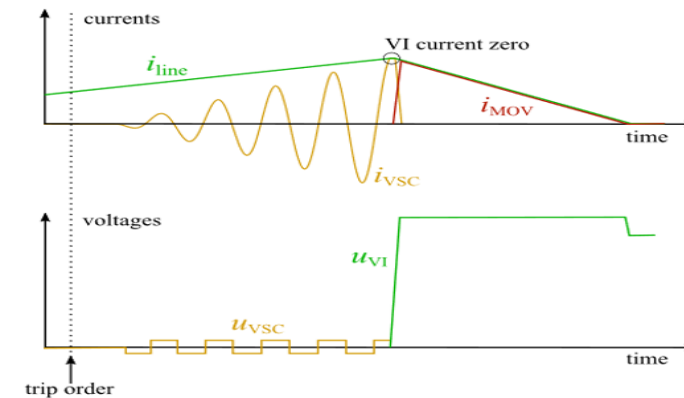
W. Grieshaber et al, "Direct Current Circuit Breaker with Adjustable Current Injection," 27th International Conference on Electricity Distribution, 2023

- Adjusted pre-charged capacitor to ensure break robustness by SuperGrid Institute



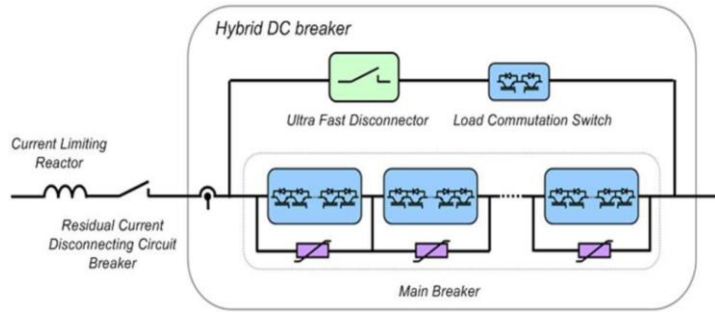
- MV DCCB with similar VARC concept by Marquette Univ (ARPA-E BREAKERS project)

Isik C. Kizilyalli, Z. John Shen, Daniel W. Cunningham, Direct Current Fault Protection: Basic Concepts and Technology Advances (Power Systems)

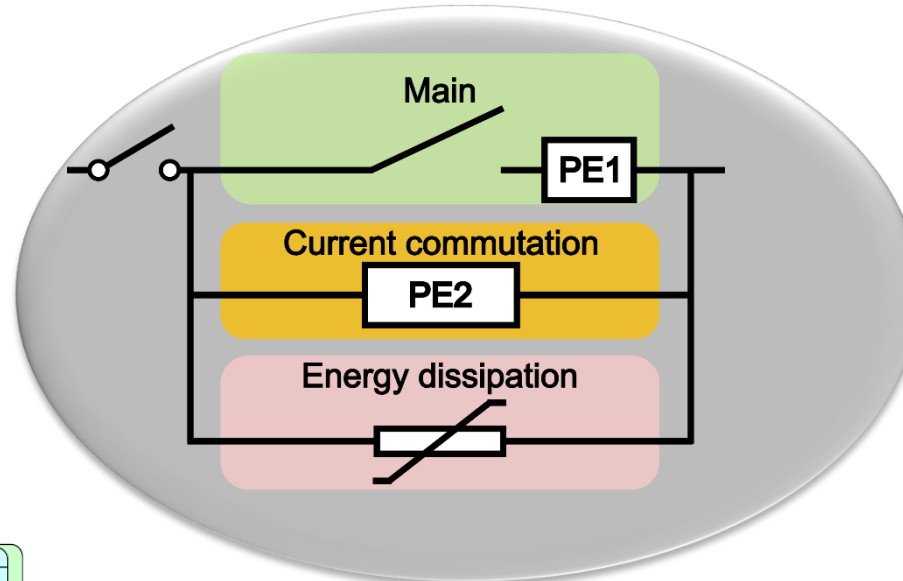
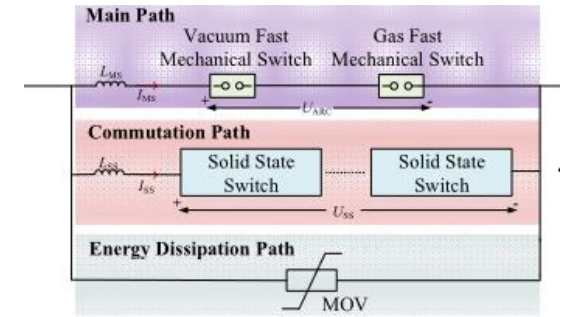


- VSC assisted resonant current (VARC) originally proposed by Scibreak (acquired by Mitsubishi Electric)
- Lower cost and lower loss than hybrid
- Robust break ... Small LC

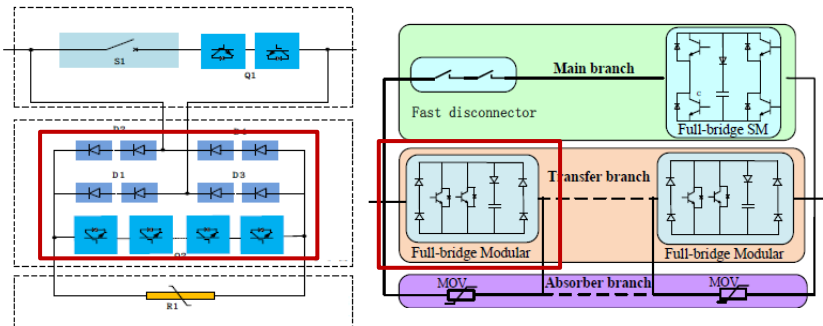
Hybrid DCCB - Innovations to Drive Robustness, Low Cost and High Density



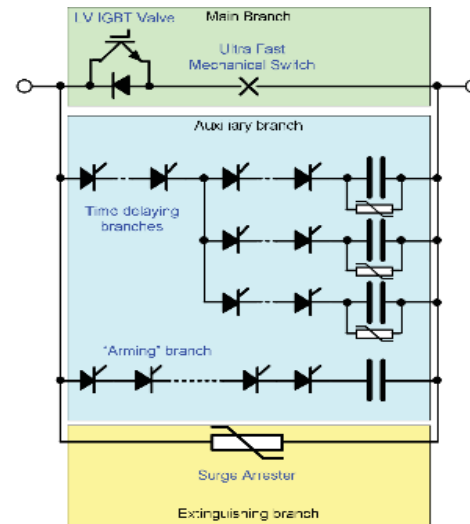
Originally proposed Hybrid DCCB by Hitachi Energy (former ABB)



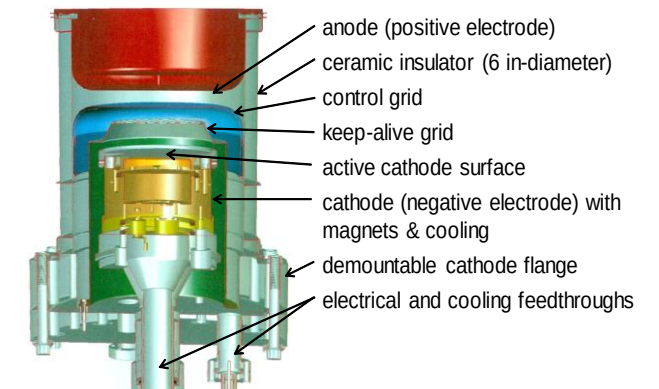
PE1 replaced by Gas Fast Mechanical Switch by Tsinghua Univ.



PE2 cost reduction with diode full-bridge-based AC switch by NR & GEPR



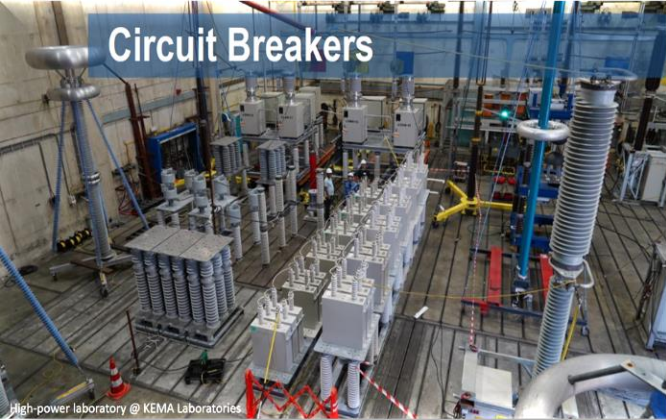
PE2 cost reduction with thyristor-based time delaying branches by GE Vernova (former Alstom)



PE2 cost reduction and ultra high-density with Gas Discharge Tube by GE Vernova (ARPA-E BREAKERS project)



Cigre B4/A3 Technical Brochure 873 "Design, test, and application of HVDC circuit breakers"



HV DCCB ... Where Are We?

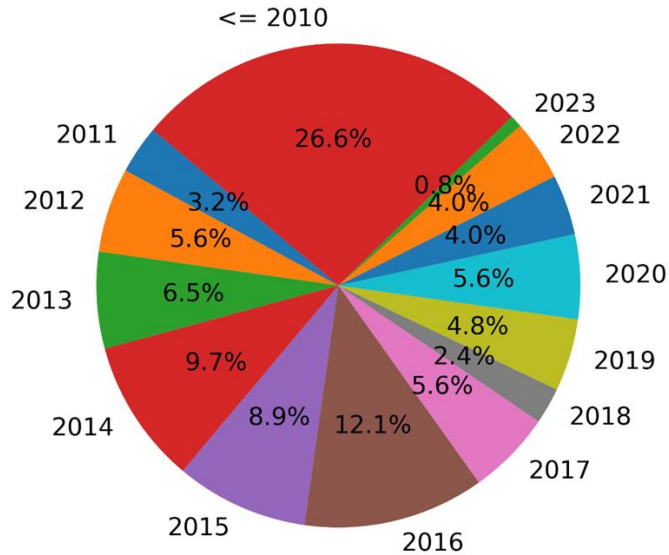
- Performance and capability successfully demonstrated in projects ... 535 kV/25 kA/3 ms
- Offshore wind market growth triggered a new wave of interests in HV DCCB development

Gaps

- Cost remains the biggest challenge ... currently \$8-10M/unit
- Need to significantly reduce size and weight for offshore wind
- Still very limited operation experience and reliability track record ... 25-40 yrs of service life expected
- Design, prototyping/production, testing facility ... well established in China (Na'ao, Zhoushan, Zhangbei) & Europe (PROMOTion)

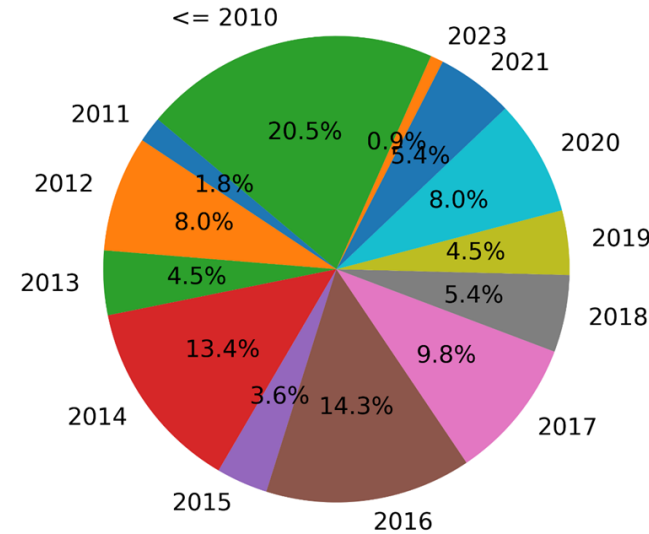
HV DCCB ... Cursory IP Landscape

US – Patent count: 125



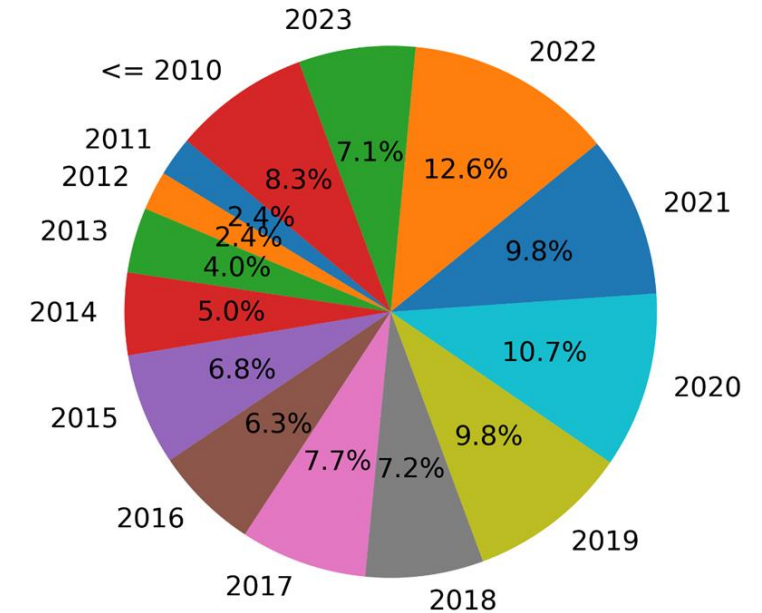
Assignees	Number	Percentage
Abb Schweiz Ag	17	13.6%
General Electric Technology Gmbh	12	9.6%
Mitsubishi Electric Corporation	6	4.8%
Square D Company	4	3.2%
Sungrow Power Supply Co., Ltd.	3	2.4%
Scibreak Ab	2	1.6%

EP - Patent count: 112



Assignees	Number	Percentage
General Electric Technology GmbH	19	16.8%
ABB Technology AG	16	14.1%
Mitsubishi Electric Corporation	9	8%
Siemens Aktiengesellschaft	8	7%
State Grid Corporation of China (SGCC)	8	7%

US, EP, CN - Patent count: 1903



Assignees	Number	Percentage
State Grid Corporation of China (SGCC)	284	14.9%
Southern Power Grid Science Academe Co., Ltd.	101	5.3%
Huazhong University of Science and Technology	63	3.3%
North China Electric Power University	53	2.8%
Tsinghua University	46	2.4%

- Similar IP filing/granted situations in US and EU
- Significantly high number of filing/granted in China ... intensified filing after 2015

Note: numbers shown here should not be taken as result of accurate & rigorous search ... they only serve as a relative reference among regions

Path to Achieve Low Cost, High Density, and Robust HV DCCB

HV DCCB

- **should not be treated as a commodity component**, chasing after increase of speed and current ratings
- **should be treated as part of system design element**, to optimize for robustness and cost, based on modular and standardized components.

1) System – low hanging fruit

2) R&D foundation

3) Innovation w/ Impact

4) Validation & Deployment

System Design & Protection Strategy

System Architecture

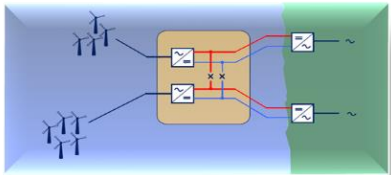
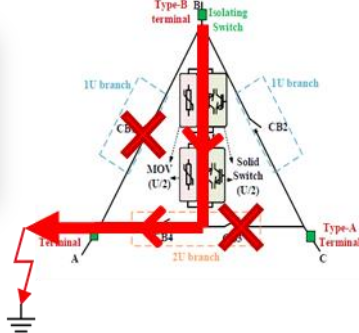
Design Capability & Experience

Novel Components & Solutions

Component & HV DCCB Test Facility

Pilot Projects

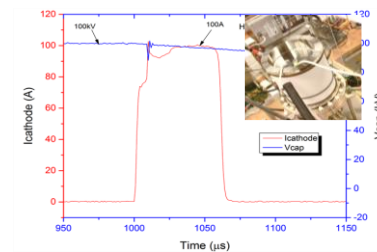
- Trade-off between operation time & interrupted current rating
- Permission to block upon fault detection?
- Fault isolation selectivity
- Multi-port HV DCCB



- Ultra-fast mechanical switch
- PE components in high volt/high curr pulsed app.
- HV engineering & structure design
- Aux power with HV isolation
- High fidelity DCCB and components modeling
- ...

High-density low-cost

- Switches, e.g. GDT 100kV/100A/5 μ s
- Schemes, e.g. VARC, thyristor-based
- Functionally decoupled components to reduce design compromise,



High voltage test lab with high current capability, e.g. Dominion Energy's HVL



HV DCCB

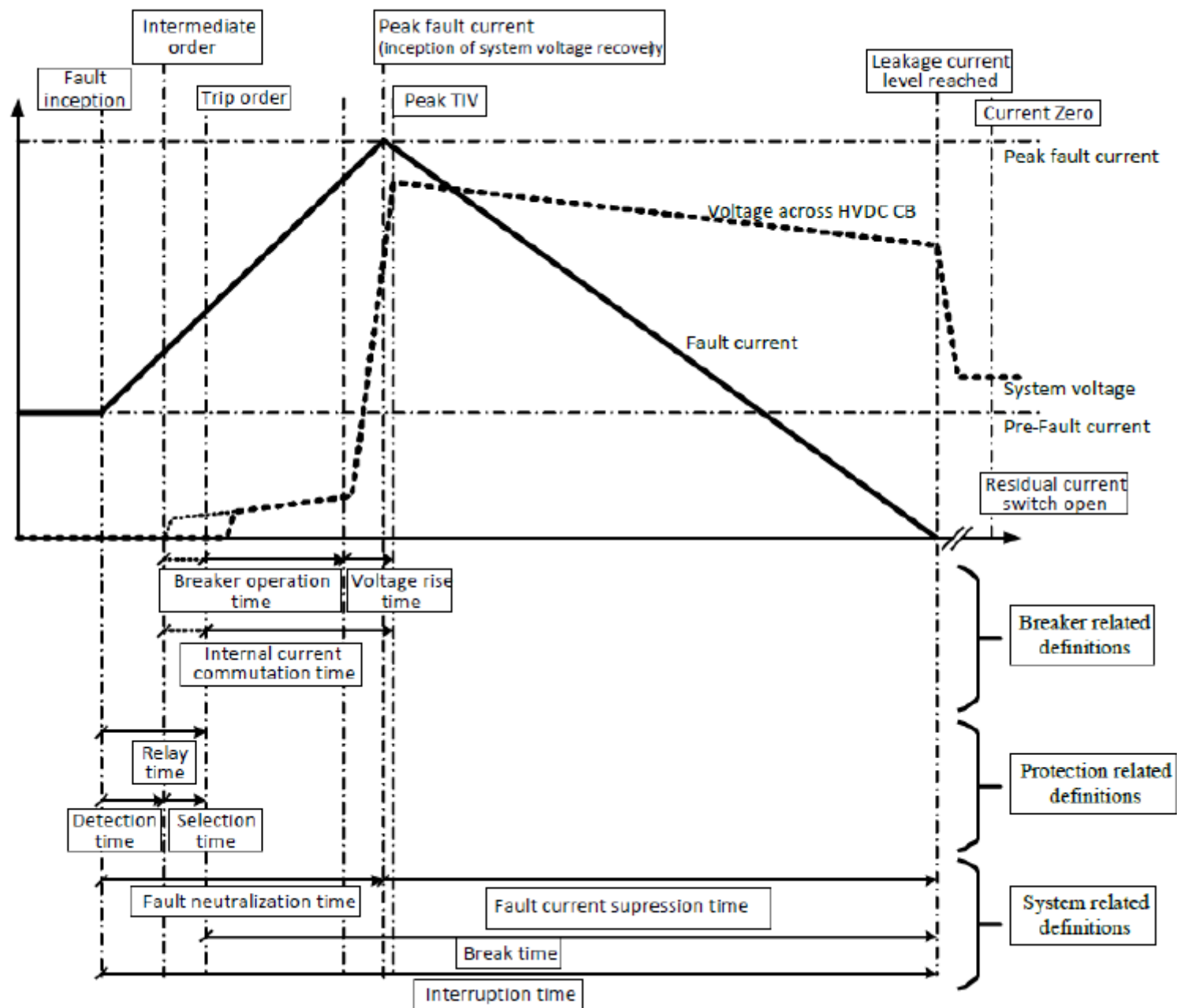
Path to the Last Holy Grail for Multi-Terminal DC Grids

Questions & Suggestions?

zhangr@vt.edu

Acknowledgement: this work is support by DOE program led by NREL under Contract No. DE-AC36-08GO28308 - Understanding the Protection and HVDC Breaker Needs for Offshore Grid Developments in the Atlantic Region

Backup



Cigre B4/A3 Technical Brochure 873 "Design, test, and application of HVDC circuit breakers"

Comparison of HV DCCB Technologies

Characteristics	Mechanical		Hybrid	Coupled negative voltage injection Hybrid	Power electronics
	Passive (oscillating)	Active (current injection)			
Breaking current	Load current	Load & fault current			
Internal current commutation time	Very long	Medium	Medium	Medium	Short
On-state losses	Low	Low	Medium	Low	Very high
Control complexity	Very low	Medium	Medium	Medium	Low
Mechanical or arc contact erosion	Medium	Medium	Low	Medium	None
Cost	Low	Medium	High	High	High

Comparison - ACI vs. Coupled Negative Voltage Injection vs. Hybrid DCCB

	Active current injection (ACI)	Coupled negative voltage injection	Hybrid
Fault current breaking location/component	Mechanical switch in main branch	PE switches in auxiliary branch	
Requirements of mechanical switch	<ol style="list-style-type: none"> 1. Higher, may still subject to fault current during break 2. Needs to withstand TRV 	<ol style="list-style-type: none"> 1. Higher, may still subject to fault current during break 2. Can provide longer time for mechanical switch to recovery dielectric strength compared with ACI 	Lower, only needs to withstand TRV
Mechanism of current commutation out of main branch	Counter current injection	Activating current commutation drive circuit (CCDC) (counter current injection)	Turning-off PE switch
Conduction loss in main branch	Low	Low	High
Requirements of cooling of PE1	N/A	N/A	Yes
Cost estimation	Potentially lower	Potentially higher	Potentially higher

