



PROMOTioN

PROGRESS ON MESHED HVDC
OFFSHORE TRANSMISSION
NETWORKS



Testing of HVDC circuit breakers

Cornelis Plet

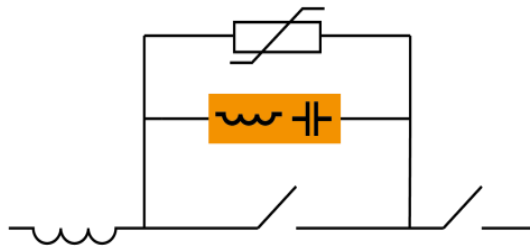
Modular design



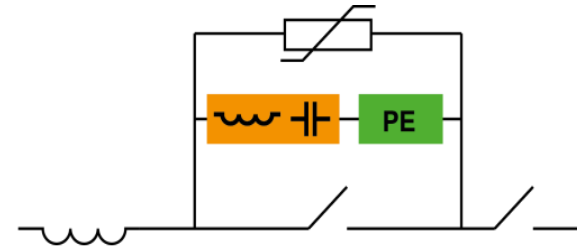
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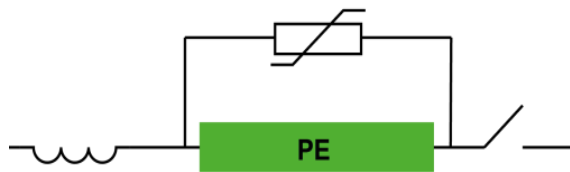
DC circuit breaker - classes



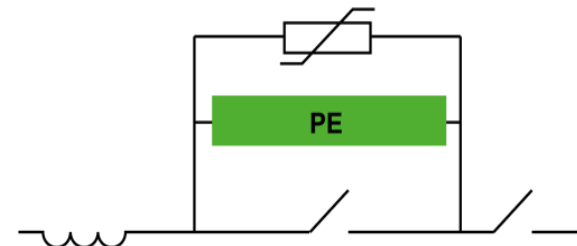
(a) Passive Oscillating



(b) Current Injection
/ Active Oscillating



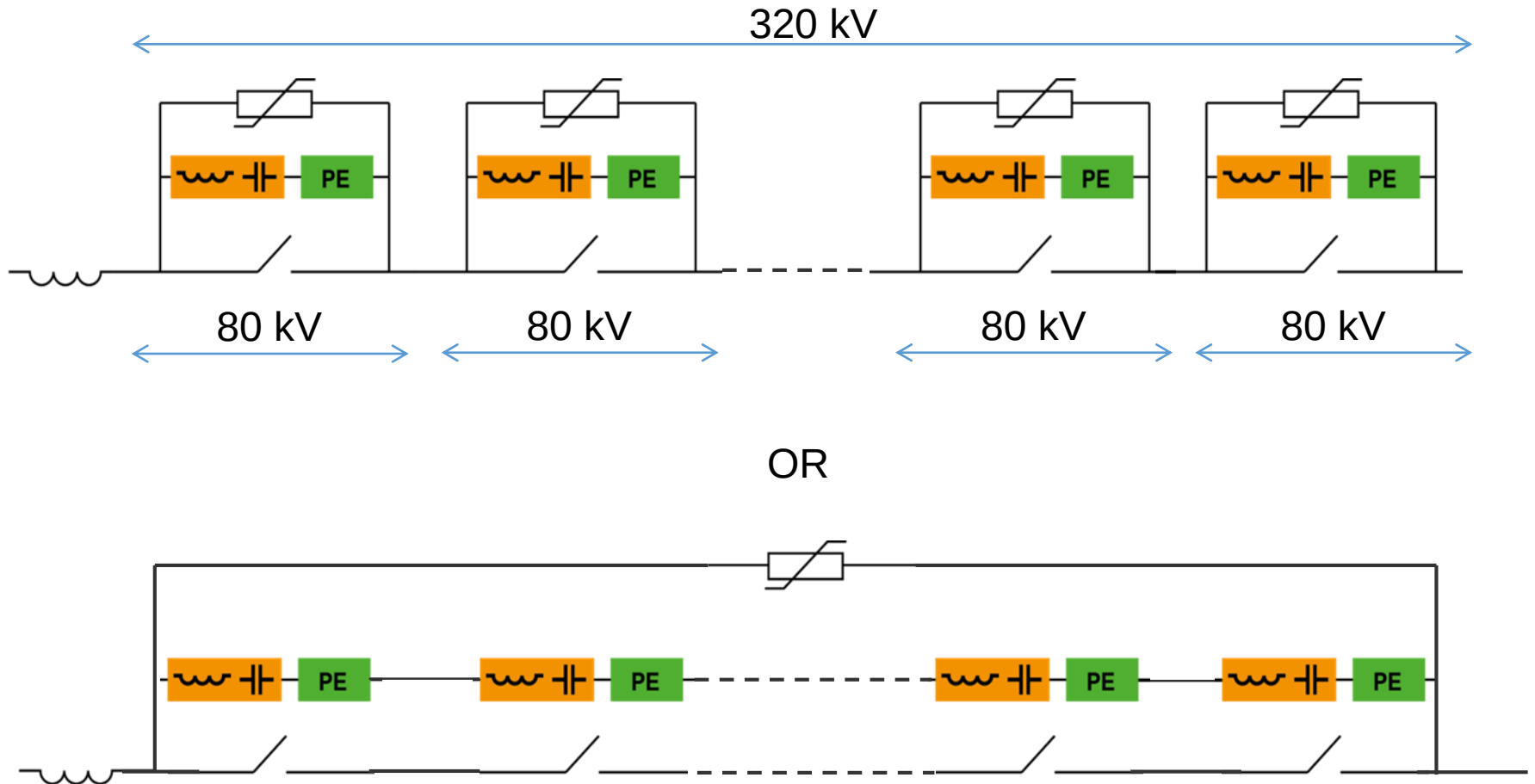
(c) Electronic



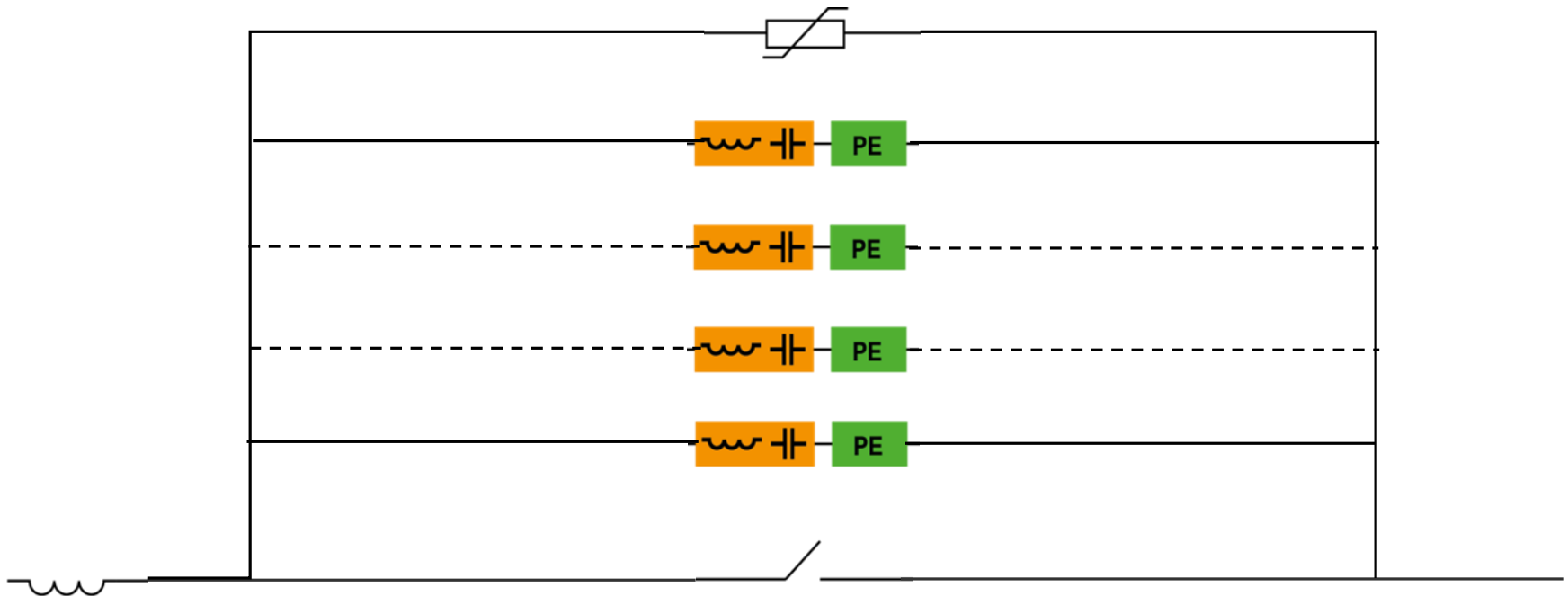
(d) Hybrid

Ref: Cigré A3-B4:34

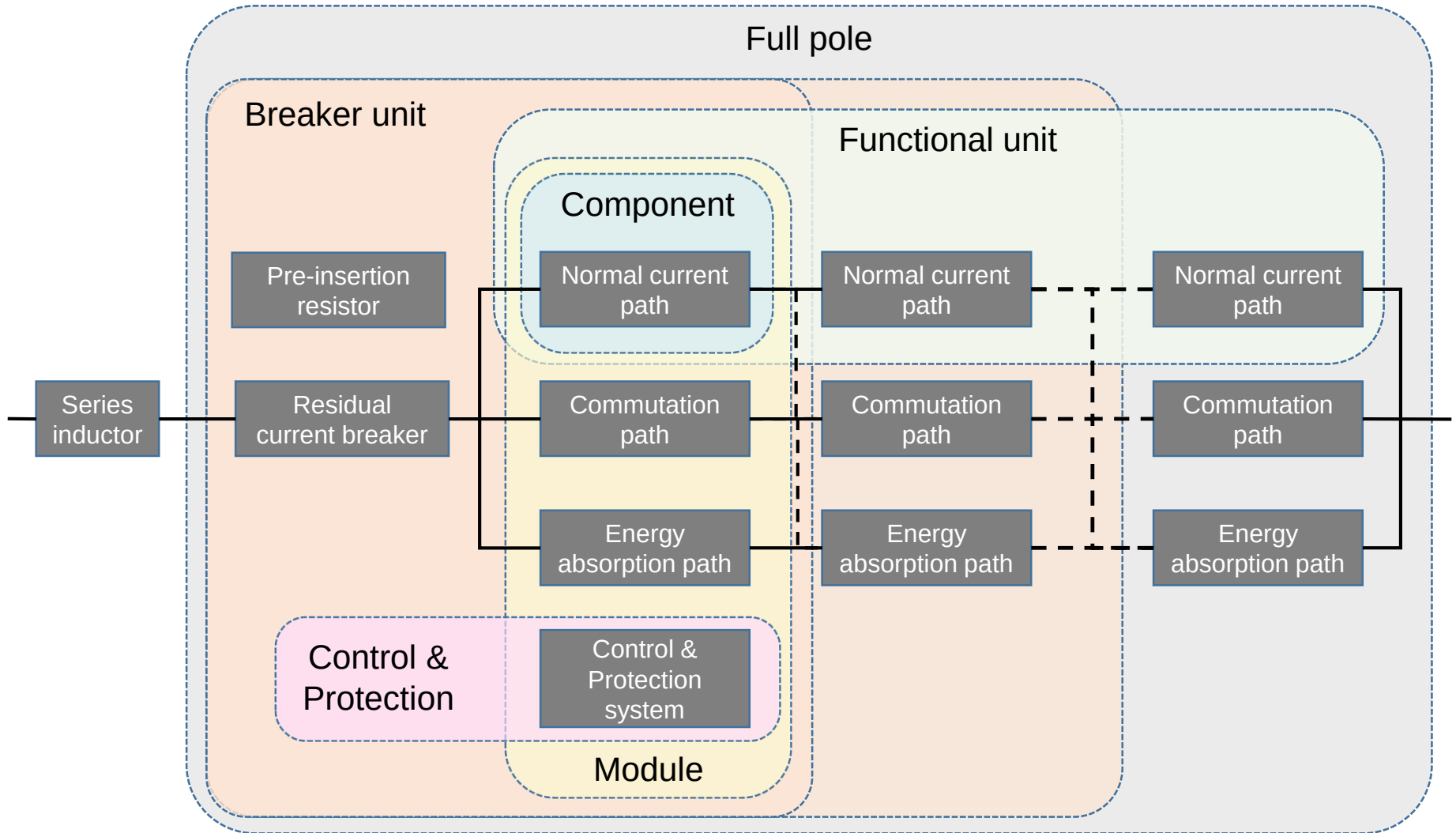
Voltage rating – series modularity



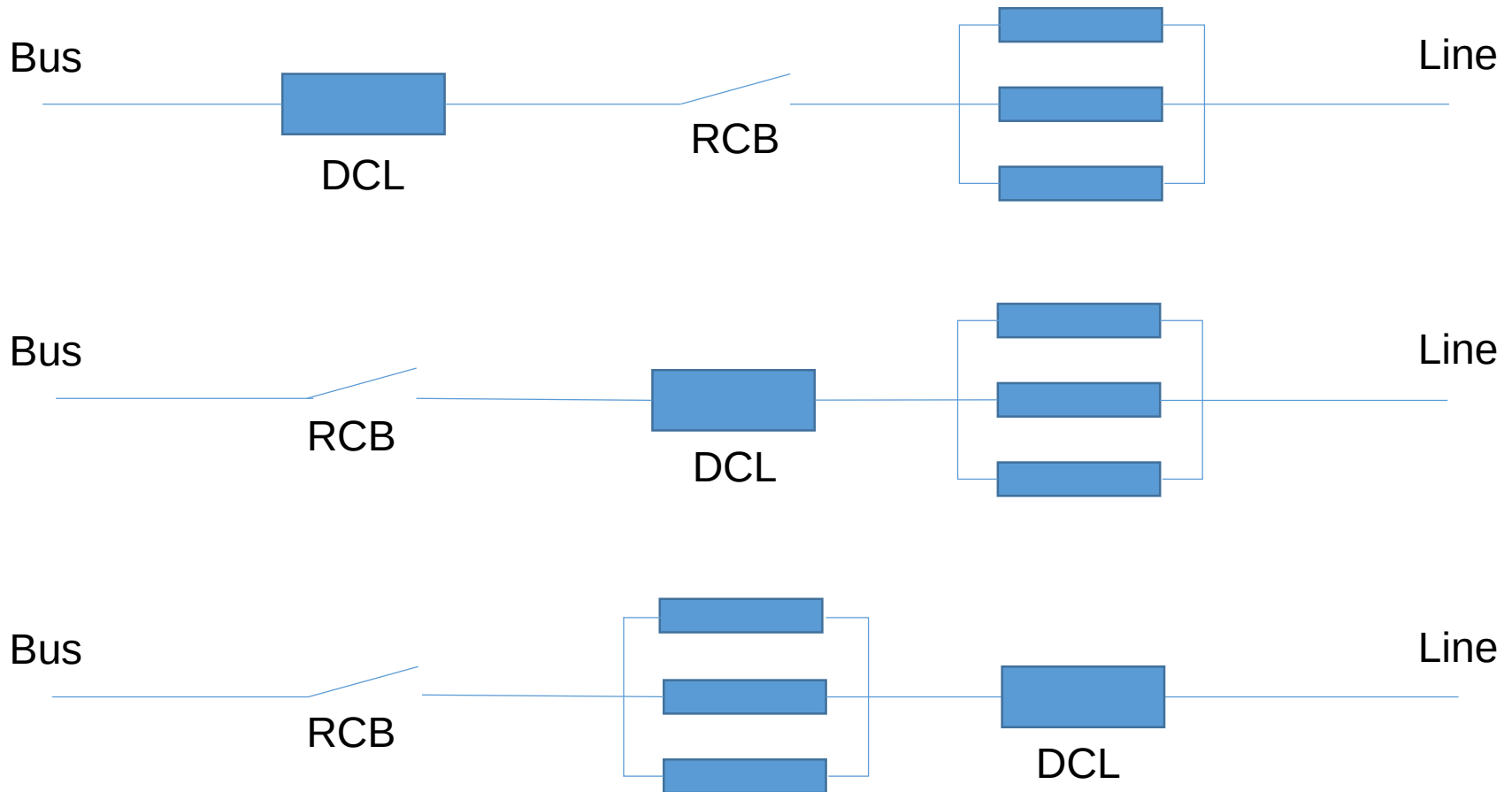
Parallel paths for additional functionality



Terminology



Series connection of functional units

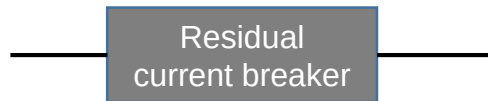


Dielectric testing – Series inductor

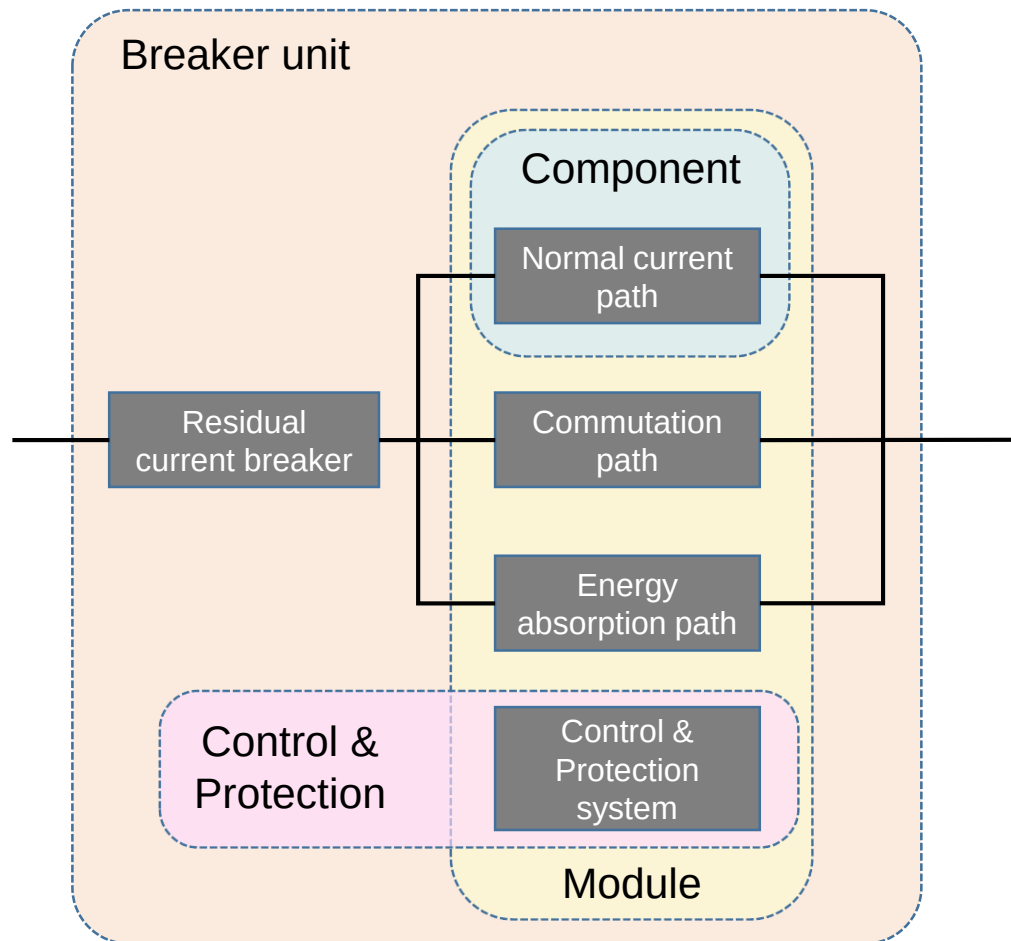
Series
inductor



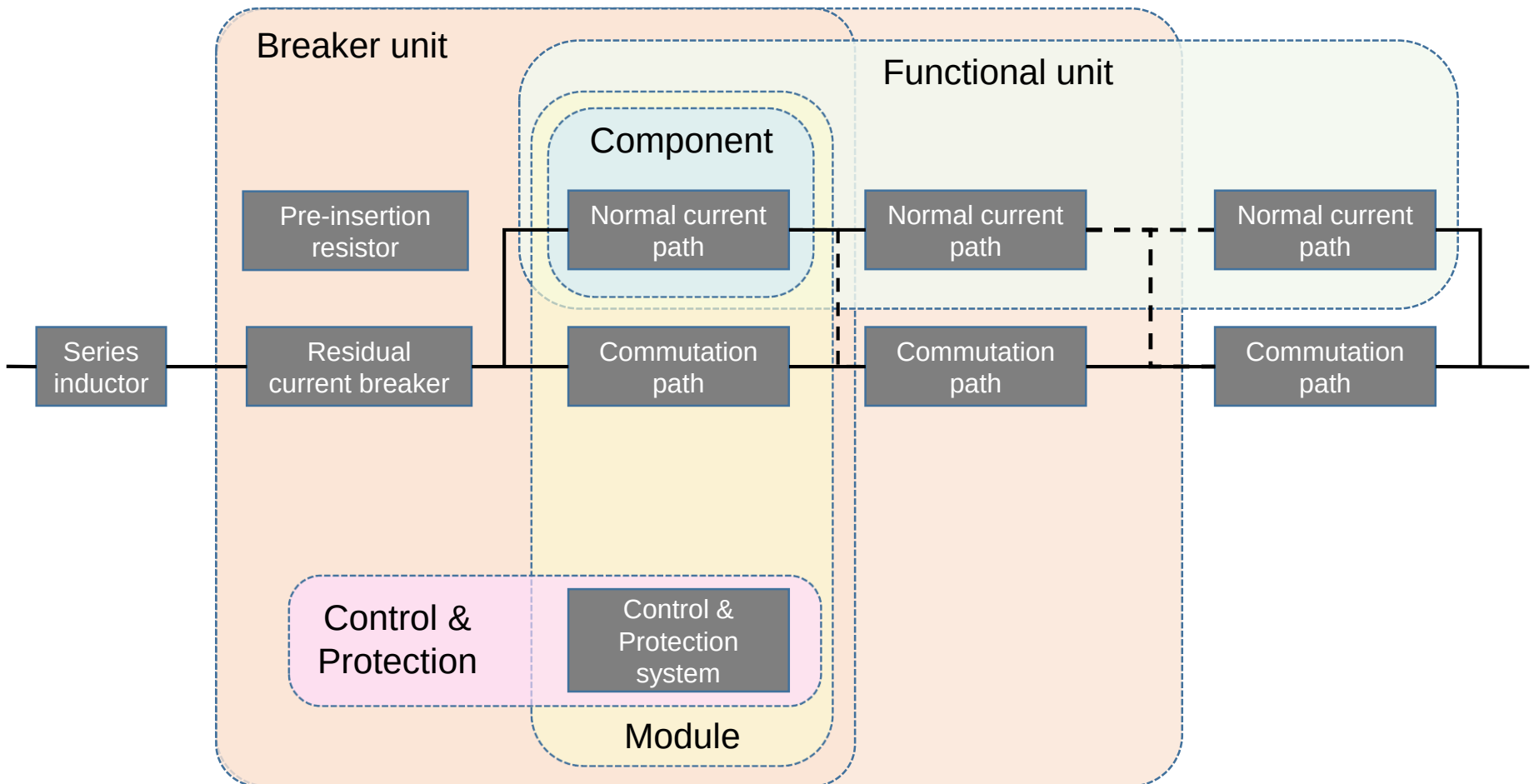
Dielectric testing – Residual current breaker



Dielectric testing – Breaker unit



Terminology – Operational test



Stresses



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Circuit breaker operations

↗ Determine idealised stresses for circuit breaker, it's functional units and components for all circuit breaker states and operations:

↗ Closed state

↗ Open state

↗ Closing

↗ Onto de-energised line

↗ Onto energised line

↗ Opening

↗ Nominal load current

↗ Fault current

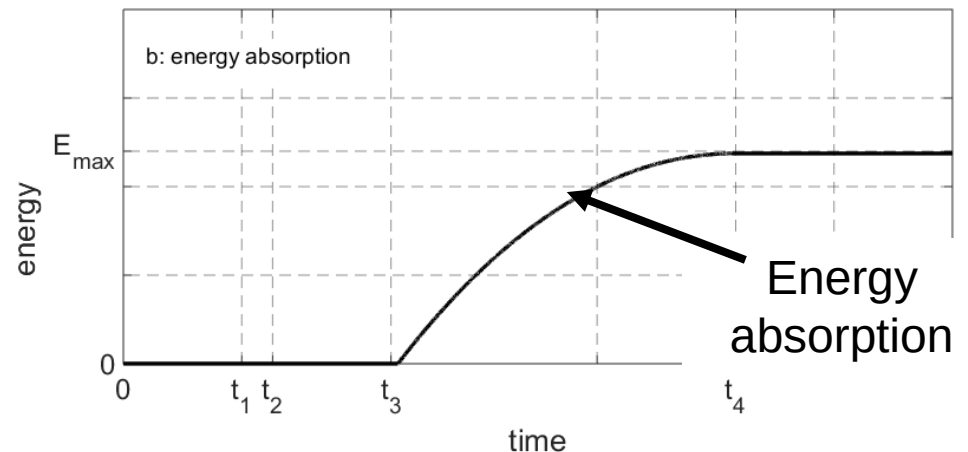
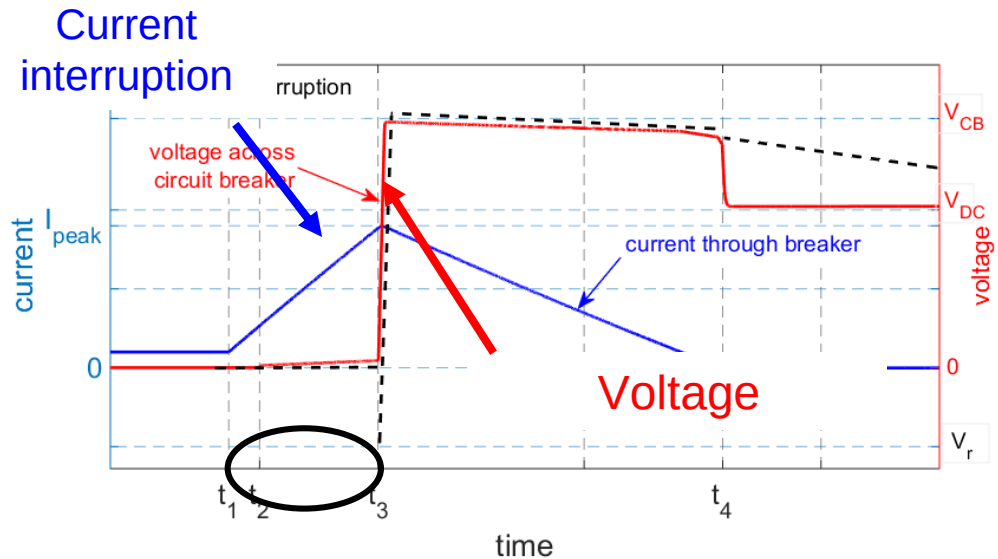
↗ Reclosing

↗ Reopening

↗ (Current limiting)

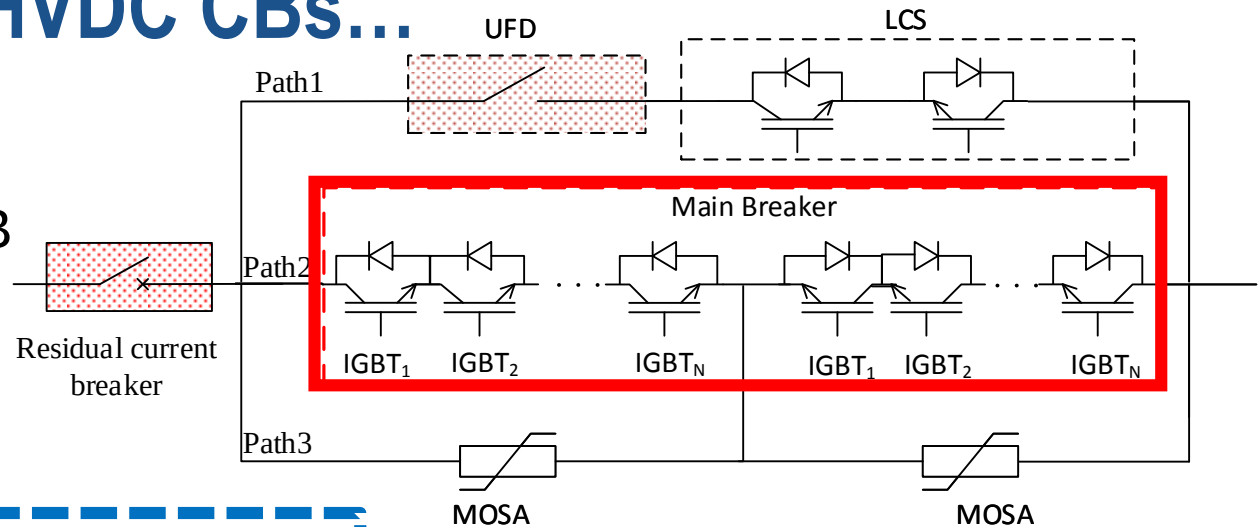
Expected stresses on HVDC CBs (current, voltage and energy)

- Current stress (di/dt , I_0 - I_{peak})
- Voltage stress (dv/dt , counter voltage generated and dielectric stress from the system)
- Energy stress (E_{max} , dE/dt ?)
- The minimum breaker operation time (t_2 - t_3)
- Is multi-part testing possible for each stress?



Overview of HVDC CBs...

Hybrid HVDC CB



Related standards:

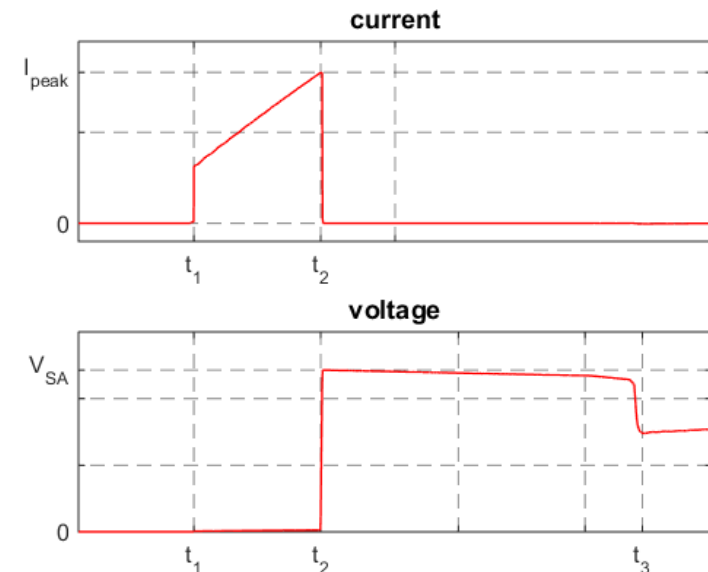
- VSC valves [IEC 62501:2009]

(Partially) covered:

- Short-circuit current test
- Maximum temporary over-load operating duty test

Limitations:

- Tests are focused on AC applications



Existing standards



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Considerations for testing

- ↗ Are stresses sufficiently covered by existing standards?
- ↗ What is the purpose of the test?
 - ↗ Type or production test? Or both?
- ↗ What tests can be done to sufficiently verify stress withstand
 - ↗ Direct tests
 - ↗ Synthetic tests
 - ↗ Tests with reduced parameters
 - ↗ DCL in test circuit not representative for DCL grid
 - ↗ Is it reasonable to reduce energy absorption requirement of MOSAs?
 - ↗ Multi-part testing
 - ↗ High voltage does not scale
 - ↗ Verify functionality at low voltage
 - ↗ Verify dielectric strength separate from functionality
 - ↗ Model validation

Twenties test requirements



index	Item	Value	Remark
1.1	Maximum DC network operating voltage	120 kV	Nominal voltage of commercially available DC-CB: 4100 V ("ARC4020", Alstom).
1.2	DC insulation level to earth of network	$1.5 \times \text{DC network operating voltage} = 180 \text{ kV}$	Factor is based on recommendation in [8]. Used as reference for the Transient Interruption Voltage.
1.3	Lightning impulse withstand level (according to IEC 60060-1, rise time=1.2 μ s, decay time=50 μ s) between terminals.	650 kV (KPI 1 component C₁)	Test value for an AC switchgear with rated voltage of 145 kV.
2.1	Prospective currents to be interrupted as a function of time for different types of switching scenarios (load + fault).	$I_{\text{load, dc}} = 1.5 \text{ kA}$ $I_{\text{fault, dc}} = 6 \text{ kA}$ Rate of rise of current = 10 kA/ms	Test values to assess KPI 1 component C₃ and C₄ .
2.2	Possible presence of current zeros? (calls for scenario descriptions)	No	Zero crossings would allow for the use of conventional AC switchgear.
2.3	Rated DC current conduction	1500 Adc	Check thermal stability
2.4	Wave forms of let-through current as a function of time. The 3 wave forms are individual tests. Inspection and maintenance on the test object is possible between the tests.	1. 3000 Adc for 1 minute (KPI 1 component C₂), 2. $5 \text{ kA} \sin(2\pi 50 \text{ Hz } t)$ for 10 ms 3. $10 \text{ kA} \sin(2\pi 13 \text{ Hz } t)$ for 1.6 ms	-

Table 23: Summary of requirements and KPI 1 components 1 to 4 for the HVDC demonstrator.

Chinese draft standard

- ↗All components to be tested according to relevant standard
- ↗Insulation tests
 - ↗Lightning impulse withstand test
 - ↗DC voltage withstand test
- ↗Measurements of resistance in major loop
- ↗Temperature rise test
- ↗Verification of protection class
- ↗Sealing test
 - ↗Mechanical operation tests under ambient air temperature
- ↗Static load tests of terminals

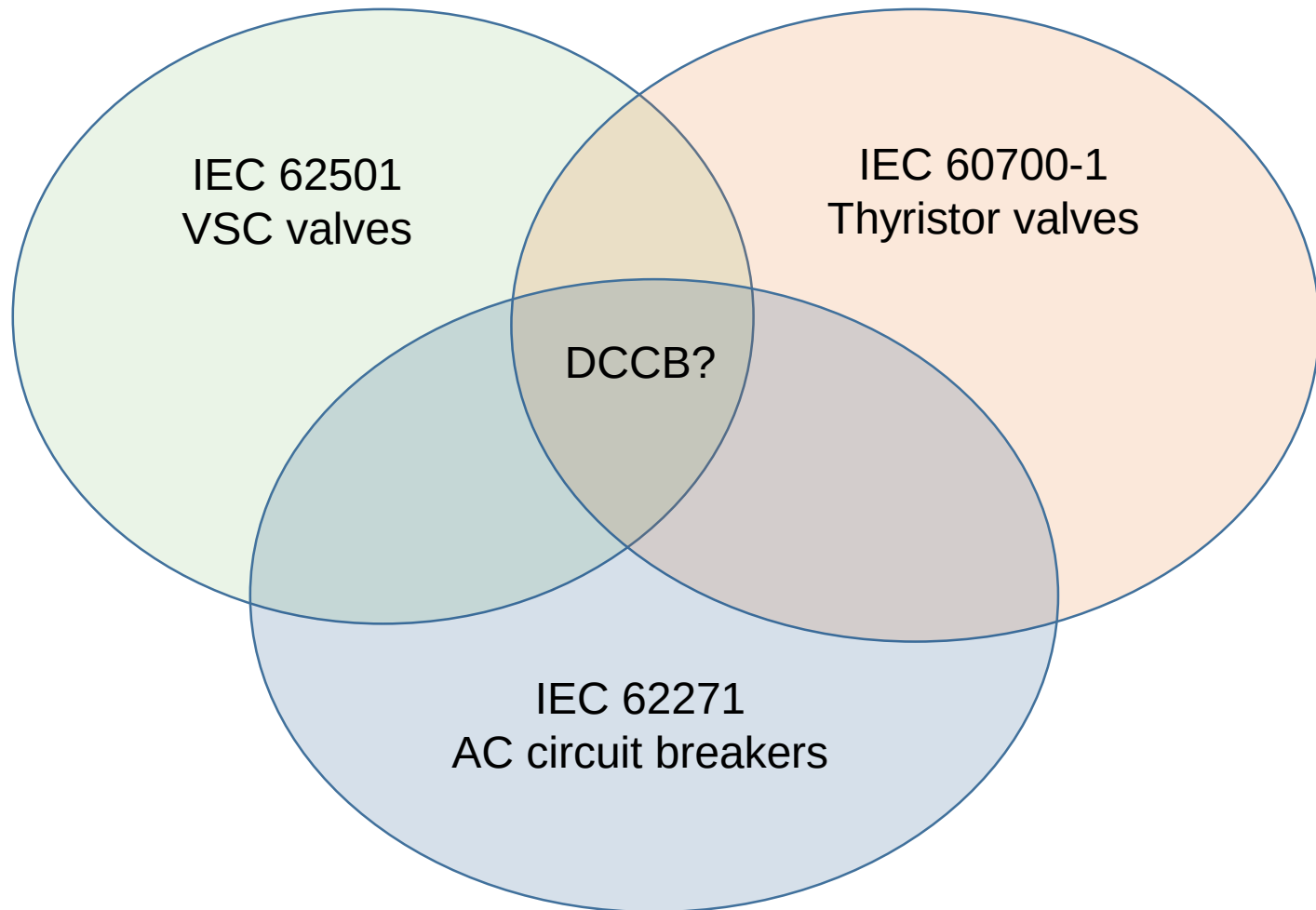
Chinese draft standard

↗ Interrupting test of DC circuit breaker

- ↗ Rated current, 50% of interruption current and 100% of interruption current
- ↗ 10 breaking operations at each duty
- ↗ Restriking phenomena should not occur after interruption

↗ Shock test

Existing standards



Test requirements



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Dielectric tests

↗ On support structure

↗ DC withstand tests

↗ Impulse withstand tests

↗ Between terminals (module)

↗ DC withstand tests

↗ Impulse withstand tests

↗ Residual current breaker

↗ Dynamic voltage distribution



Operational tests

↗ Measurement of resistance of normal current path

↗ Temperature rise test

↗ *Measurement of on-state power losses*

↗ Short-time current withstand test

↗ Temporary overload withstand

↗ Short-time short-circuit current withstand



Making & breaking tests

↗ Making tests

- ↗ Closing onto energised line
- ↗ Closing onto de-energised line
- ↗ Closing onto short-circuit
- ↗ Reclosing onto short-circuit

↗ Breaking tests (module)

- ↗ Short-circuit current interruption test
- ↗ Current commutation tests
- ↗ Energy absorption tests
- ↗ Residual current breaker operation

↗ Self-protection



Endurance tests

- ↗Power electronics insensitivity to electromagnetic disturbance
- ↗Mechanical endurance
- ↗Electrical endurance



Test object & pre-conditioning

- ↗Reactor is tested separately
- ↗Control & protection system can be tested separately
- ↗Surge arrestors should be disconnected during dielectric tests
- ↗Thermal effects should be taken into account during dielectric tests (?)
- ↗Power electronic components can be preheated to maximum junction temperature prior to short-time current withstand tests
- ↗Surge arrestors can be preheated to test reclosing (?)



Test circuits

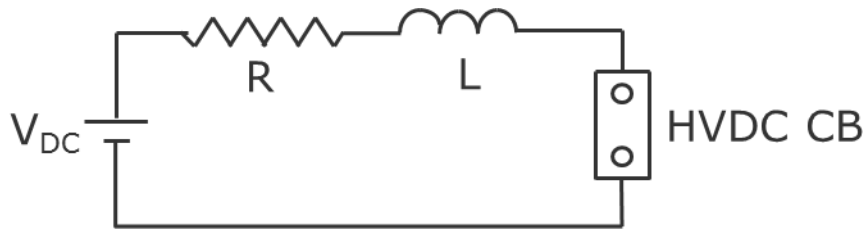


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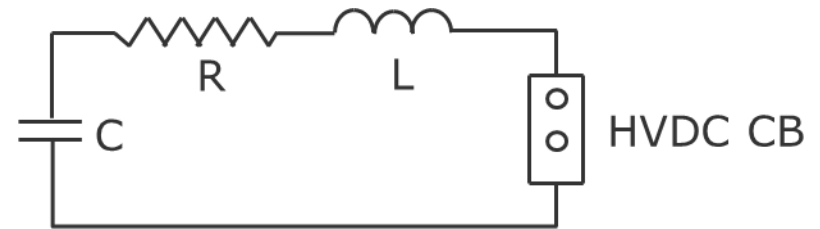
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DC circuit breaker test circuits

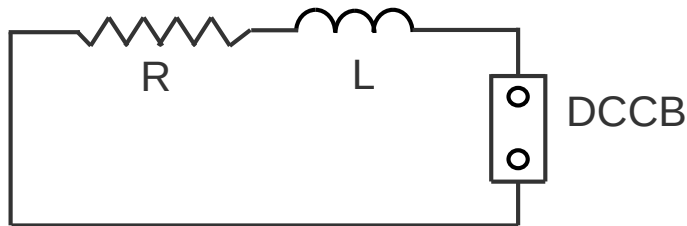
❖ Ideal DC Test Circuit



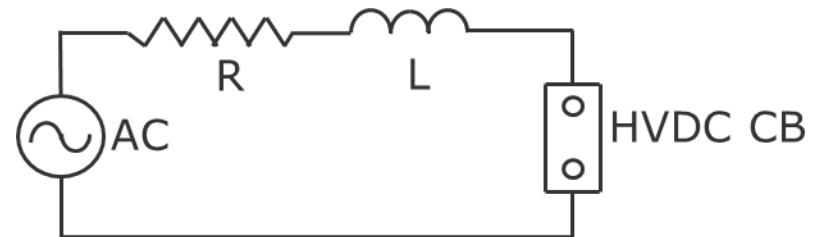
❖ Charged Capacitor



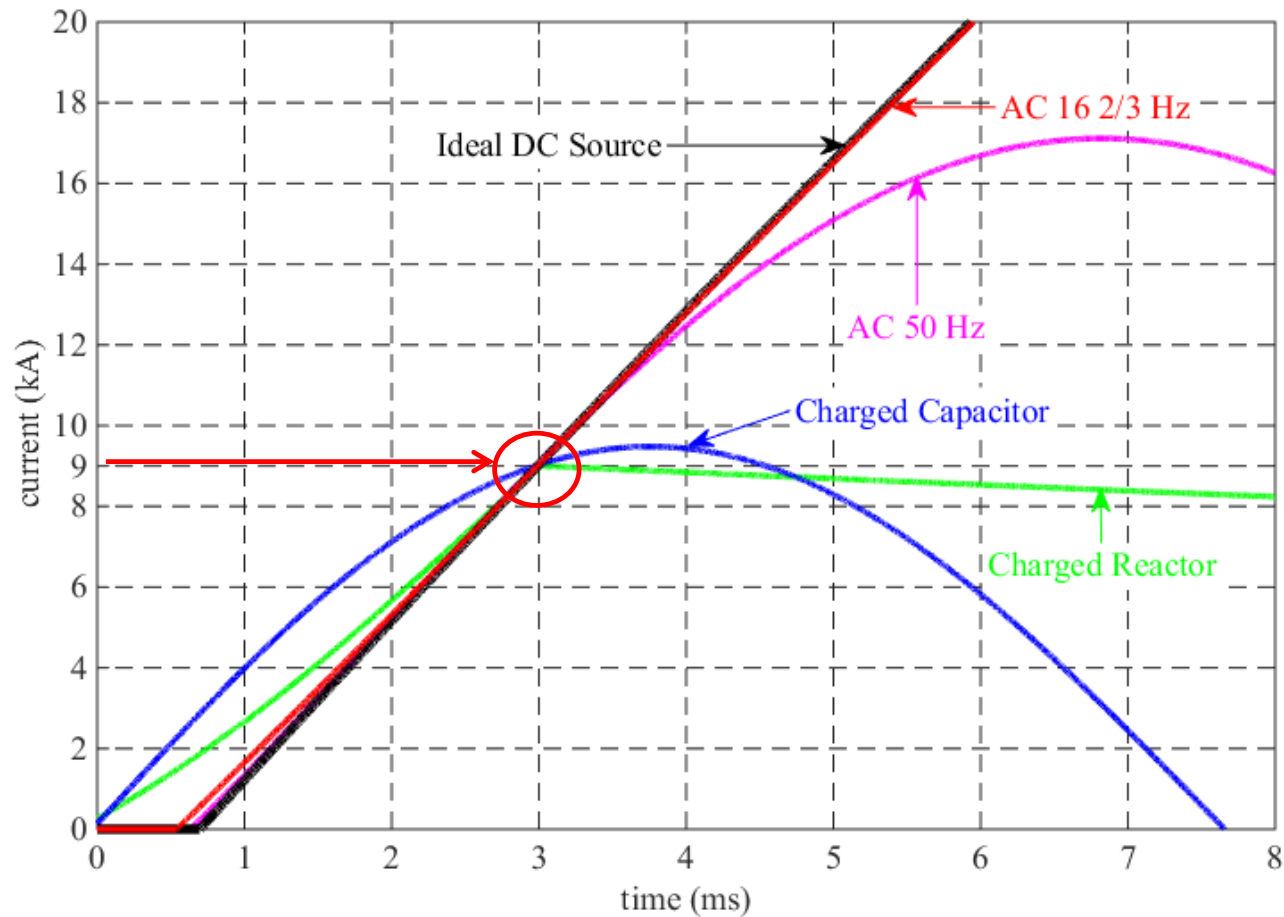
❖ Charged reactor method



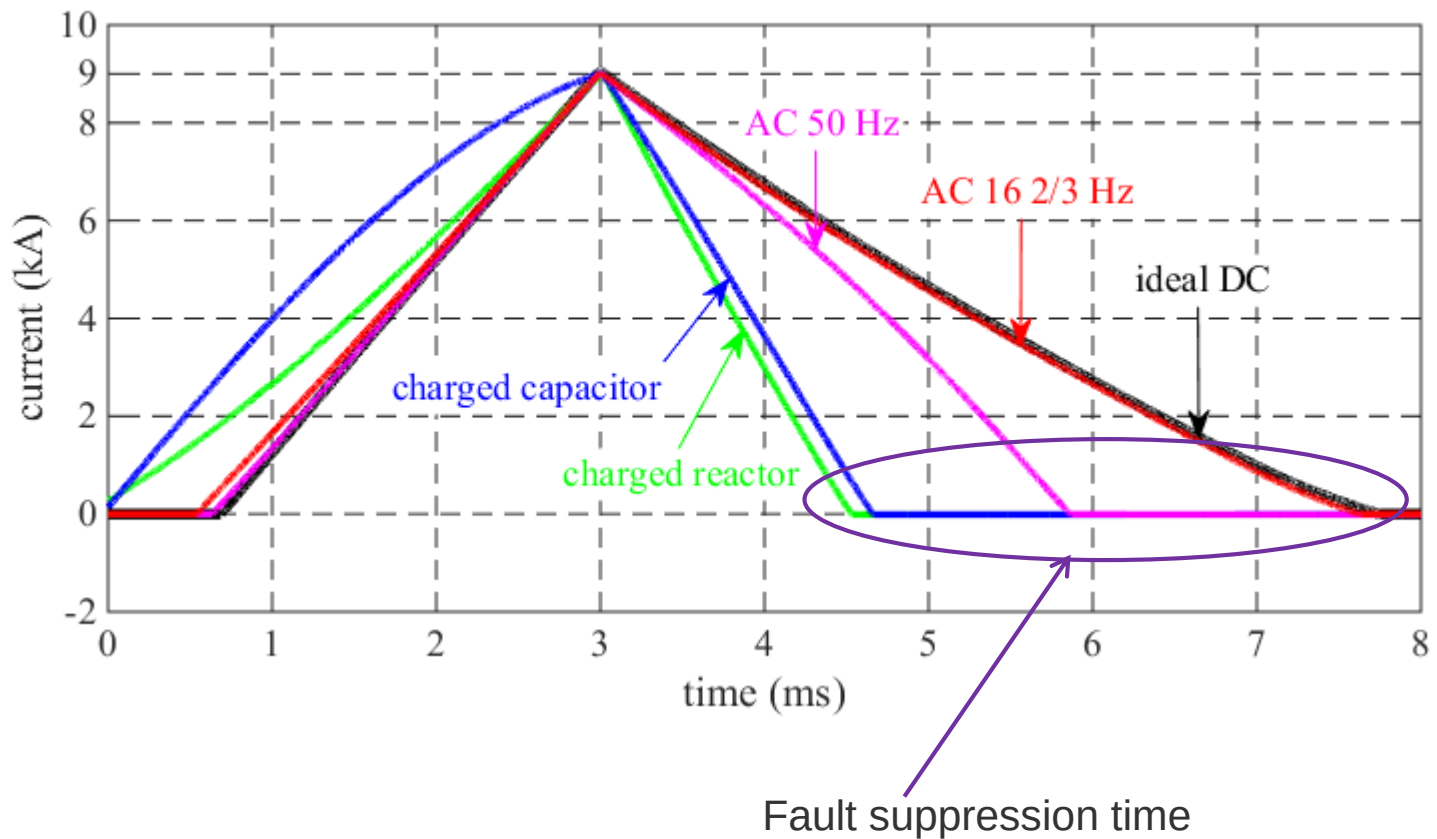
❖ Variable Frequency AC



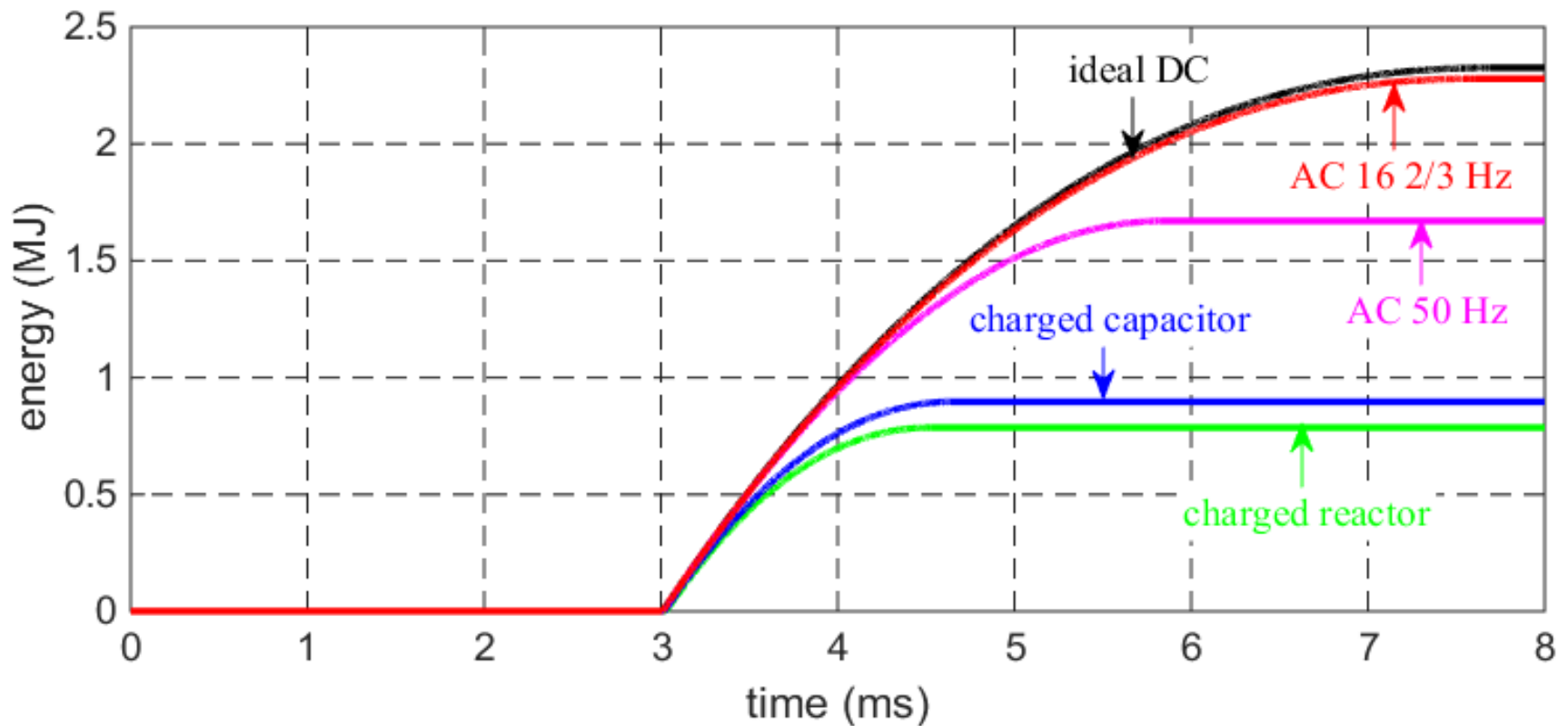
Prospective currents



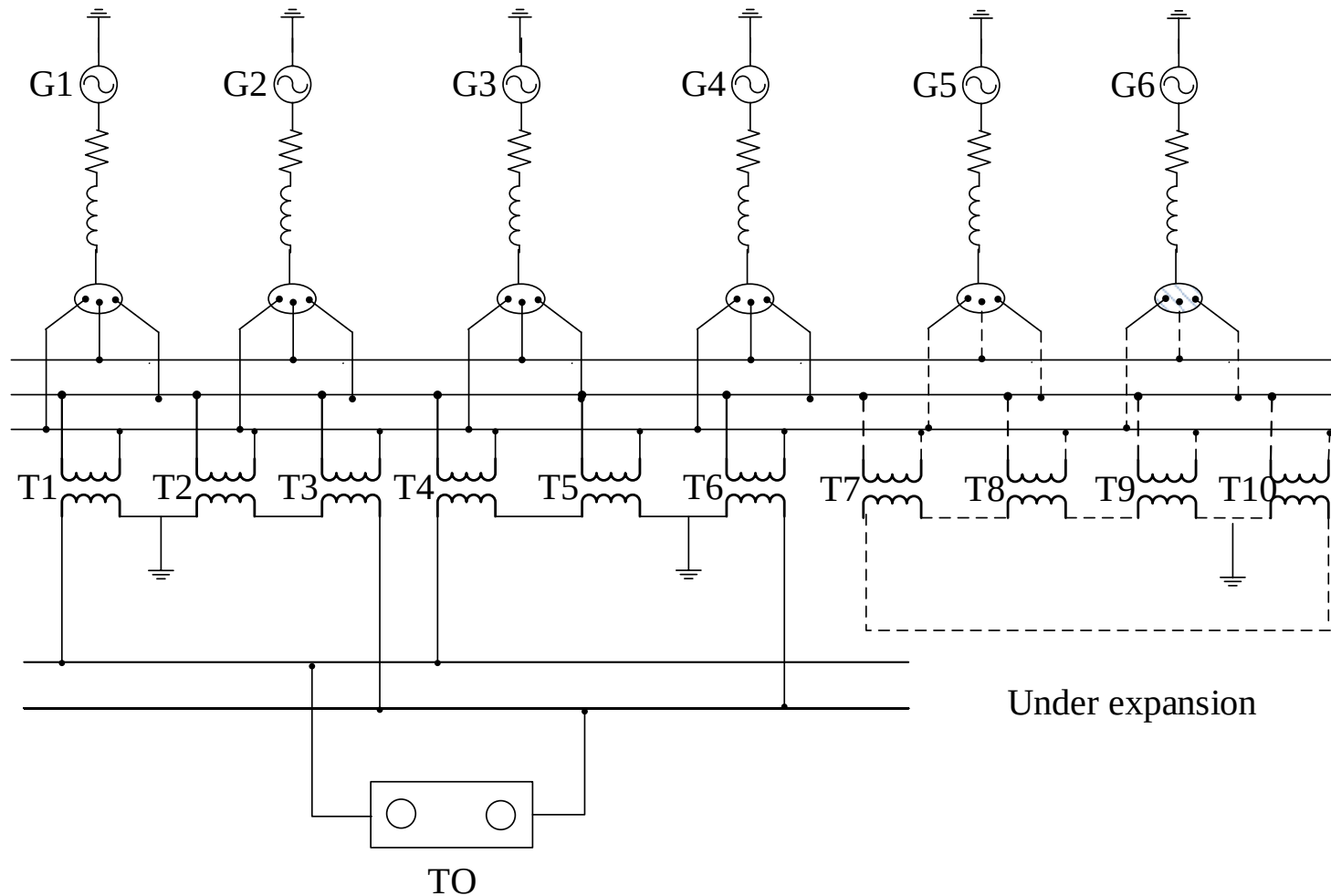
Current interruption curves



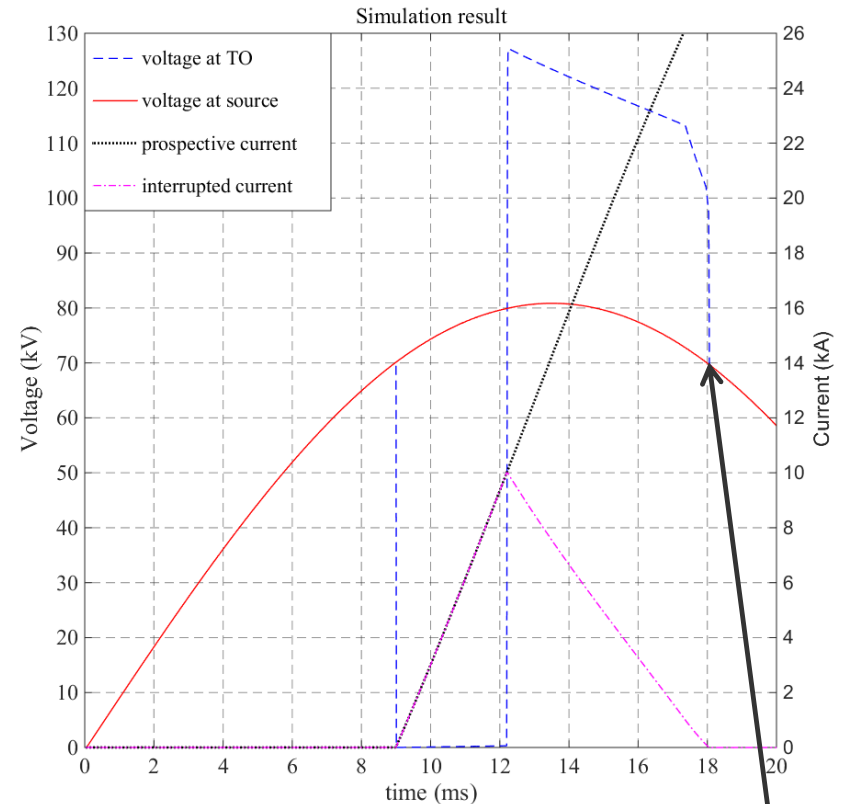
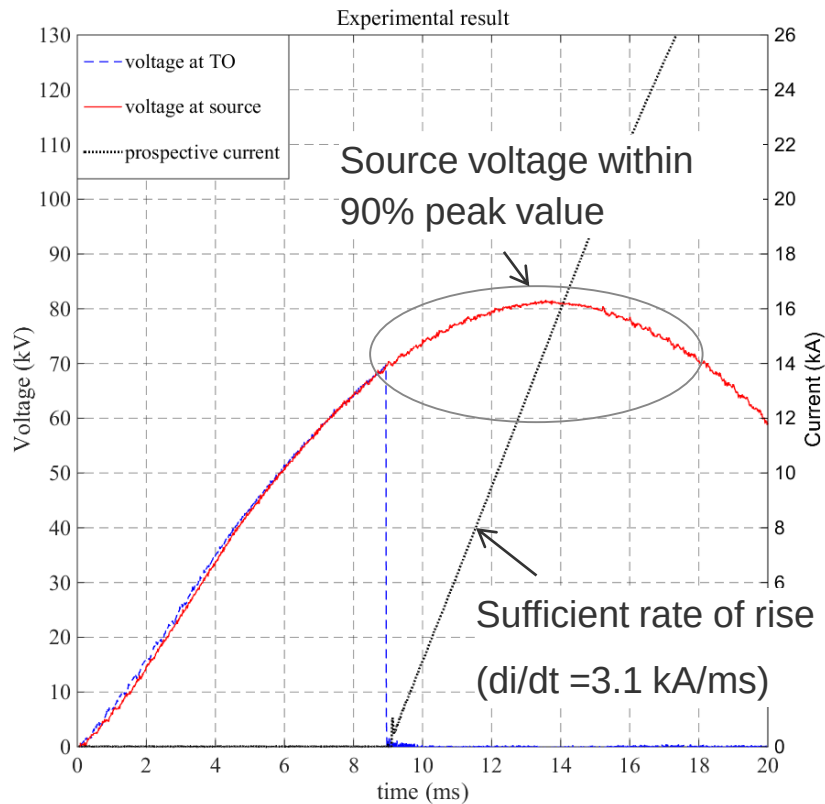
Absorbed energy curves



KEMA Laboratories test set-up



Experimental verification



- ❖ Using low frequency sufficient test parameters such as di/dt , source voltage and energy stored in system reactance can be achieved
- ❖ Prospective tests at 120 kV was also conducted

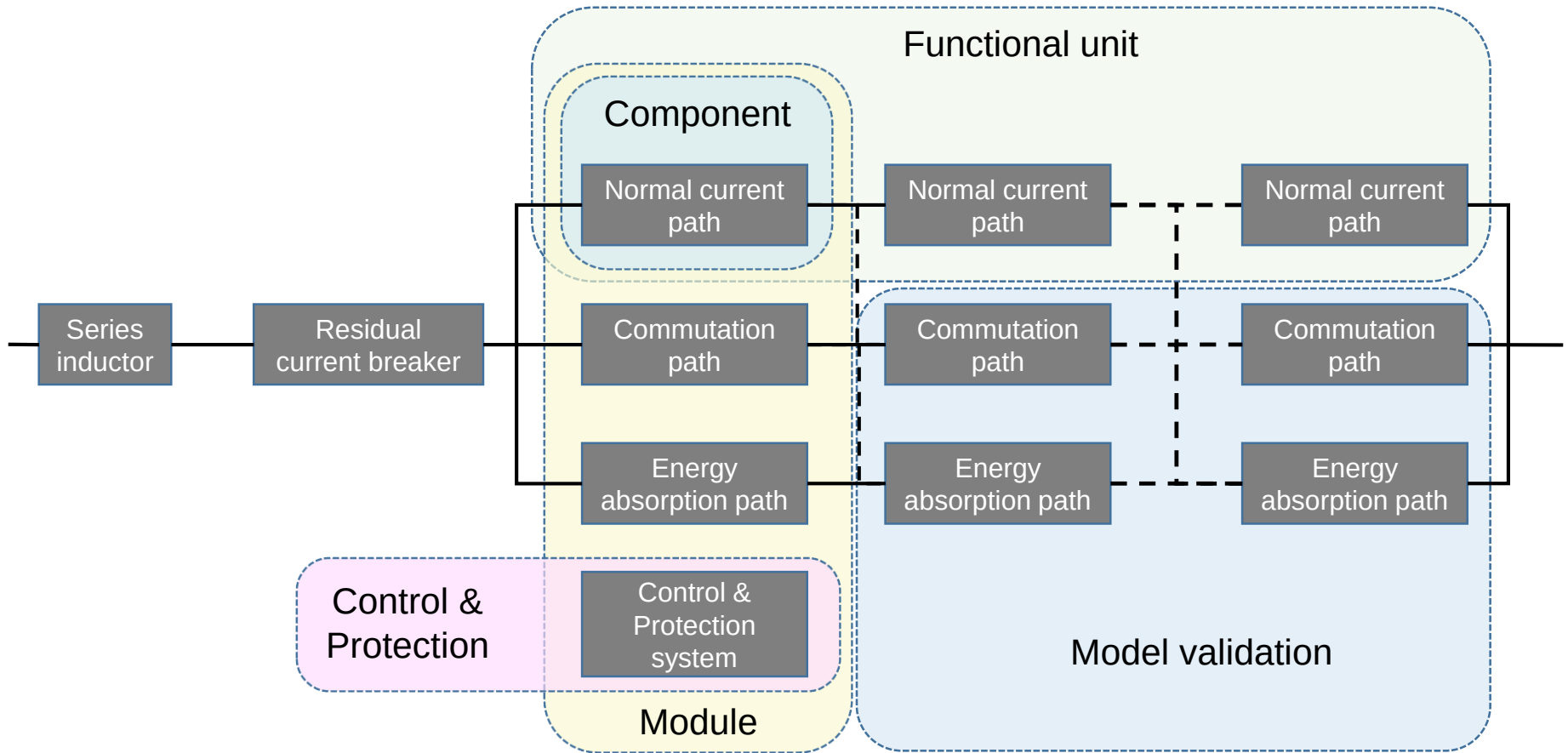
Test circuit limitations



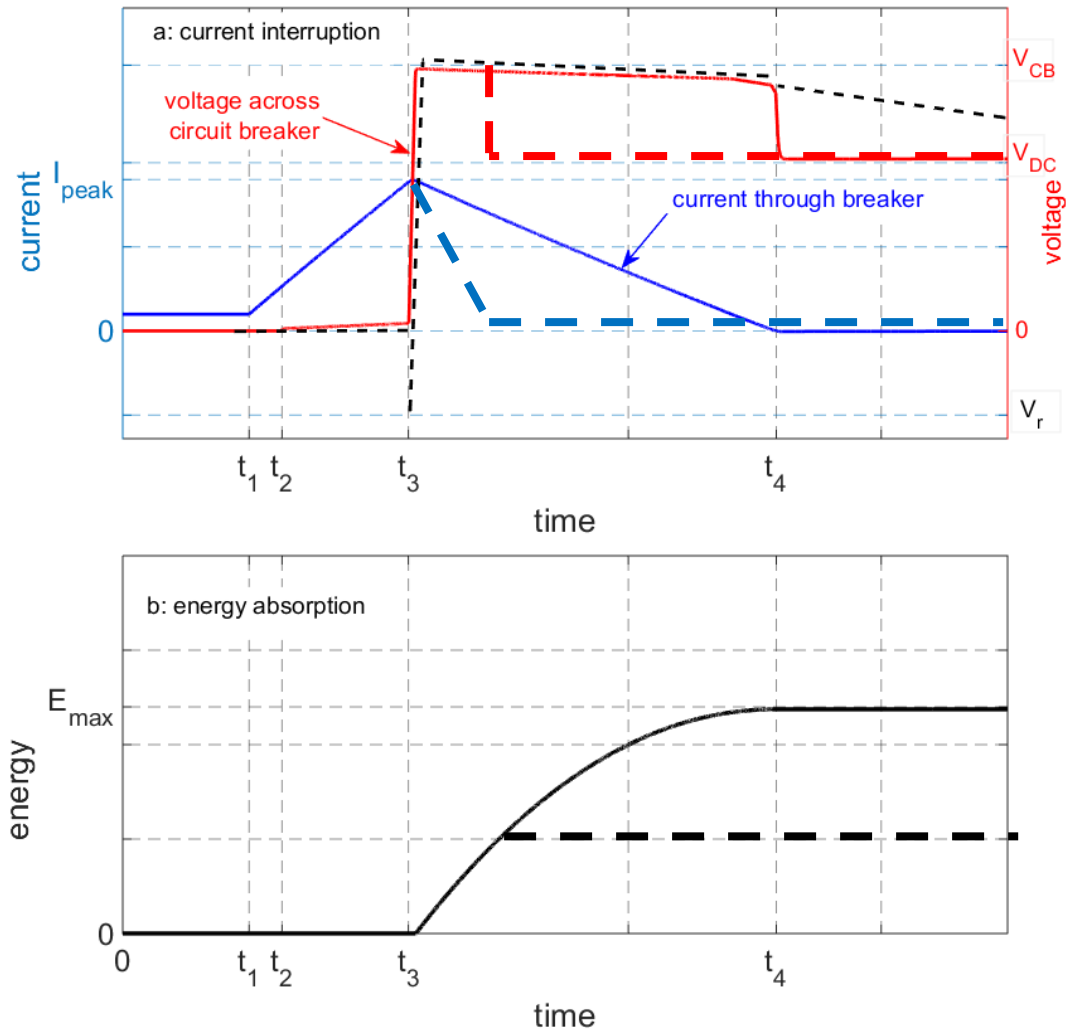
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Multi-unit / synthetic testing



Testing with reduced parameters



Conclusions

- ↗ DCCBs are systems, rather than components
 - ↗ Desired functionality and ratings achieved through combination of parallel and series connected subcomponents
- ↗ No economically feasible test circuit exists to test DCCB according to full ratings and functionality
- ↗ Subparts of DCCB must be tested to verify ratings and functionality separately
- ↗ Stresses on each subpart must be determined by analysis
- ↗ Different test circuits exist to verify different ratings and functionalities
- ↗ Low frequency AC short-circuit generators can deliver voltage and current stresses simultaneously for one or more modules
- ↗ There is no substitute for high voltage high power testing





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Thank you! Any questions?



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APPENDIX

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Dielectric tests

↗ On support structure

↗ DC withstand tests

- ↗ Maximum continuous operating voltage x test factor
- ↗ Long duration
- ↗ Thermal cycles

↗ Impulse withstand tests

- ↗ According to insulation coordination of station
- ↗ Surge arrestor protective voltage x test factor
- ↗ Should withstand impact of travelling waves

↗ Pass criteria

- ↗ No flashover / breakdown
- ↗ Acceptable level of partial discharge – refer to existing standards

Dielectric tests

↗ Between terminals (module)

↗ DC withstand tests

- ↗ Surge arrestor protective level x test factor
- ↗ Short duration
- ↗ ‘cold’ and ‘hot’

↗ Impulse withstand tests

- ↗ should withstand impact of travelling wave
- ↗ should represent ‘reverse spikes’
 - ↗ Remnant capacitor charge
 - ↗ Reverse recovery effects

↗ Pass criteria

- ↗ No flashover / breakdown
- ↗ Acceptable level of partial discharge – refer to existing standards

Operational tests

- ↗ Measurement of resistance of normal current path
 - ↗ Use DC current to measure normal current path resistance / forward voltage drop
 - ↗ Resistance should be within spec

- ↗ Temperature rise test
 - ↗ Apply nominal DC load current
 - ↗ Sufficiently long duration for thermal equilibria to be reached
 - ↗ Temperature rise should be within spec

- ↗ *Measurement of on-state power losses*
 - ↗ Apply nominal DC load current
 - ↗ Power losses should be within spec

Operational tests

↗ Short-time current withstand test

↗ Temporary overload withstand

- ↗ Temperature of normal current path components should be highest steady state junction temperature
- ↗ Apply max DC load current
- ↗ Limited duration
- ↗ Temperature rise must be within spec

↗ Short-time short-circuit current withstand

- ↗ Temperature of normal current path components should be highest steady state junction temperature
- ↗ Apply downstream fault current
- ↗ Limited duration (protection response time, or converter blocking time?)
- ↗ Temperature rise must be within spec

Making & breaking tests

↗ Making tests

- ↗ Closing onto energised line

 - ↗ Cold state

- ↗ Closing onto de-energised line

 - ↗ Cold state

- ↗ Closing onto short-circuit

 - ↗ Cold state

- ↗ Reclosing onto short-circuit

 - ↗ Pre-condition all circuit breaker parts to steady-state temperature resulting from energy absorption of one breaking operation.

Making & breaking tests

↗ Breaking tests (module)

↗ Short-circuit current interruption test

- ↗ Apply fault current with suitable di/dt
- ↗ Apply sufficient counter voltage during suppression
- ↗ Test duties
- ↗ Verification of current interruption capability
- ↗ Verification of break time
- ↗ Application of dielectric stress after interruption

↗ Current commutation tests

↗ Energy absorption tests

↗ Residual current breaker operation

↗ Self-protection



Endurance tests

- ↗Power electronics insensitivity to electromagnetic disturbance
- ↗Mechanical endurance
- ↗Electrical endurance



AC circuit breaker testing (IEC 62271)

↗ Dielectric tests

- ↗ Power Frequency

- ↗ Lightning impulse

- ↗ Switching impulse (for higher rated voltages)

↗ Temperature Rise Tests (with measurement of resistance before and after test for verification)

↗ Short time current tests (Short circuit current for 1 or 3s on closed CB with measurement of resistance before and after test for verification)

↗ Mechanical & Environmental tests (with gas tightness (leakage) test before and after as verification)

- ↗ Mechanical endurance (2000 or 10000 CO operations)

- ↗ Low and High Temperature test

AC circuit breaker testing (IEC 62271)

↗ Breaking and making Tests

- ↗ T10, T30, T60, T100s (breaking and making), T100a
- ↗ Single phase and double-earth fault tests
- ↗ Short Line fault
- ↗ Out-of-phase tests
- ↗ Capacitive current Switching tests

↗ Electrical endurance tests (determines the lifetime/maintenance of breaker) – IEC 62271-310

↗ Inductive Switching tests (for breakers dedicated to shunt reactors/motors switching) - IEC 62271-110

VSC valve testing (IEC 62501)

↗Operational tests

- ↗ Maximum continuous operating duty test
- ↗ Maximum temporary over-load operating duty test
- ↗ Minimum d.c. voltage test

↗Dielectric tests on valve support structure

- ↗ Valve support d.c. voltage test
- ↗ Valve support a.c. voltage test
- ↗ Valve support switching impulse test
- ↗ Valve support lightning impulse test

↗Dielectric tests on multiple valve unit (MVU)

- ↗ MVU d.c. voltage test to earth
- ↗ MVU a.c. voltage test
- ↗ MVU switching impulse test
- ↗ MVU lightning impulse test



VSC valve testing (IEC 62501)

- ↗ Dielectric tests between valve terminals
 - ↗ Valve a.c. – d.c. voltage test
 - ↗ Valve impulse tests (general)
 - ↗ Valve switching impulse test
 - ↗ Valve lightning impulse test
- ↗ IGBT overcurrent turn-off test
- ↗ Short-circuit current test
- ↗ Tests for valve insensitivity to electromagnetic disturbance
- ↗ Tests for dynamic braking valves