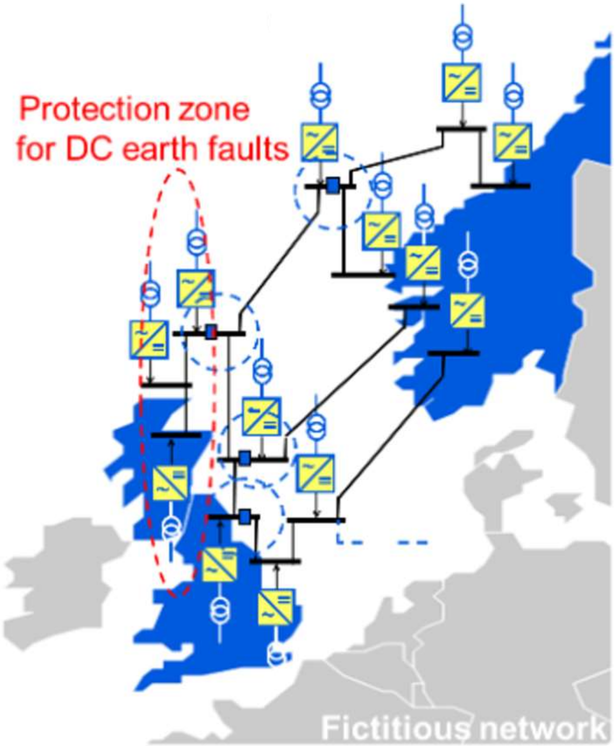

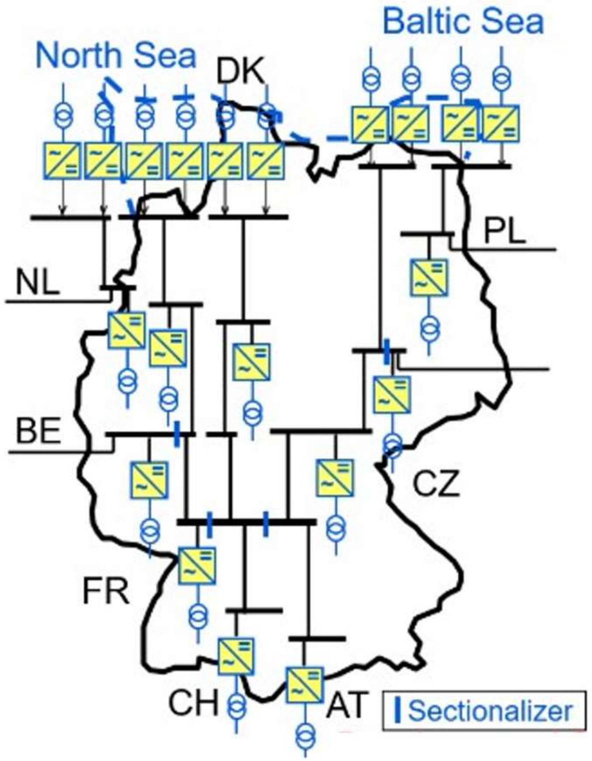

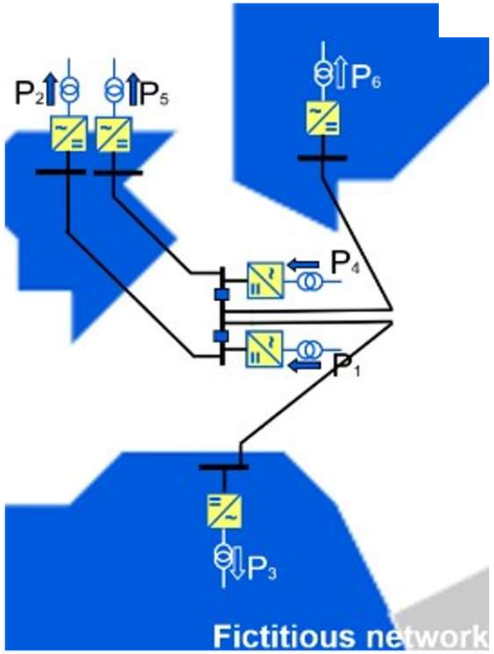

HVDC Transmission networks - HVDC Grid

Multi-terminal HVDC, DC Grid, HVDC Light, VSC

Kerstin Lindén, Senior Principal Lead Engineer, HVDC

2024-11-13

Hitachi Energy

Speaker: Kerstin Lindén

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Pictures on title page from left to right:

Presented by Kerstin Lindén in London June 6, 2011 at “North Sea Offshore Networks; Enabling Offshore Wind and Balancing Power” UK-Norway Forum and Roadmapping Workshop. With sectionalizing DC breakers. Inspired by planned “bootstrap” HVDC projects in UK, North-sea plans and interconnections to Scandinavian spinning reserves.

Presented by Kerstin Lindén in Germany 2011. Building a DC grid - from several point-to-point links, through radial multi-terminal to connected HVDC system with sectionalizing DC breakers. DC grid topology inspired by Swedish AC transmission system design and Germany´s network development plans.

Presented by Kerstin Lindén in Germany 2012. With sectionalizing DC breakers. Inspired by the Kriegers flak project.

Hitachi Energy/ABB

DC GRID

2012-2024	Lead Engineer in the tender and project for the Caithness Moray Shetland HVDC link in Scotland, UK
2019-	Lead Engineer in tenders
2009-2012	R&D Project Manager for the HVDC Grid project
1998-2004	Technical Manager at ABB T&D University and Power System Engineer at HVDC System Design

HVDC

HVAC SYSTEM

STRI AB

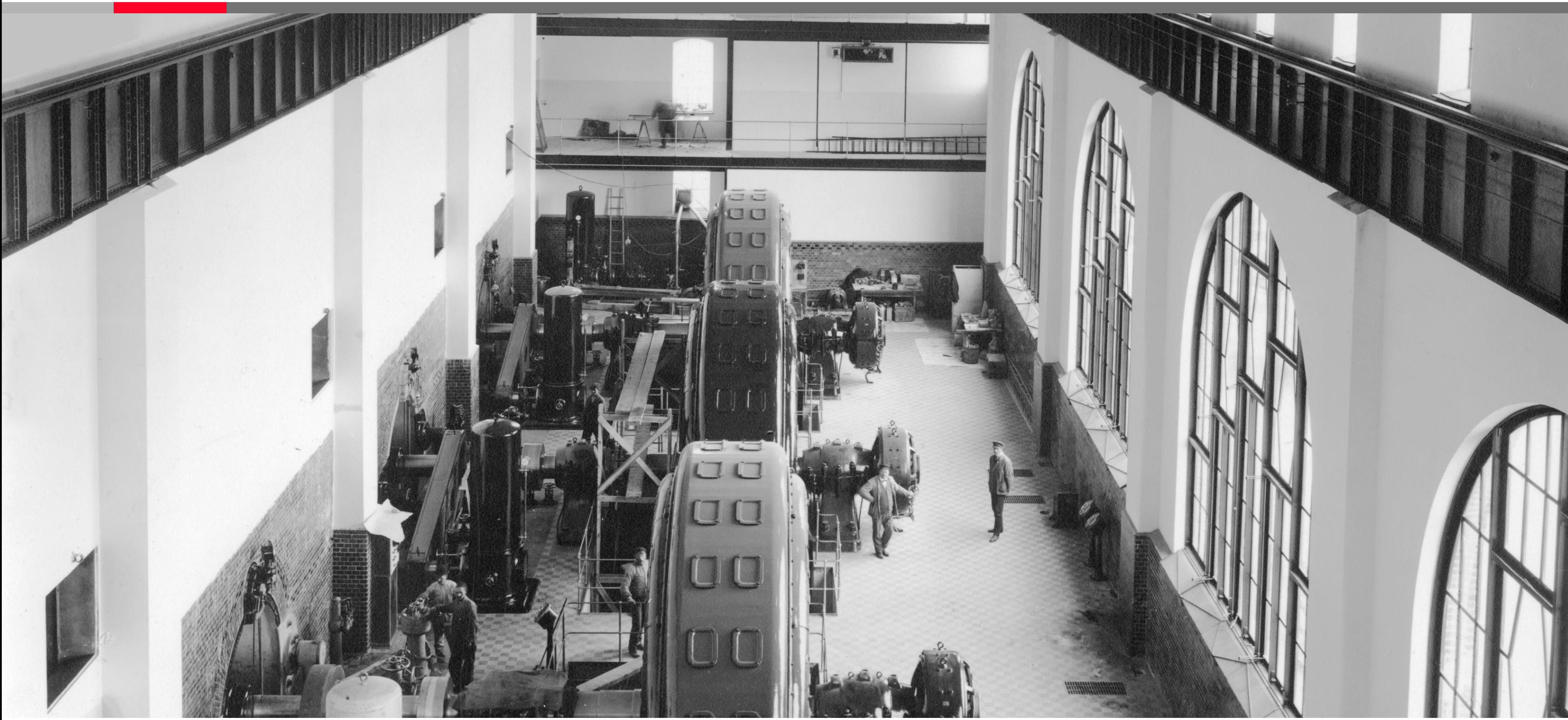
2004-2009	Technical Manager for Power System Analysis and Simpow development. Senior Specialist. Manager for Consulting Services
1993-1998	Research manager for Power Systems. Research project manager

Universities

TEACHER

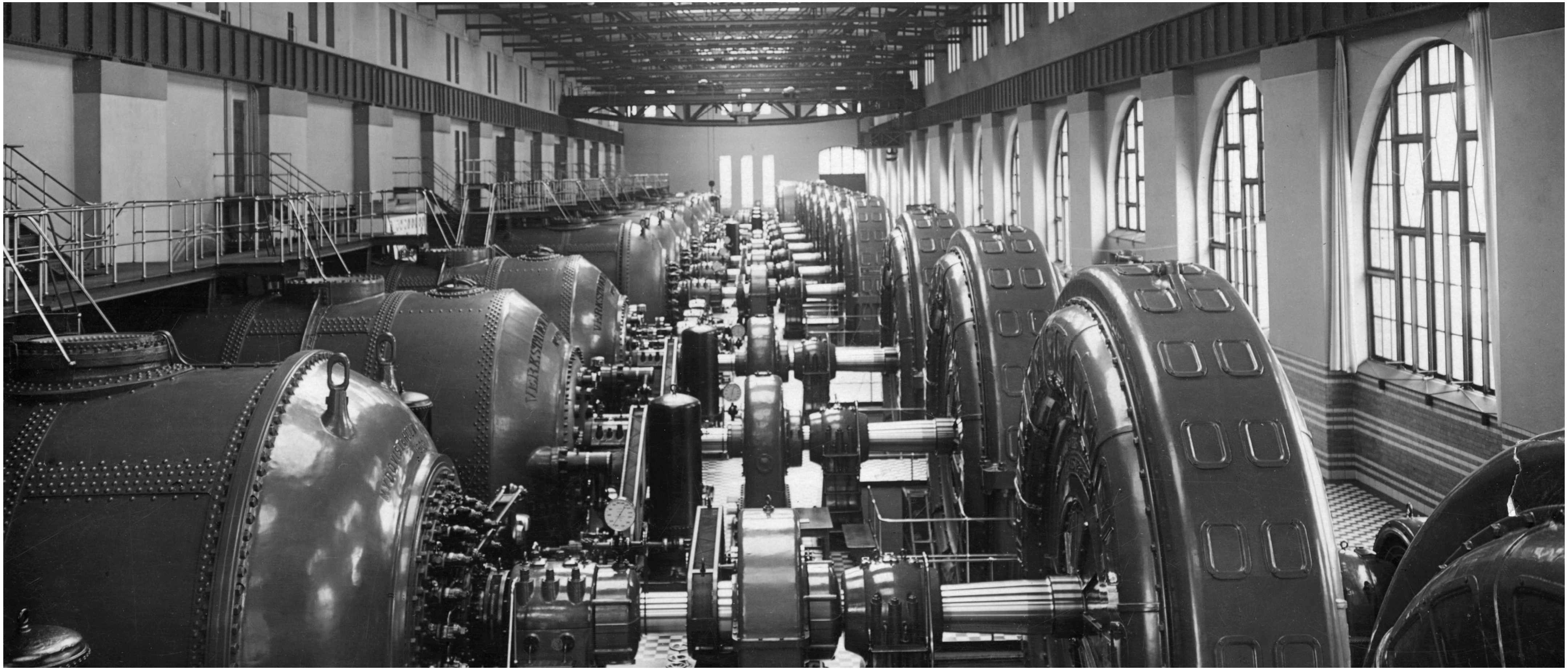
1993-1998	Lecturer at Mälardalen University
	Lic. Eng. and M. Sc. E. E. from Chalmers University of Technology, Göteborg, Sweden, 1992 and 1988.

Hundred years ago, in Älvkarleby…



Tekniska muséet via DigitaltMuseum, Photographer: Unknown. CC pdm.

and in Trollhättan hundred years ago…



Tekniska muséet via DigitaltMuseum. Photographer: Samuelsson, Dan (1893 - 1980)/Bohusläns museum. CC pdm.

Development of the first multi-purpose AC grids
From electrical islands to interconnected grid - 1922

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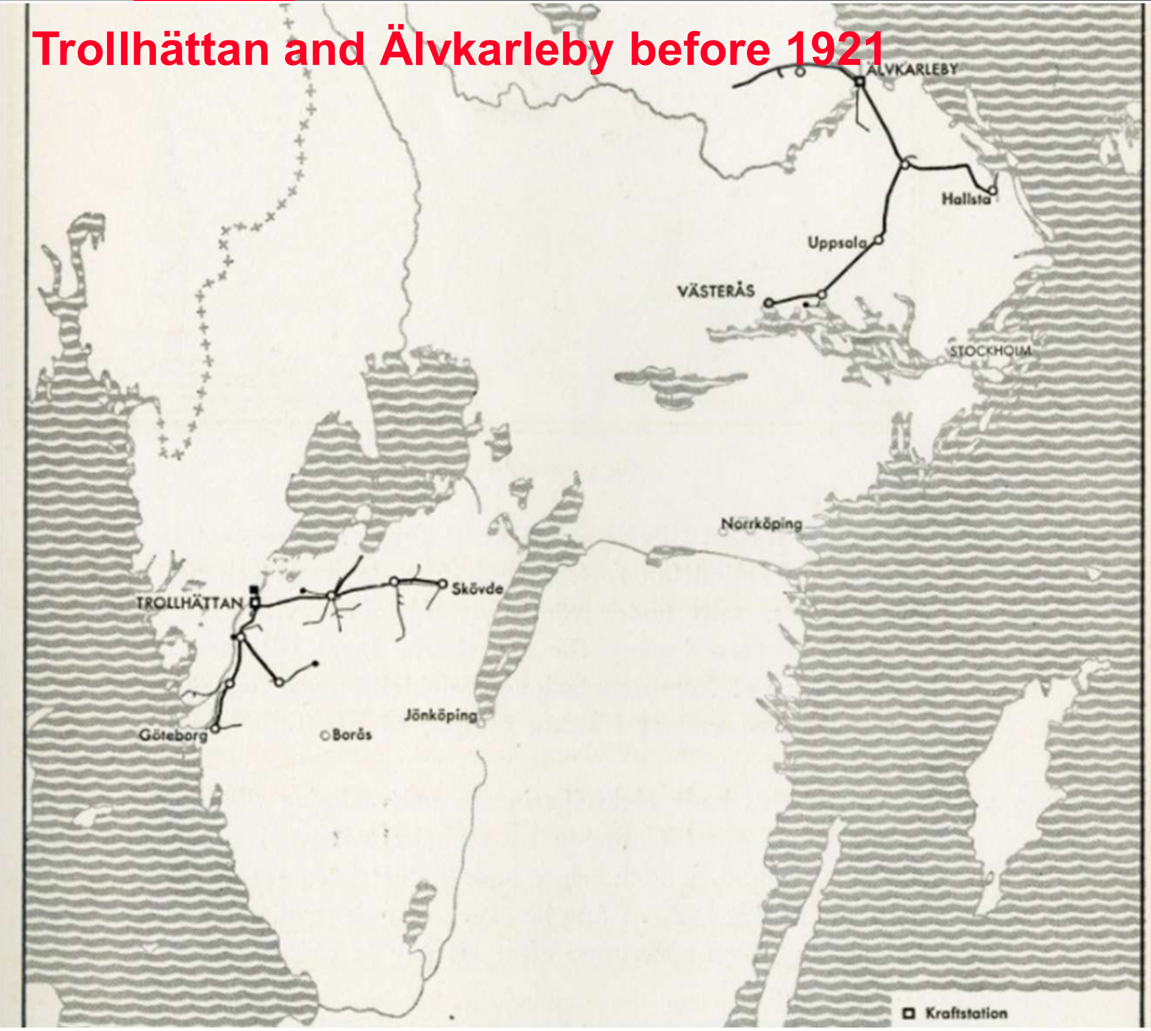
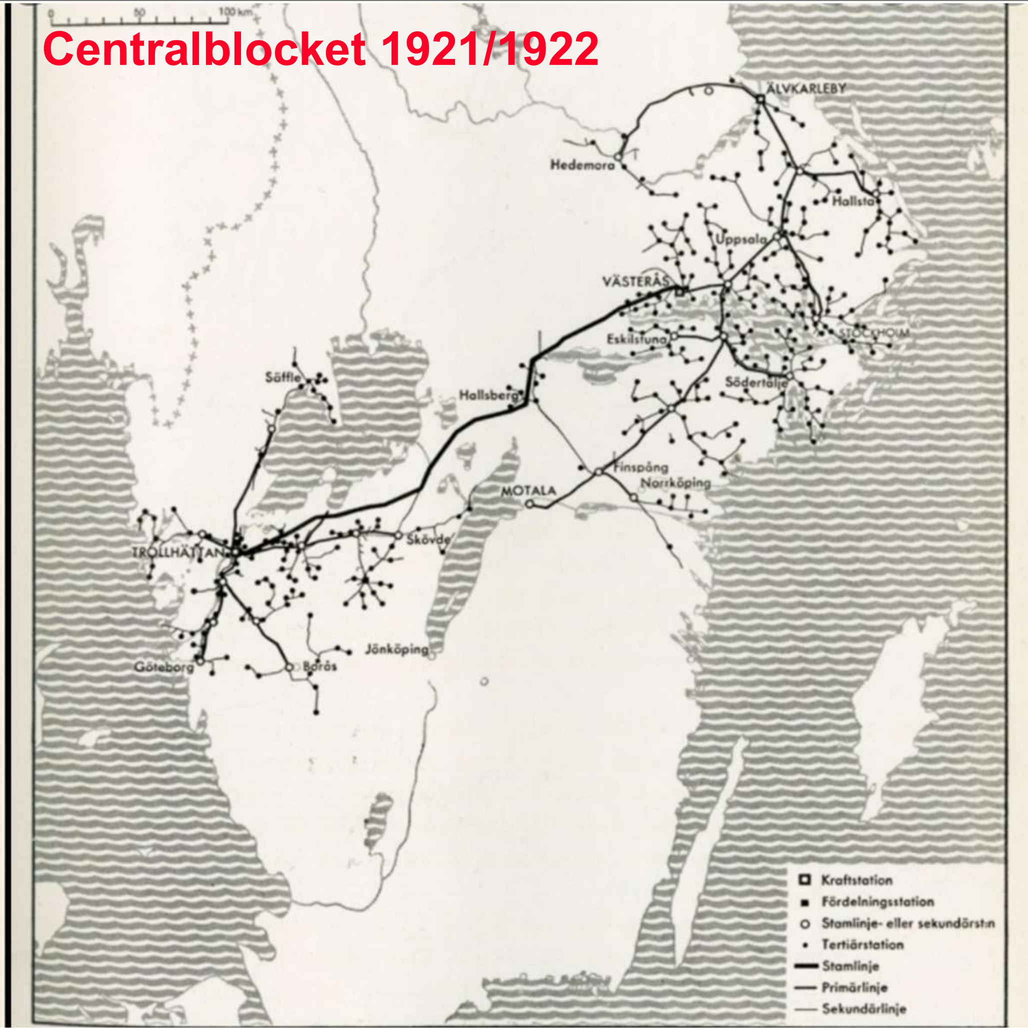
Trollhättan and Älvkarleby before 1921



Centralblocket 1921/1922



Kungliga Vattenfallsstyrelsen 1909-1934 – Historisk översikt

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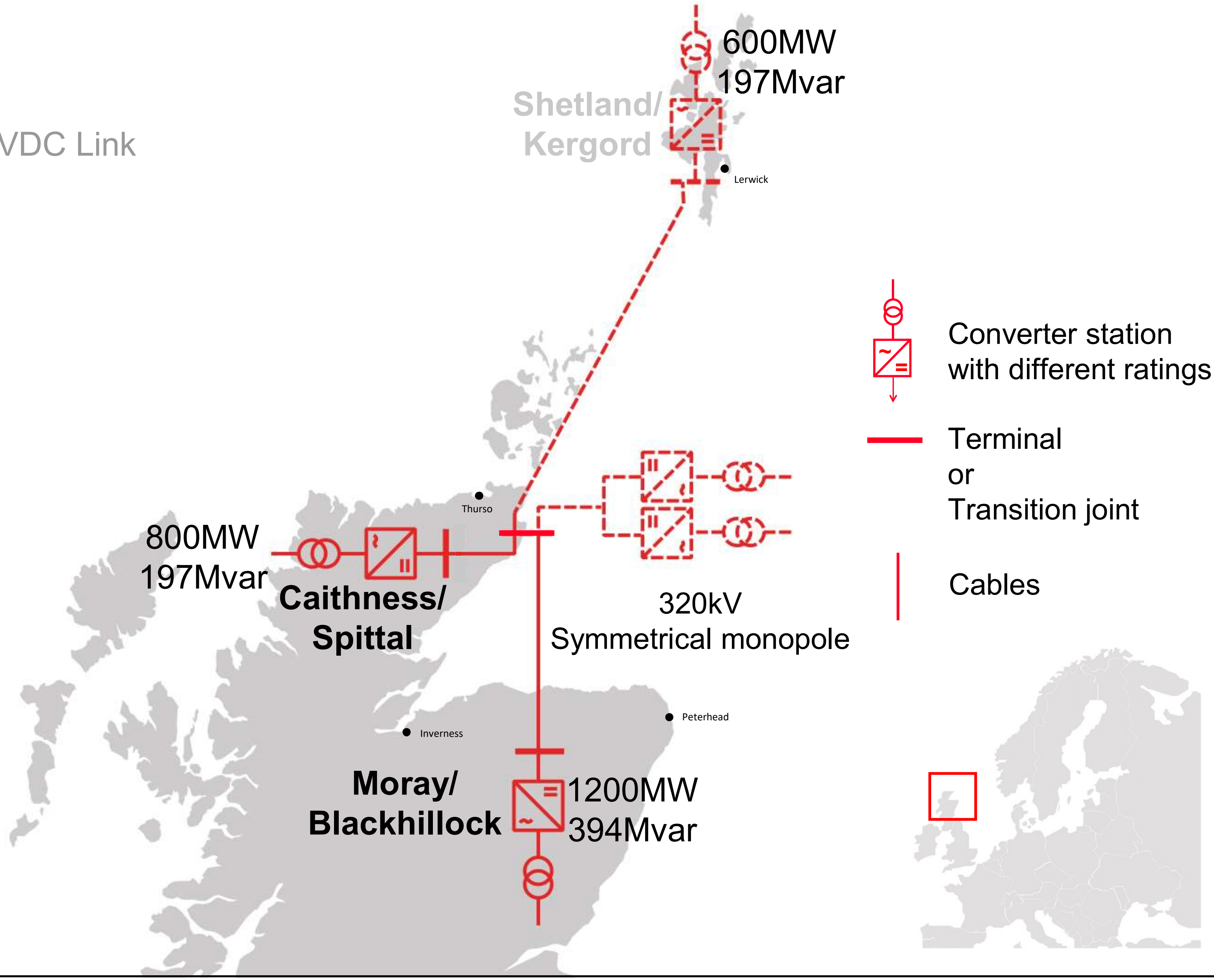
Multi-purpose HVDC

Caithness – Moray – Shetland HVDC Link

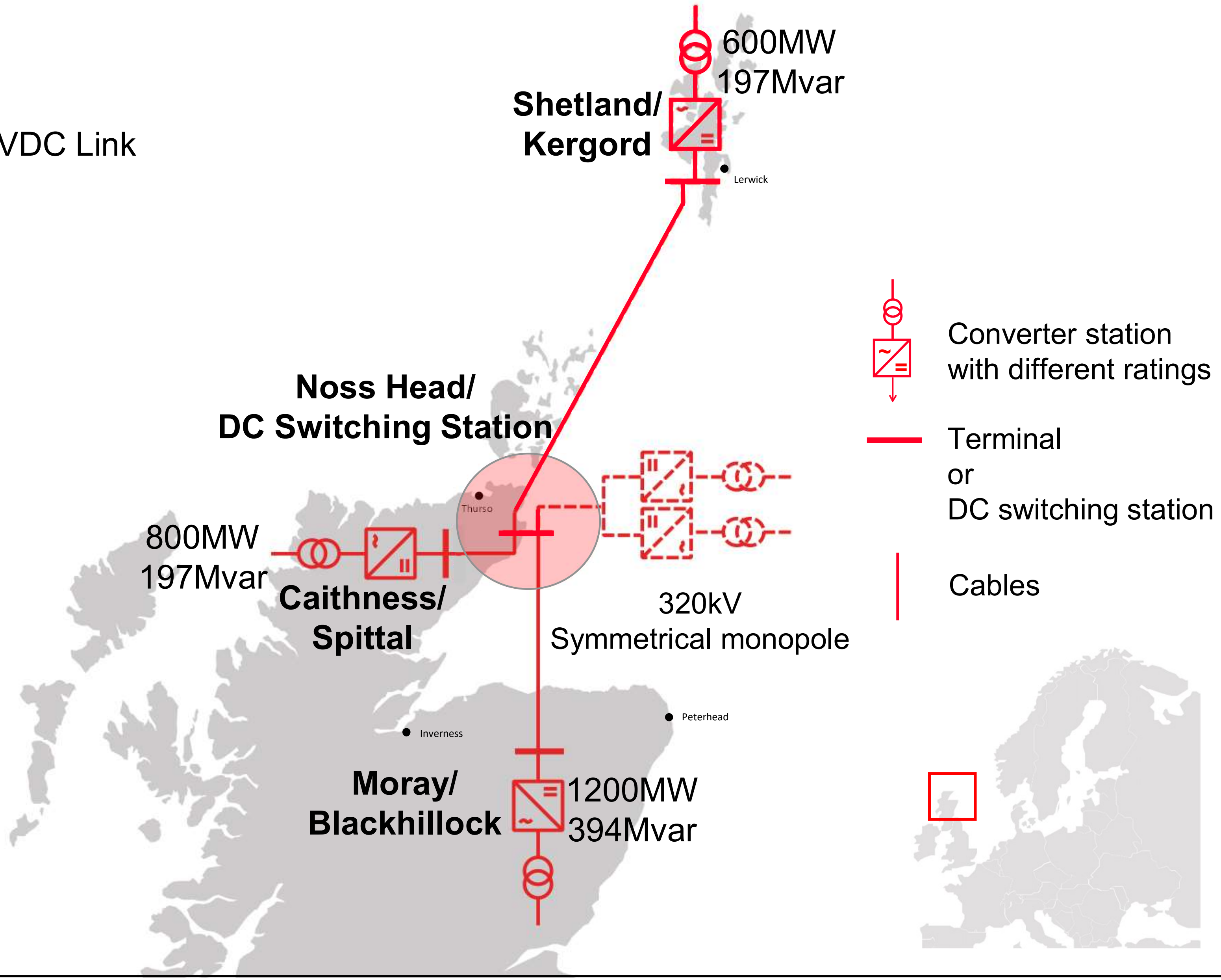


Cigré Paris session 48, 2020, B4-116,
Linden, Hanson and McHardy,
"Planning and implementation of an
HVDC link embedded in a low fault
level AC system with high penetration
of wind generation"

Multi-purpose HVDC

Caithness – Moray – Shetland HVDC Link

No DC Breaker (DCCB)



CMS – Noss Head DC Switching station

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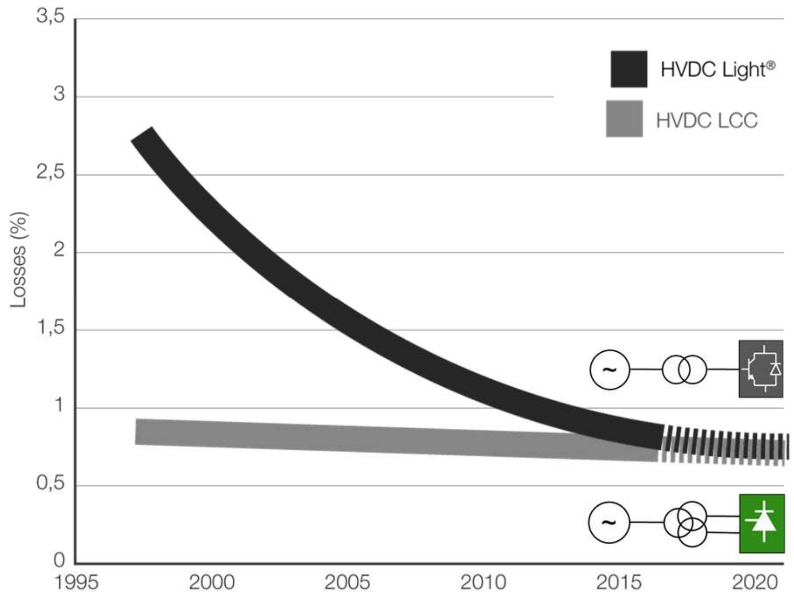
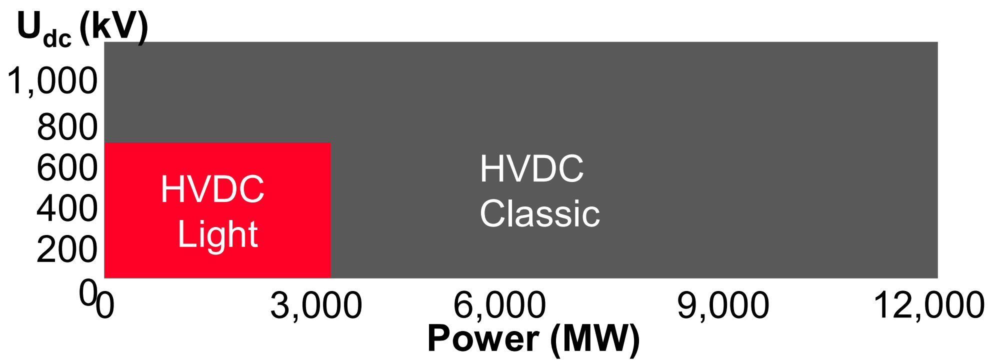
HVDC Grid essentials

HVDC Light

- DC Grid Master Controller
- DC voltage control sharing
- Fault separation
- Building a DC grid





Public

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HVDC Grid essentials

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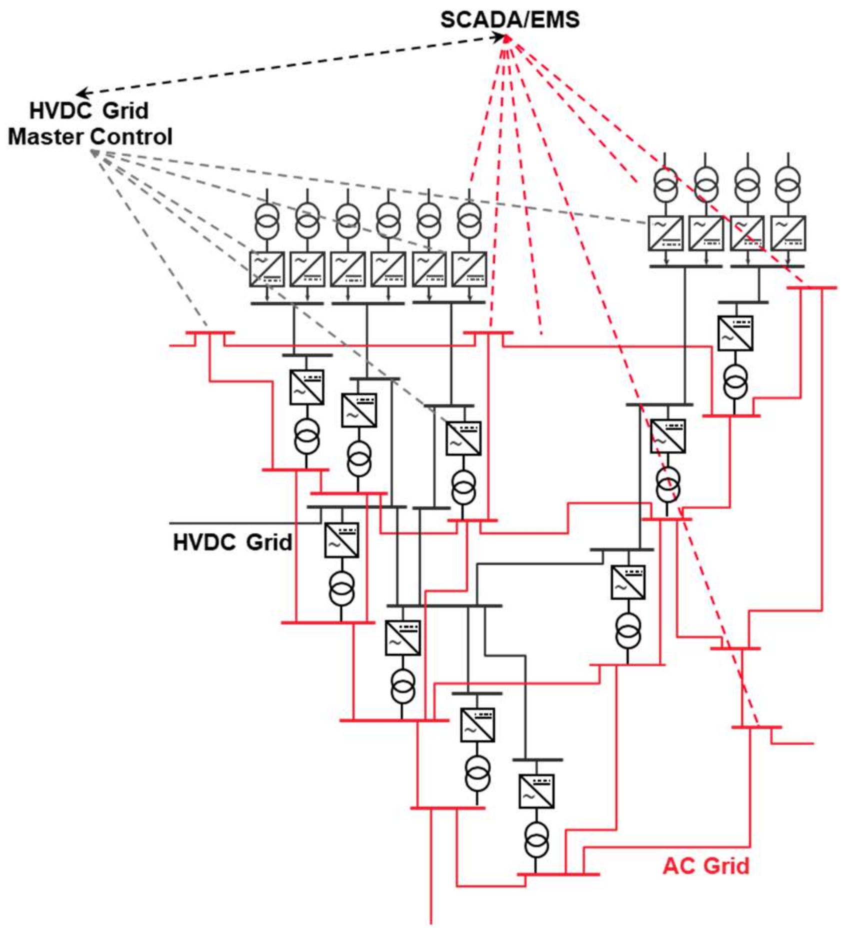
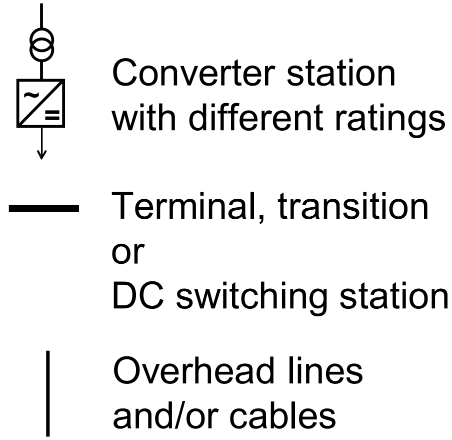
– Building a DC grid

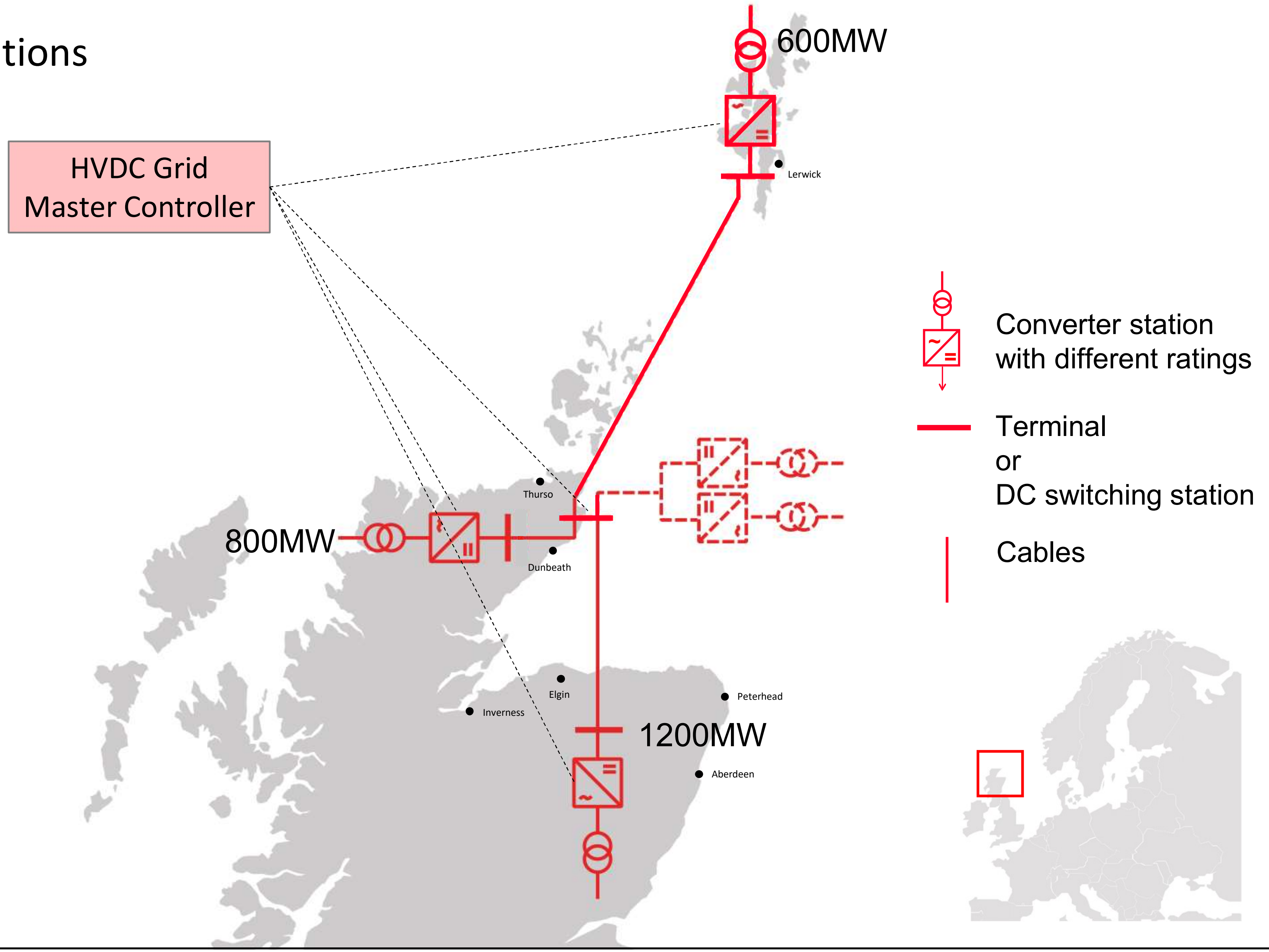




Interlocks between stations

Master sequences:
DC cable connect
DC cable disconnect
DC connect
DC disconnect

Congestion monitoring
Control mode swap



Switch out/in any converter/cable during operation – without disturbances

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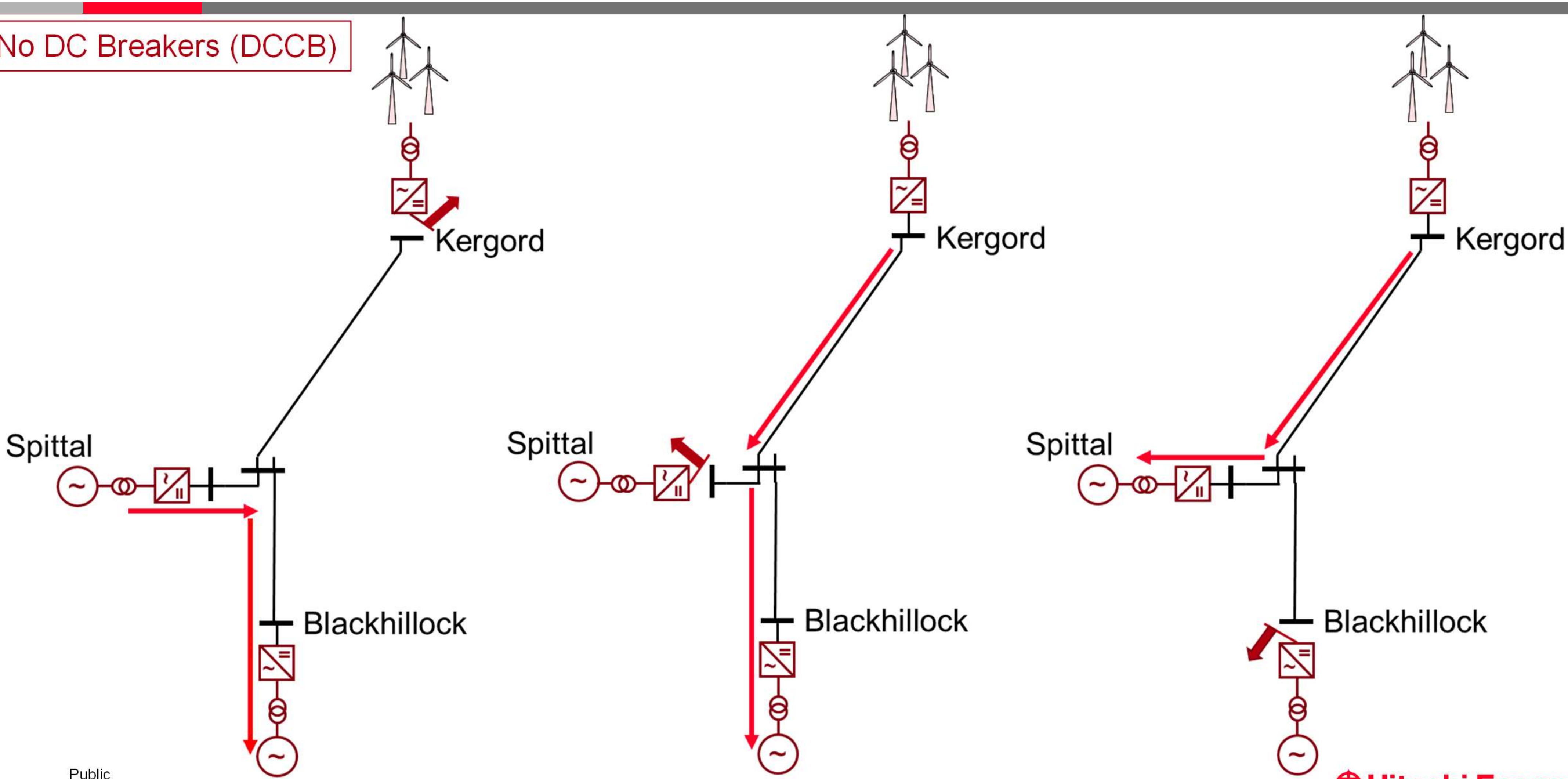
No DC Breakers (DCCB)



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HVDC Grid essentials

HVDC Light

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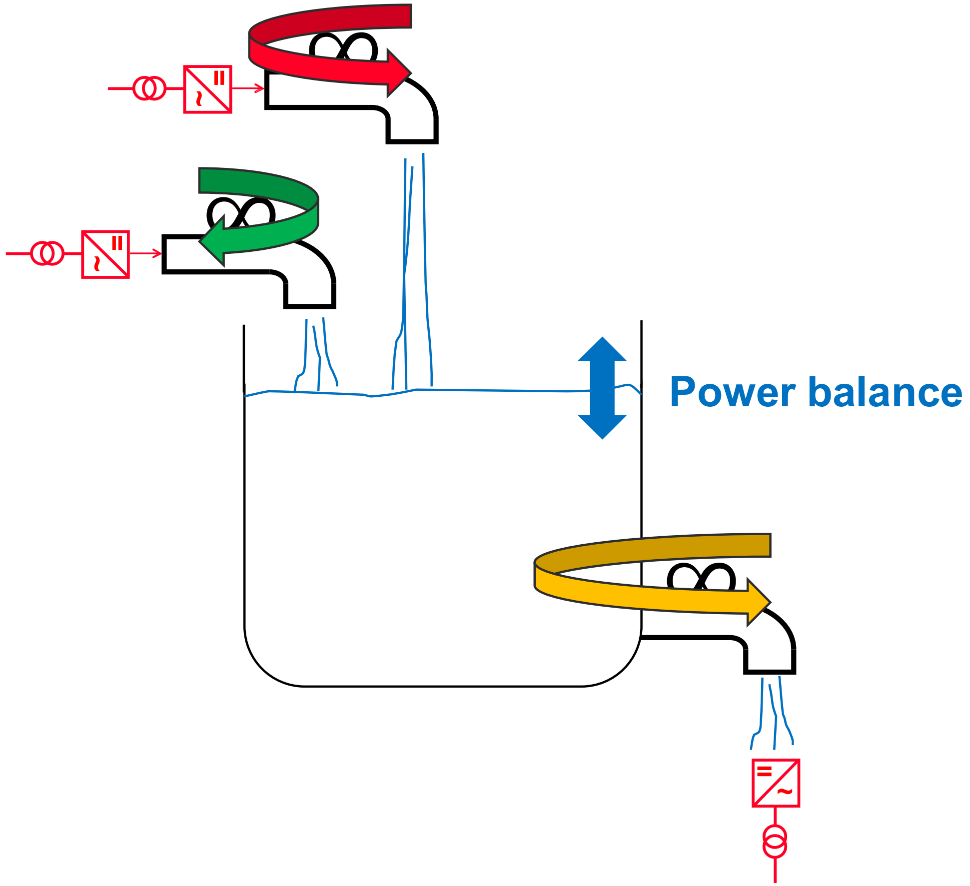
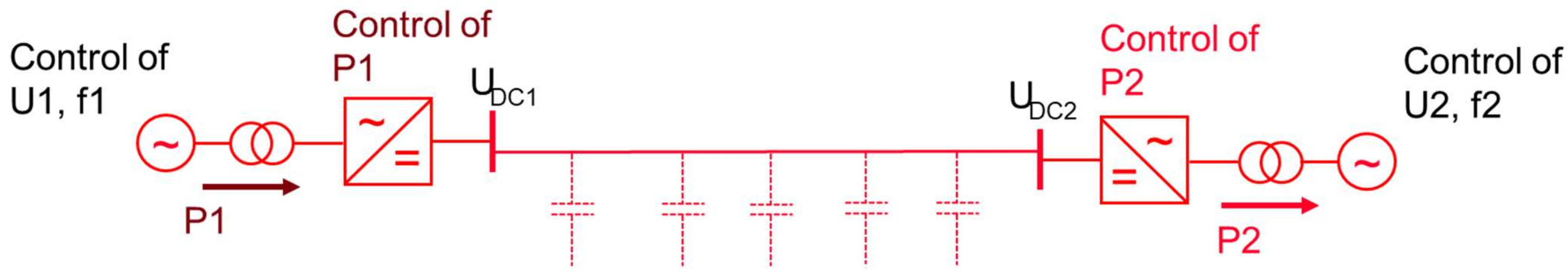
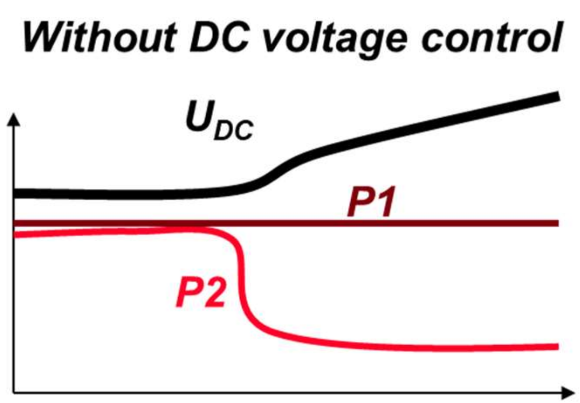
– Building a DC grid

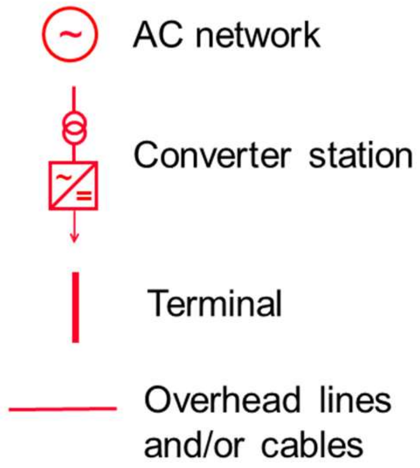


Public

Basic control principles - Power balance
DC voltage control – Active power control

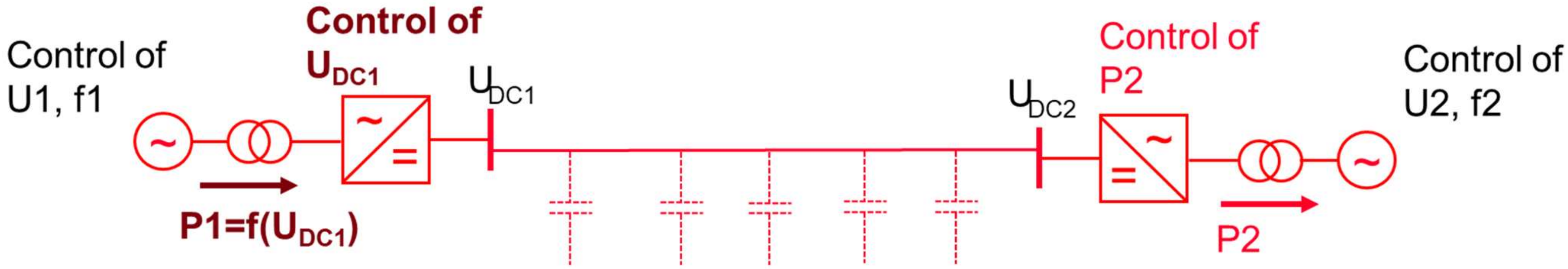




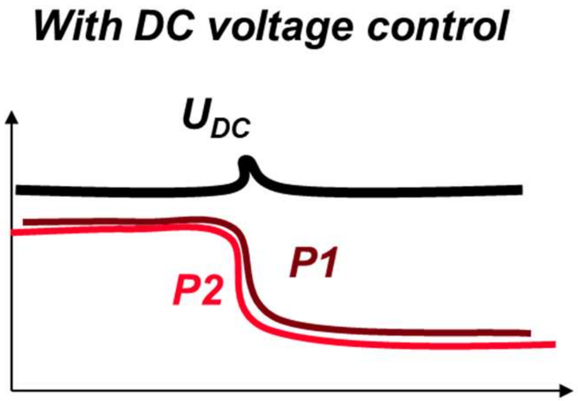


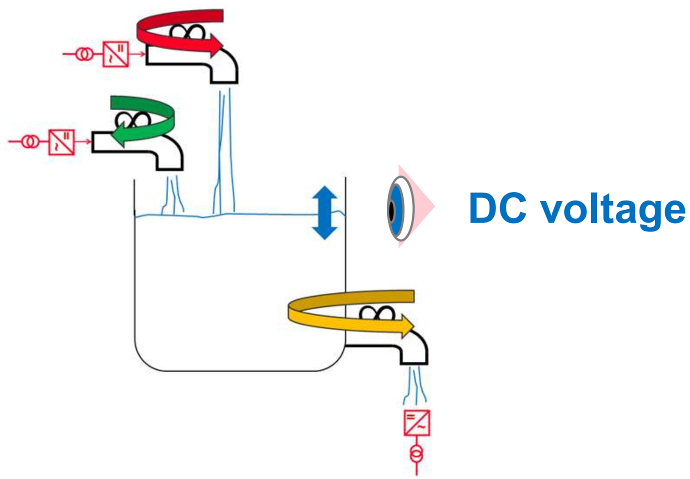
Basic control principles - Power balance
DC voltage control – Active power control

HITACHI
Inspire the Next



The DC-voltage controlling converter acts as slack





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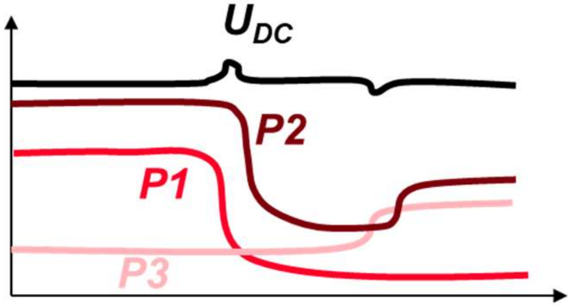
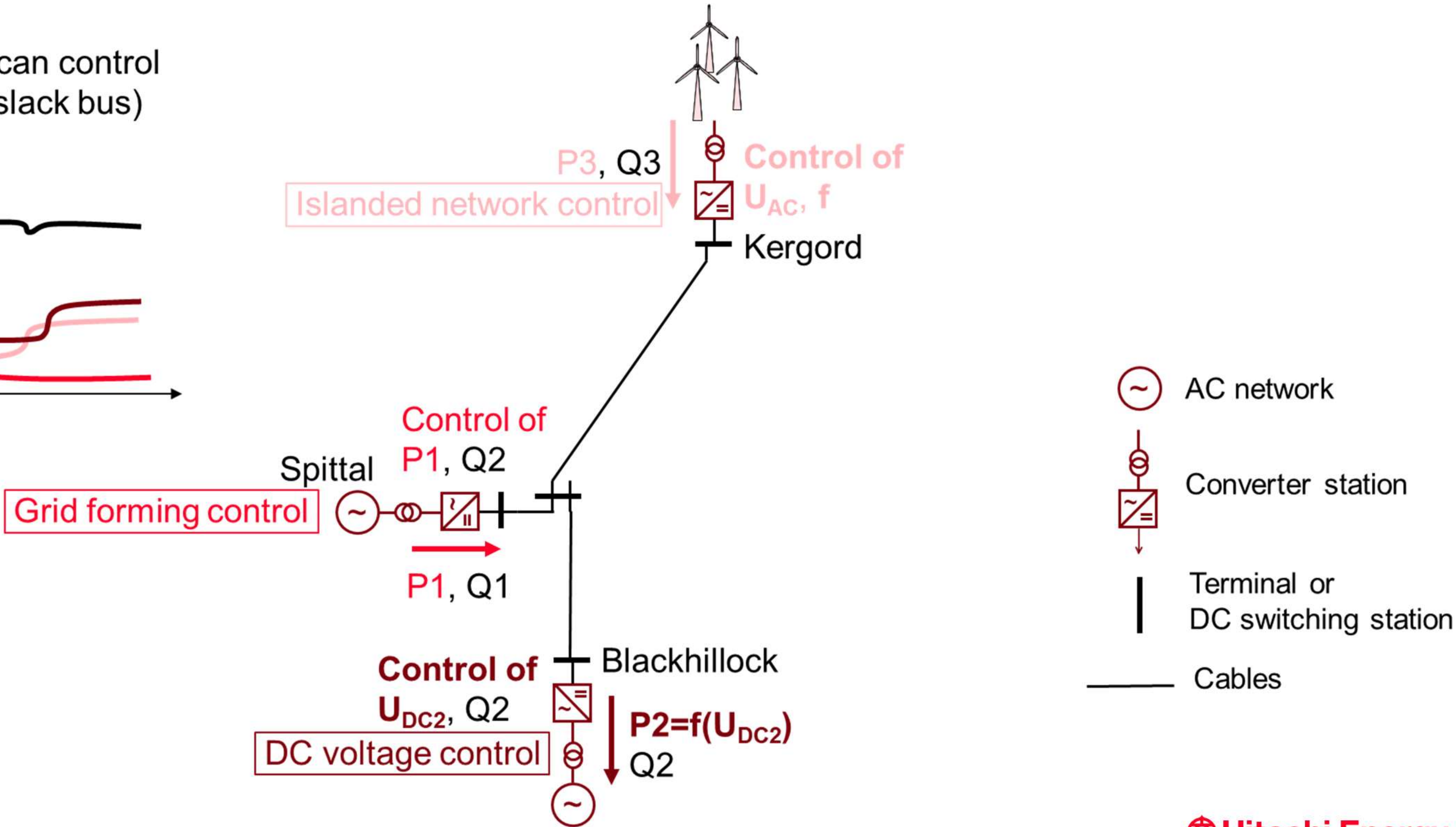
MTDC DC voltage control

Still one terminal can control the DC-voltage (slack bus)





MTDC=MultiTerminal Direct Current

DC voltage control sharing - Dead-band together with droop control

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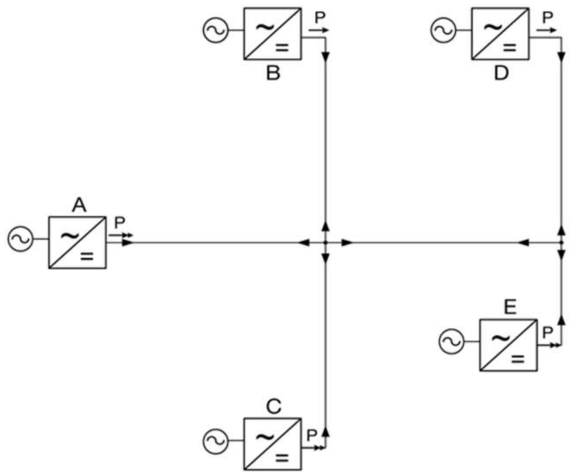
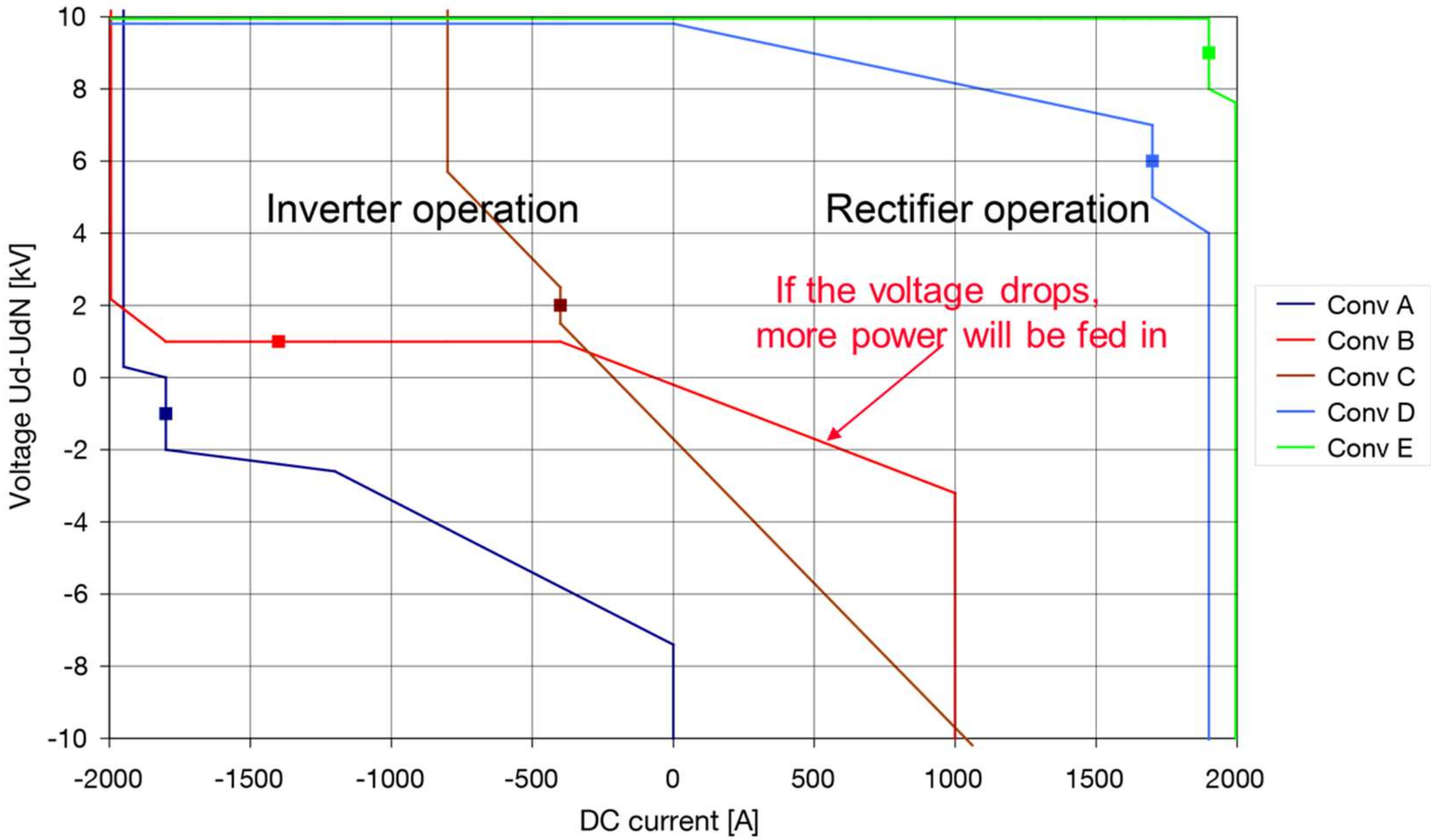
Operating points

Horizontal/vertical lines with operating points = dead-band





Characteristics of five converters, three in inverter operation and two in rectifier operation

Cigré Technical brochure No 533 "HVDC Grid Feasibility Study", April 2013, Cigré Technical brochure No 699 "Devices for load flow control and methodologies for direct voltage control in a meshed HVDC Grid", September 2017.

HVDC Grid essentials

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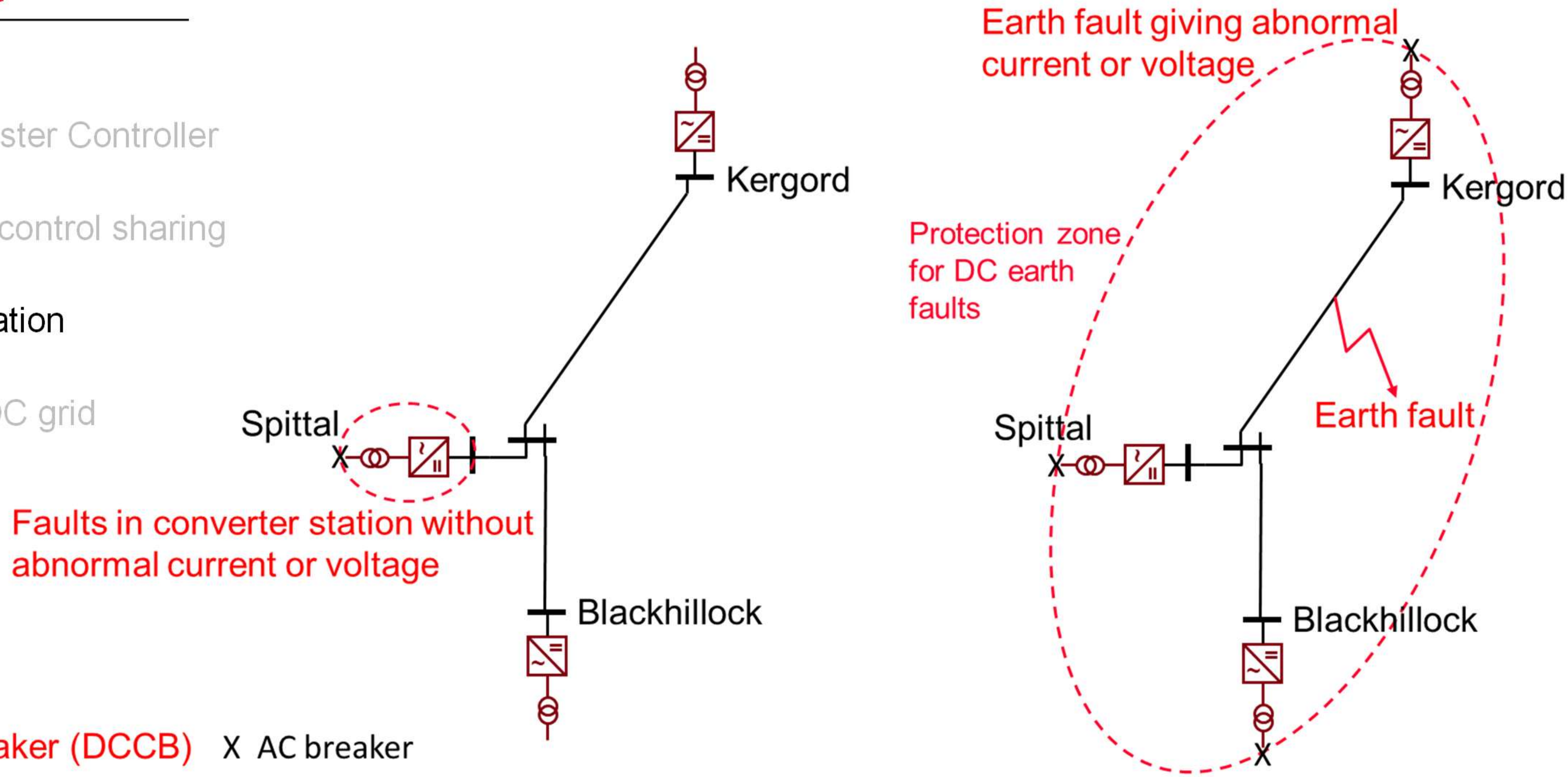
HVDC Light

– DC Grid Master Controller

– DC voltage control sharing

– Fault separation

– Building a DC grid



No DC Breaker (DCCB) X AC breaker

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Diod-bridge and lines - fault currents

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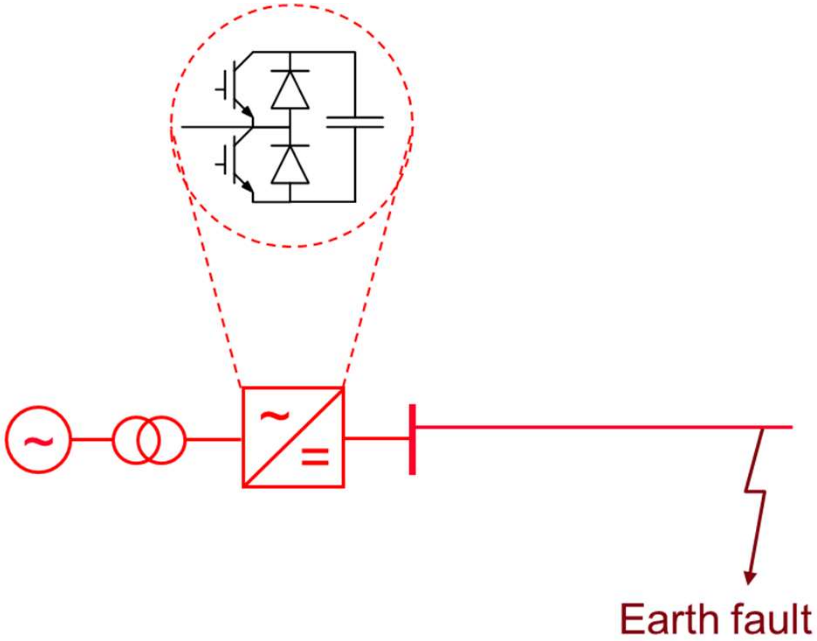

=

Currents from the AC-side

+

Surges from DC capacitors

Surges from e.g. cables: Udc/Zv,

61660-1 © IEC:1997

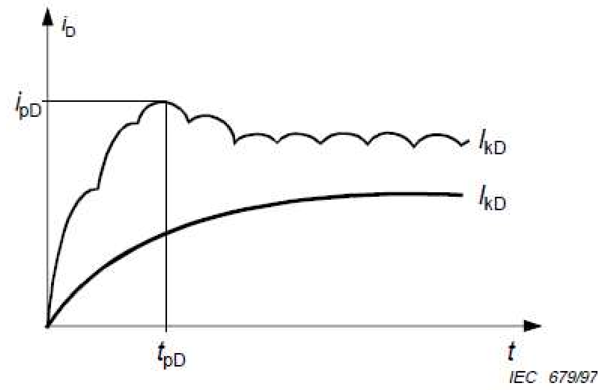

Figure 1a – Rectifier without and with smoothing reactor

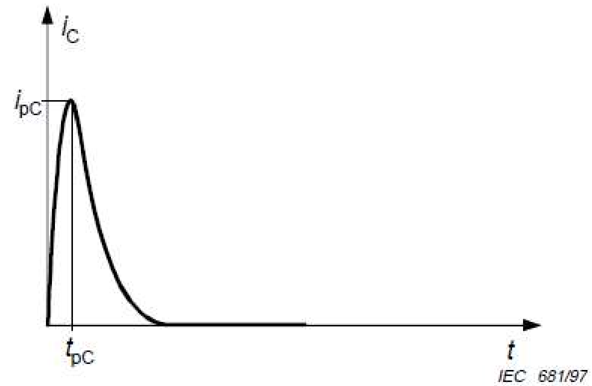

Figure 1c – Capacitor

Fault currents in a DC grid – DC breaker requirements

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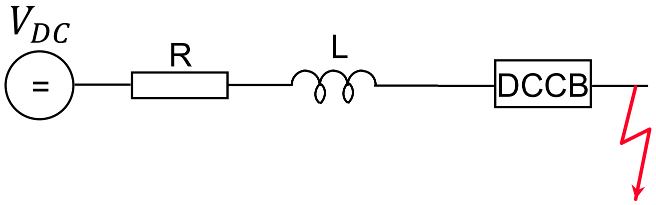
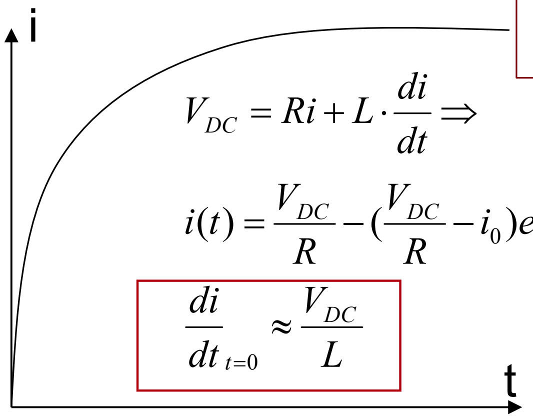


Simplified equivalent circuit for fault clearance in a DC Grid

R = ac reactance and dc resistance, combined
L = inductance in the circuit
DCCB DC Circuit Breaker

Neglected capacitive surge



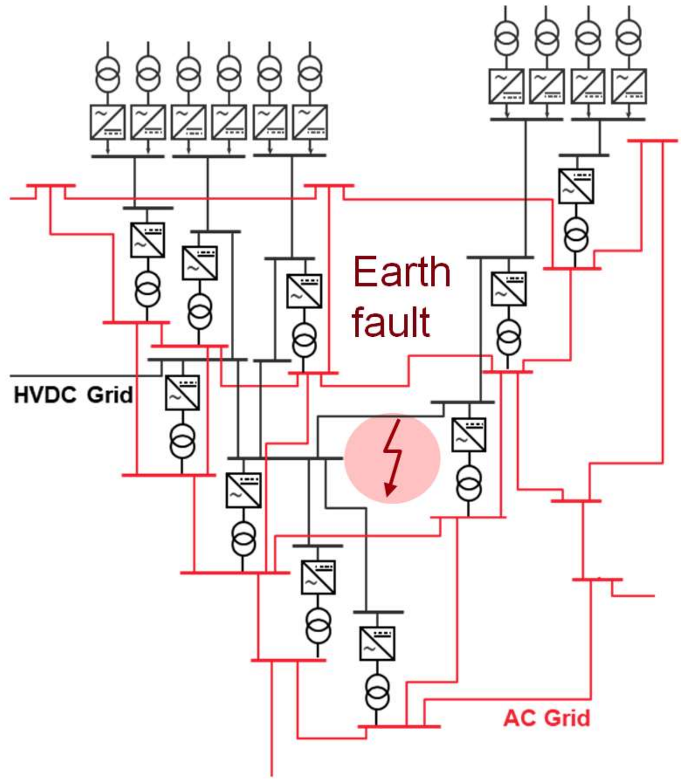
$$i \approx \frac{V_{DC}}{R}$$

$$V_{DC} = Ri + L \cdot \frac{di}{dt} \Rightarrow$$

$$i(t) = \frac{V_{DC}}{R} - \left(\frac{V_{DC}}{R} - i_0\right)e^{-\frac{R}{L}t}$$

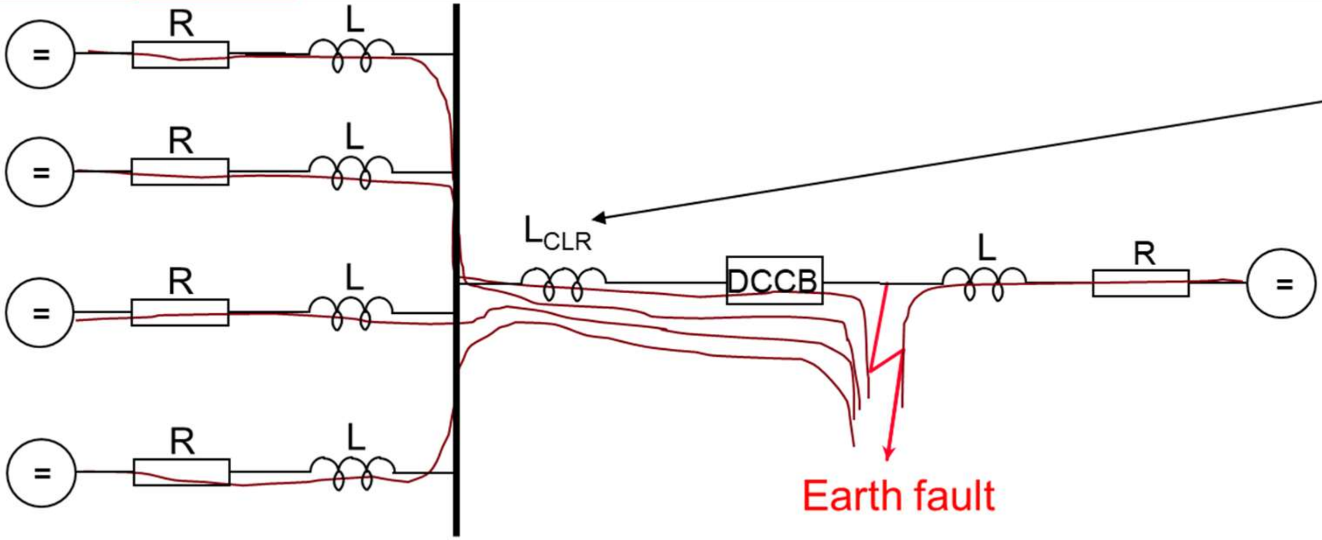
$$\frac{di}{dt}_{t=0} \approx \frac{V_{DC}}{L}$$

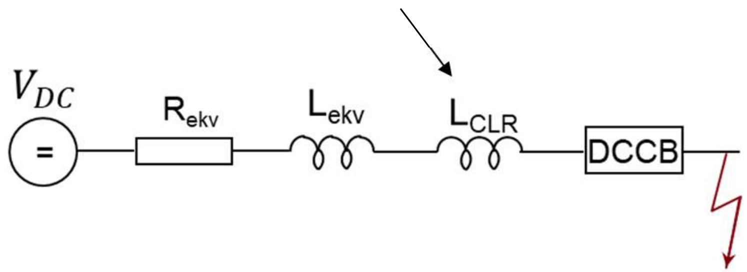
Steady state levels after ~50-70ms (depends on network size)

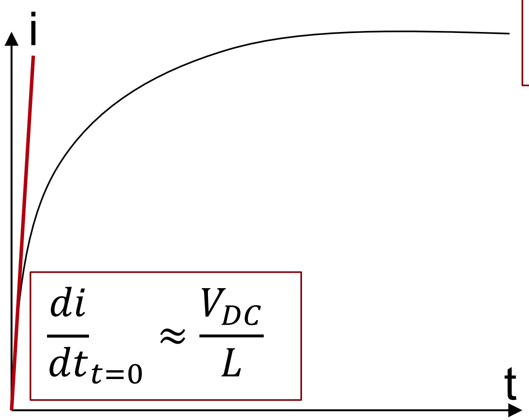


High rate of rise currents to high values

Current limiting reactor to limit the current rate of rise







$$I \approx \frac{V_{DC}}{R}$$

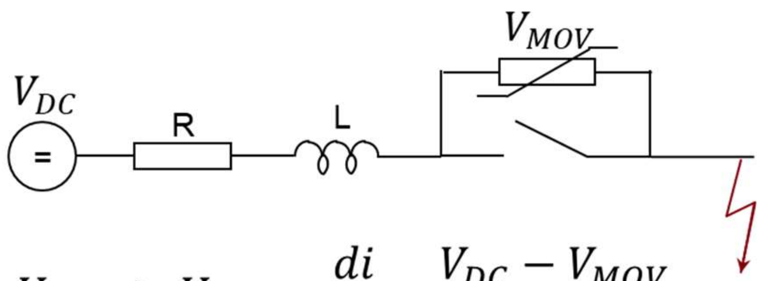
$$\frac{di}{dt}_{t=0} \approx \frac{V_{DC}}{L}$$

Current limiting reactor, 100 mH: Time vs current to break in a 525 kV grid.

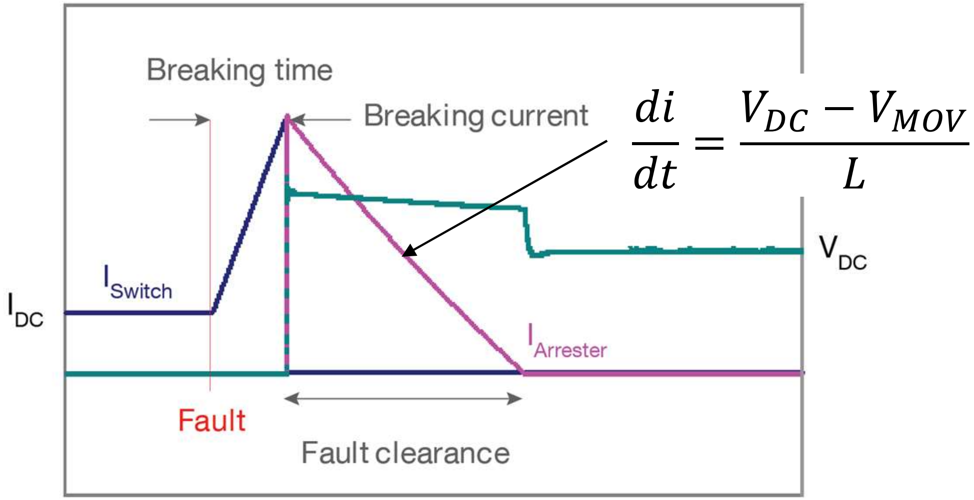
Detection and breaking time ms	Necessary breaking current kA
1	5.25
2	10.5
5	26.25
10	52.5

DCCB = DC Circuit Breaker

No natural current zero-crossings - Energy

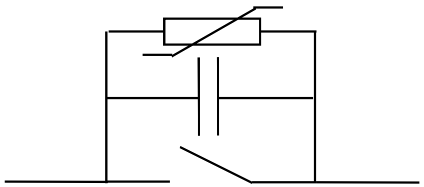


$V_{MOV} > V_{DC}$ $\frac{di}{dt} = \frac{V_{DC} - V_{MOV}}{L}$



Arrester (MOV) dissipate fault energy:

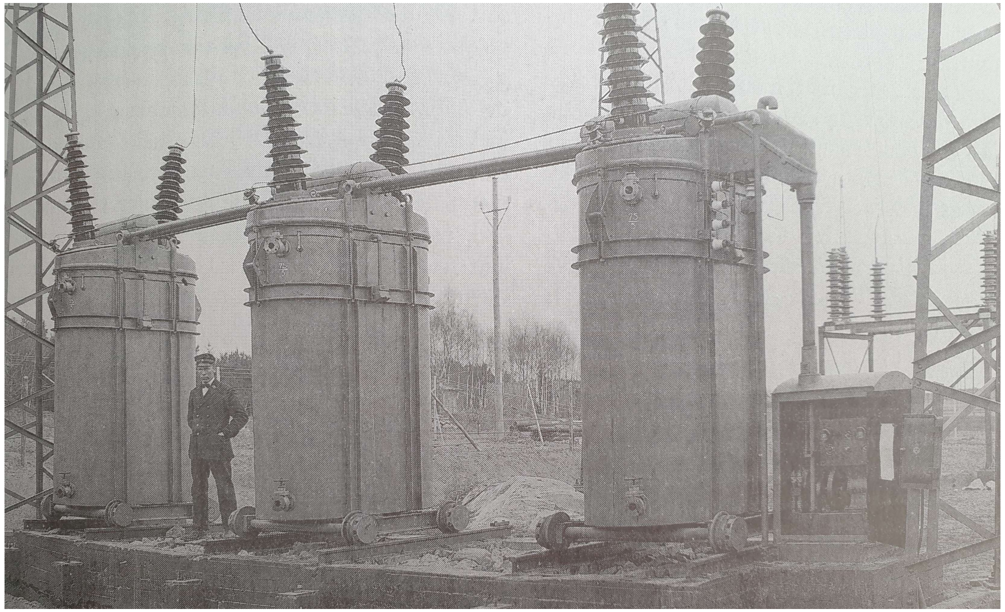
$$E = \frac{1}{2} L \cdot i^2$$



Mechanical or/and electronic switches, capacitors w/o active circuits etc, but all DCCBs need to handle energy

Large Current Limiting Reactor -> sizable reactor and arresters

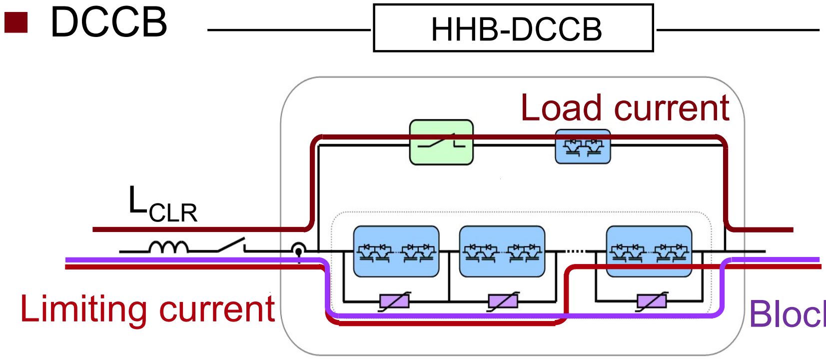
132kV AC breaker 1925-1935 vs 350kV DCCB 2020



Sizable 132kV AC breaker in Moholm 1925-1935.
Expected to be 9 meters high for 220kV and 60 tons.

X AC breaker

- DCCB



Den gemensamma utvecklingen – Staten, storföretaget och samarbetet kring den svenska elkrafttekniken, avhandling av Mats Fridlund i teknikhistoria, 1999. HV-testing at KEMA during 2020 in the EU-funded PROMOTioN project.

Reactors also essential for Fault Detection

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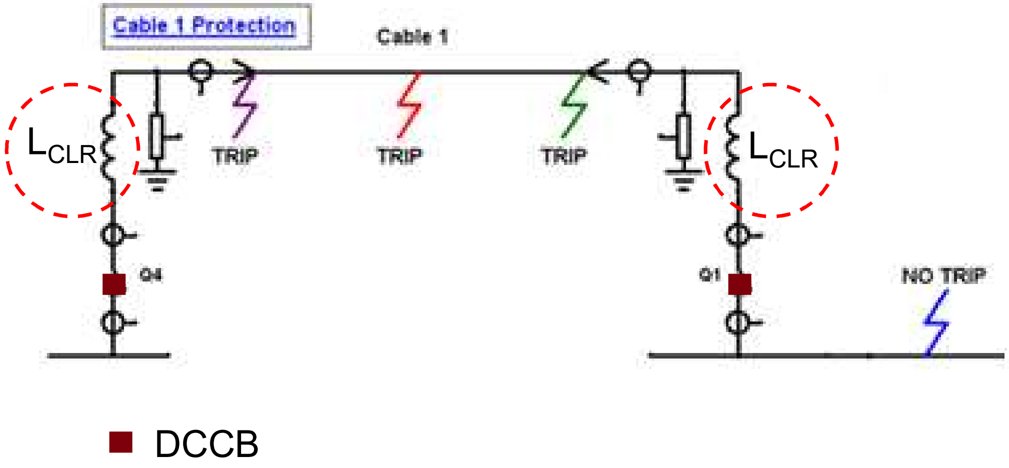

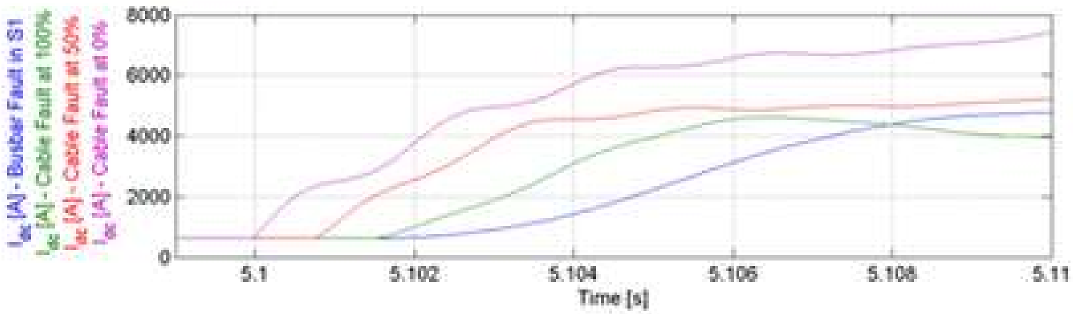

Current limiting reactors close to the measuring device

Derivative and travelling wave protection for selective detection

Within few milliseconds, with:

Selectivity - take out only the faulty line/zone

Stability - stable for disturbances

Challenging!

Cigré Technical brochure No 533 “HVDC Grid Feasibility Study”, April 2013

Hitachi Energy

Will the DC grid survive? The need for speed!

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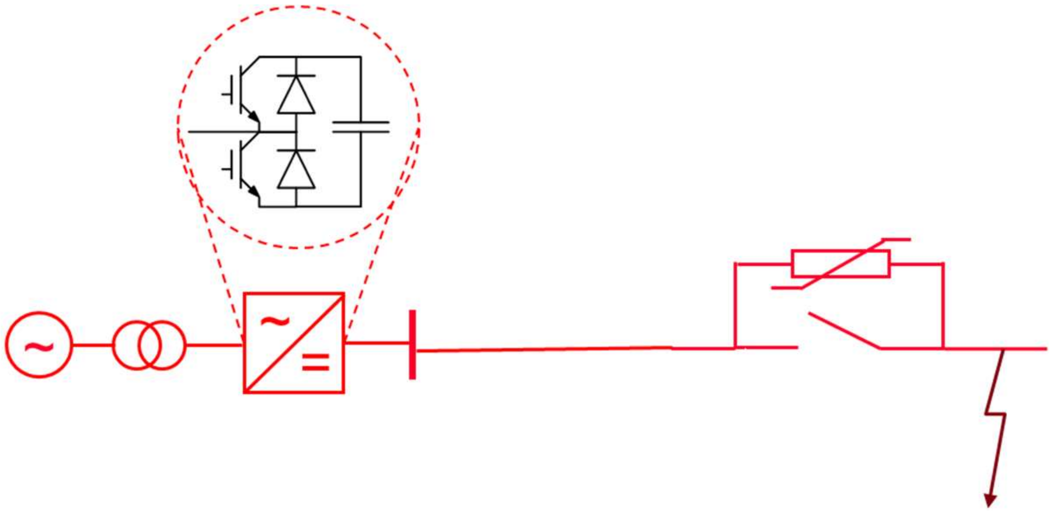
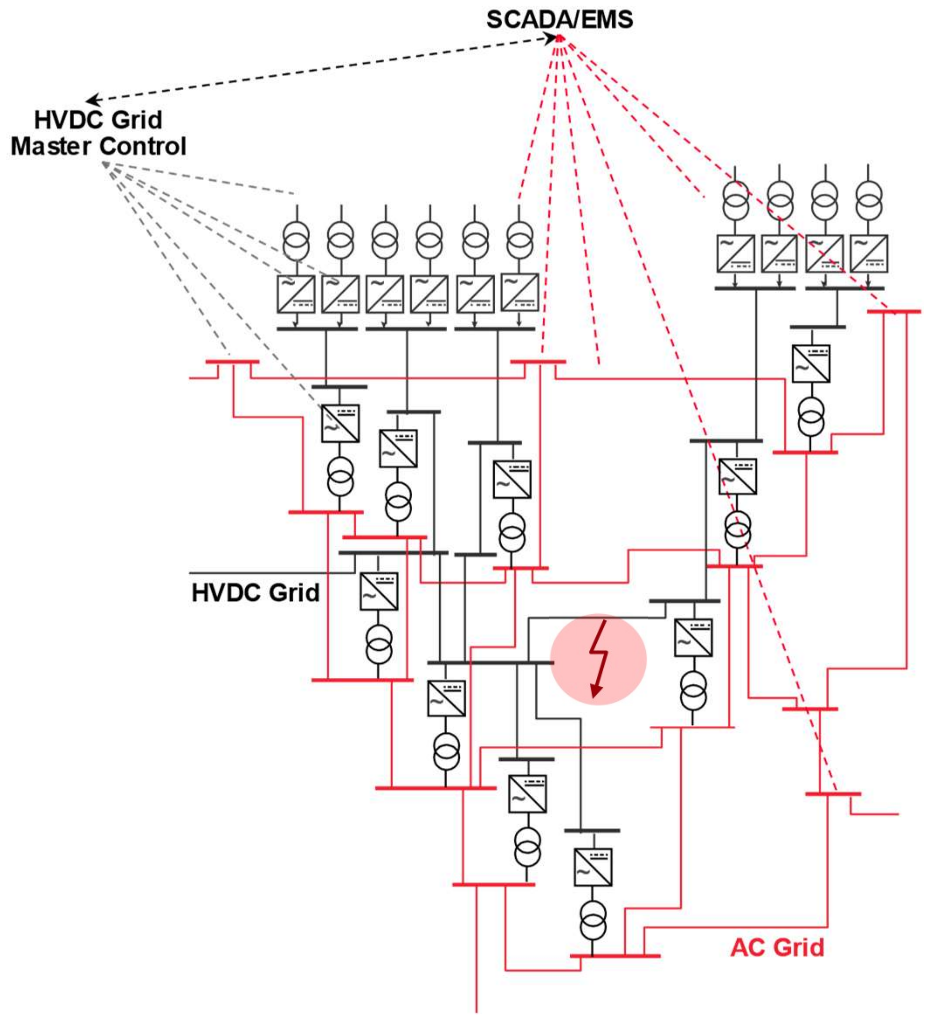
HVDC grid

- Fast and deep fault penetration
- Keep DC voltage at reasonable levels to maintain operation of converter stations

→ Fast DC Breakers with breaking times <3 ms range required to avoid voltage collapse in HVDC grid





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HVDC Grid essentials

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HVDC Light

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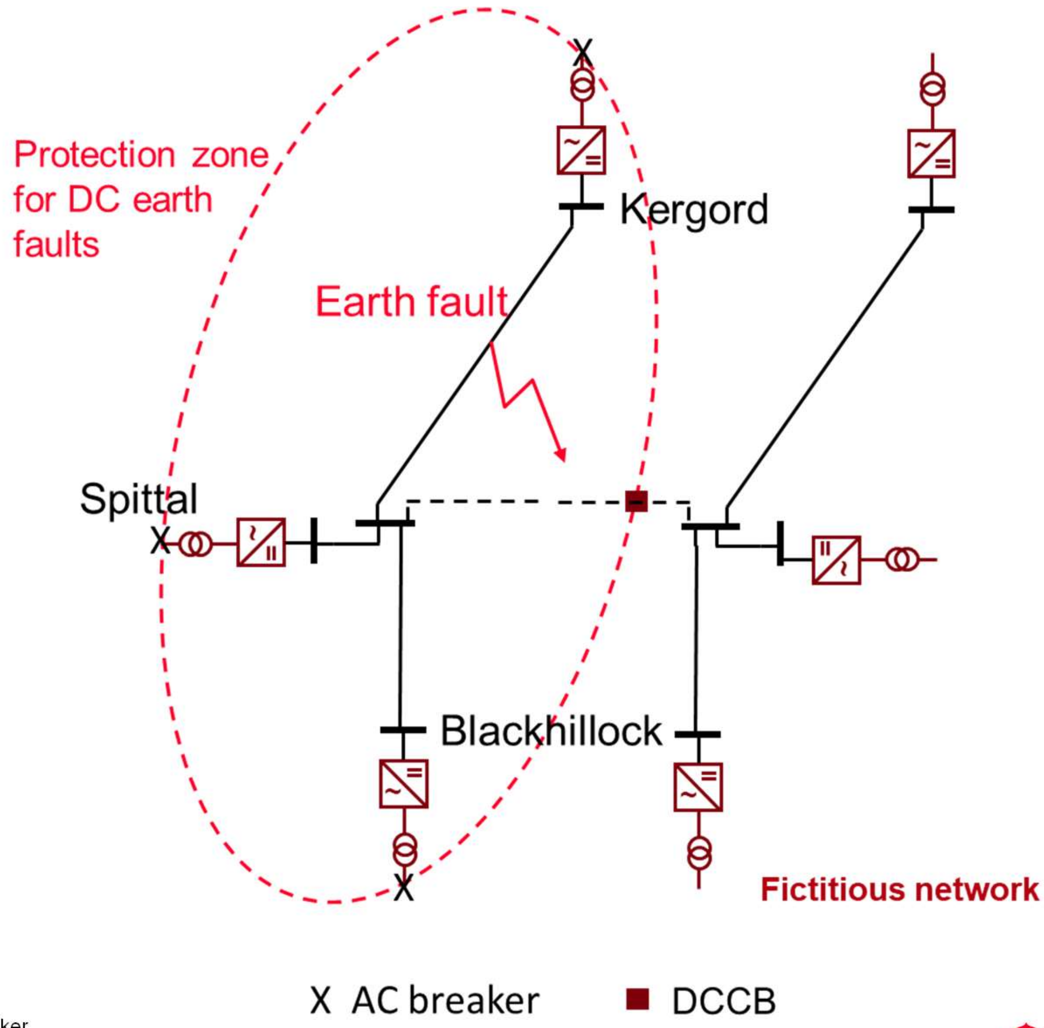

DCCB = DC Circuit Breaker

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HVDC Light

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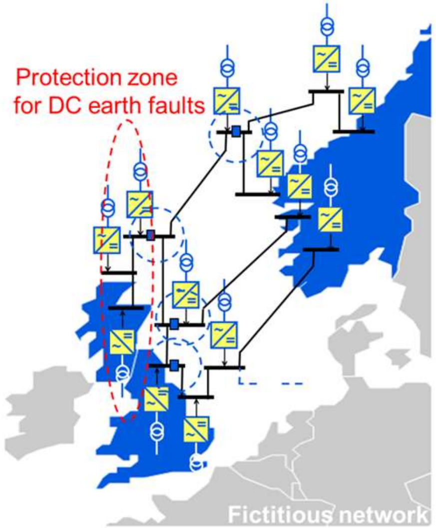

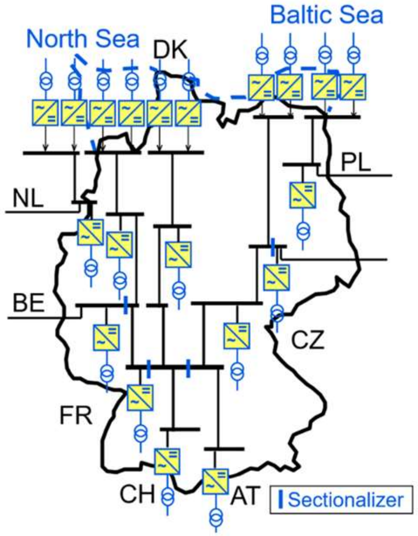

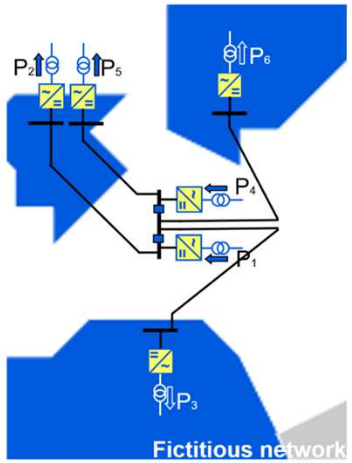

Public

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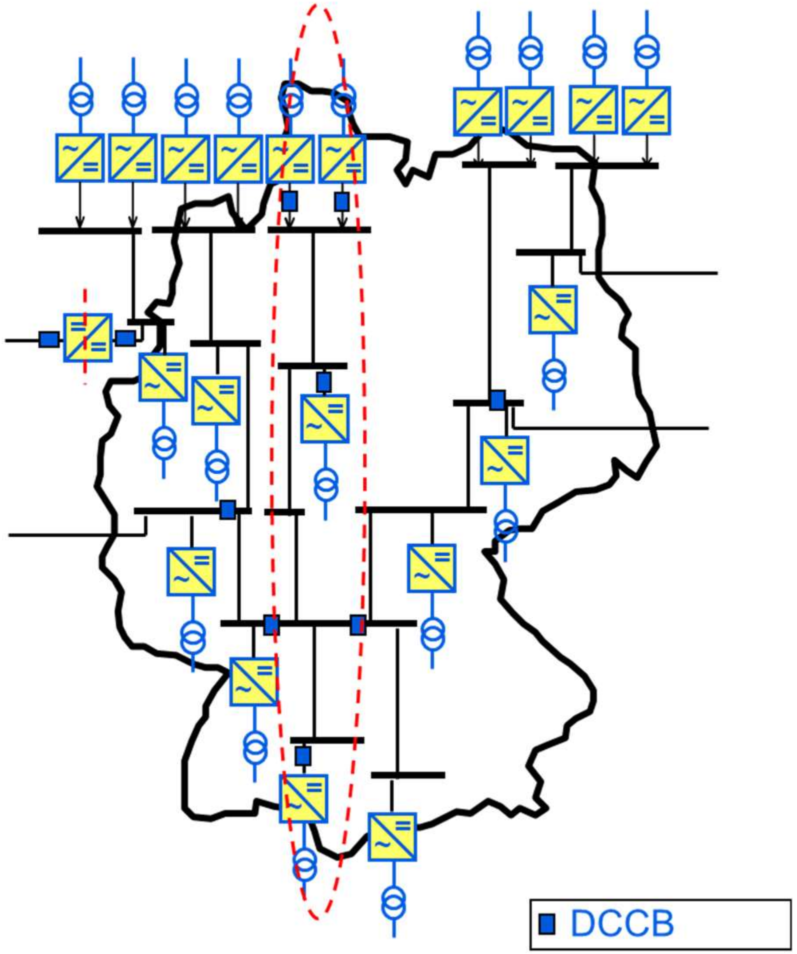
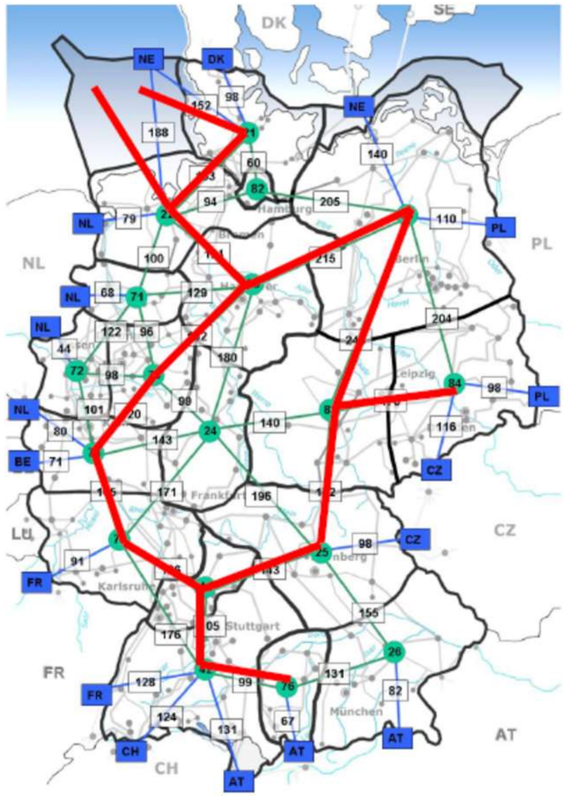
Building a DC Grid – stage wise





Building a DC Grid – stage wise – First stage

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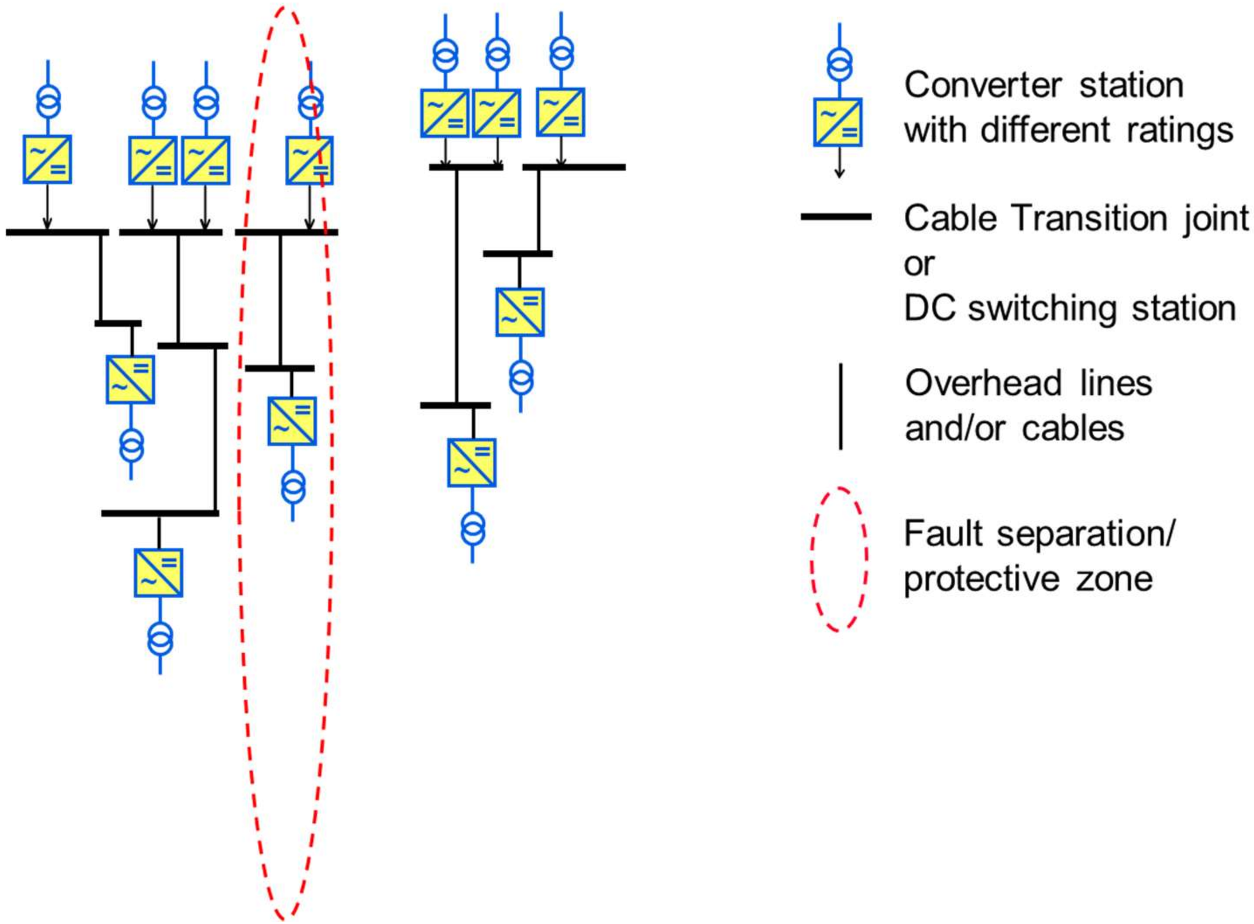

First stage
P2P multiterminal ready links

P2P = Point-to-point HVDC links

Building a DC Grid – stage wise – Second stage

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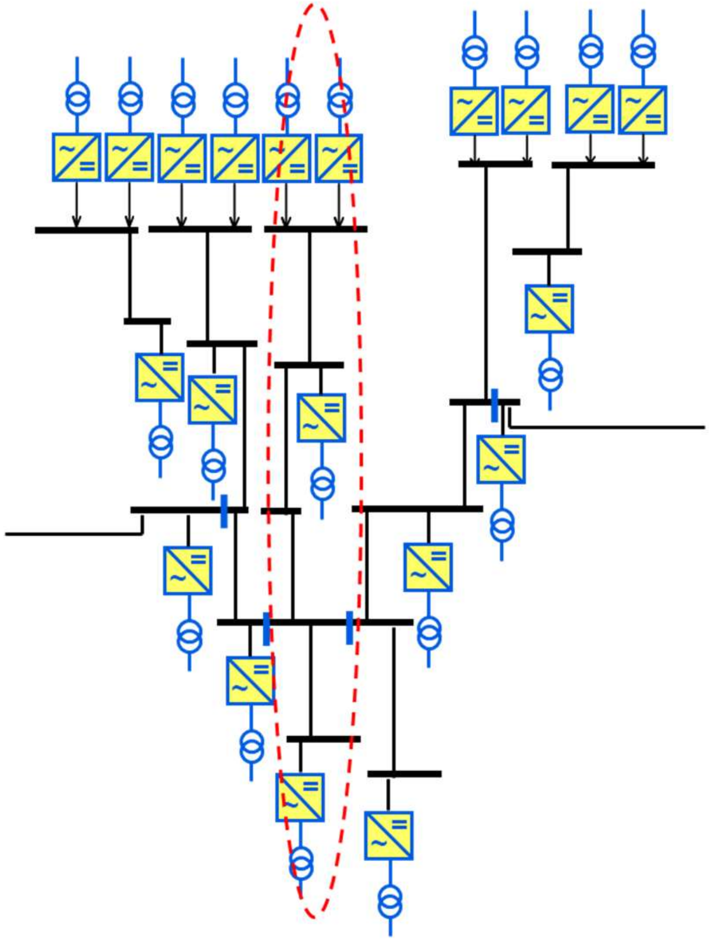

First stage
P2P multiterminal ready links

Second stage
P2P and/or radial multi-terminal with sectionalizing disconnectors

Public

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Building a DC Grid – stage wise – Third stage

HITACHI
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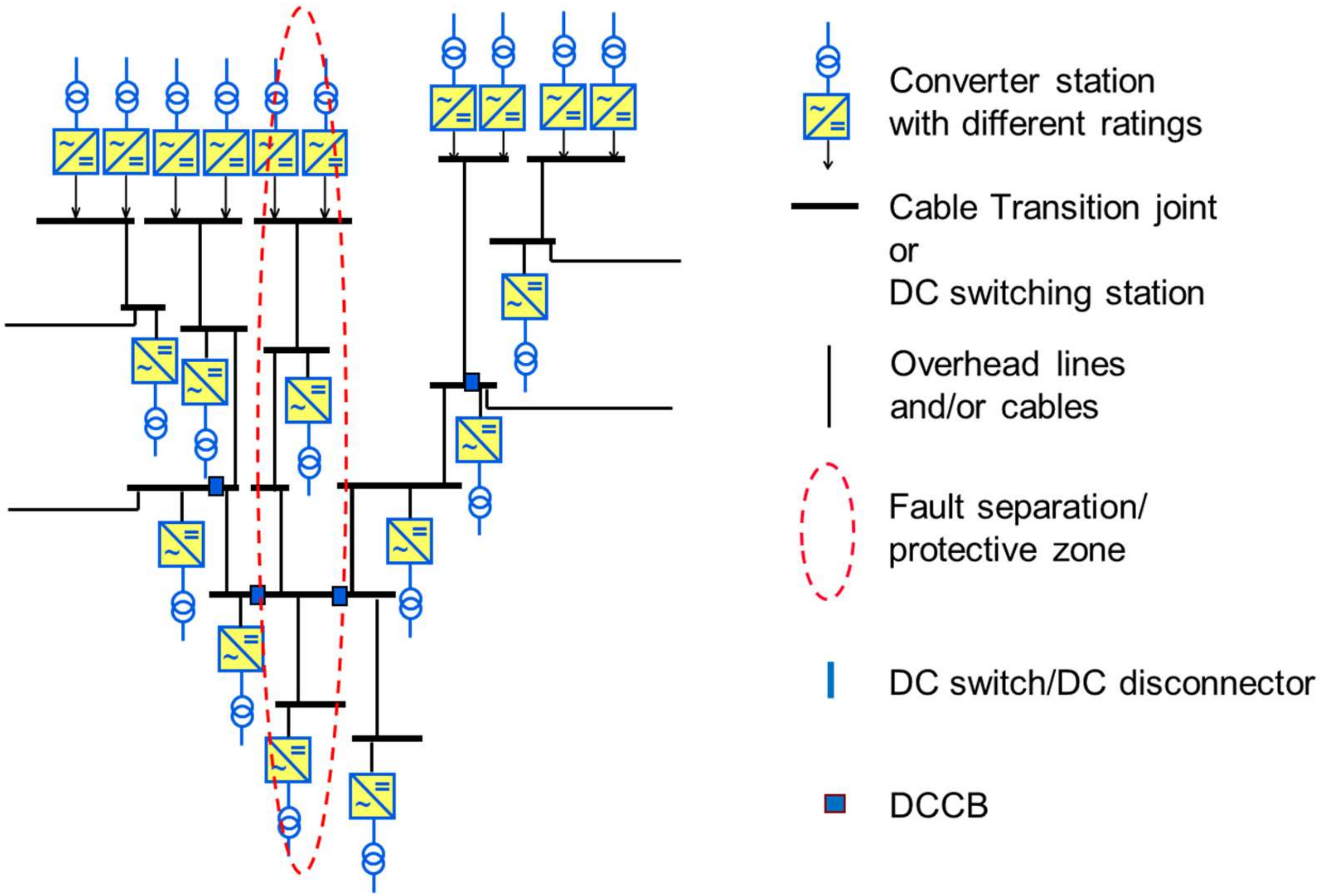

First stage
P2P multiterminal ready links

Second stage
P2P and/or radial multi-terminal with sectionalizing disconnectors

Third stage
Connect the different multiterminals through sectionalizing DCCBs

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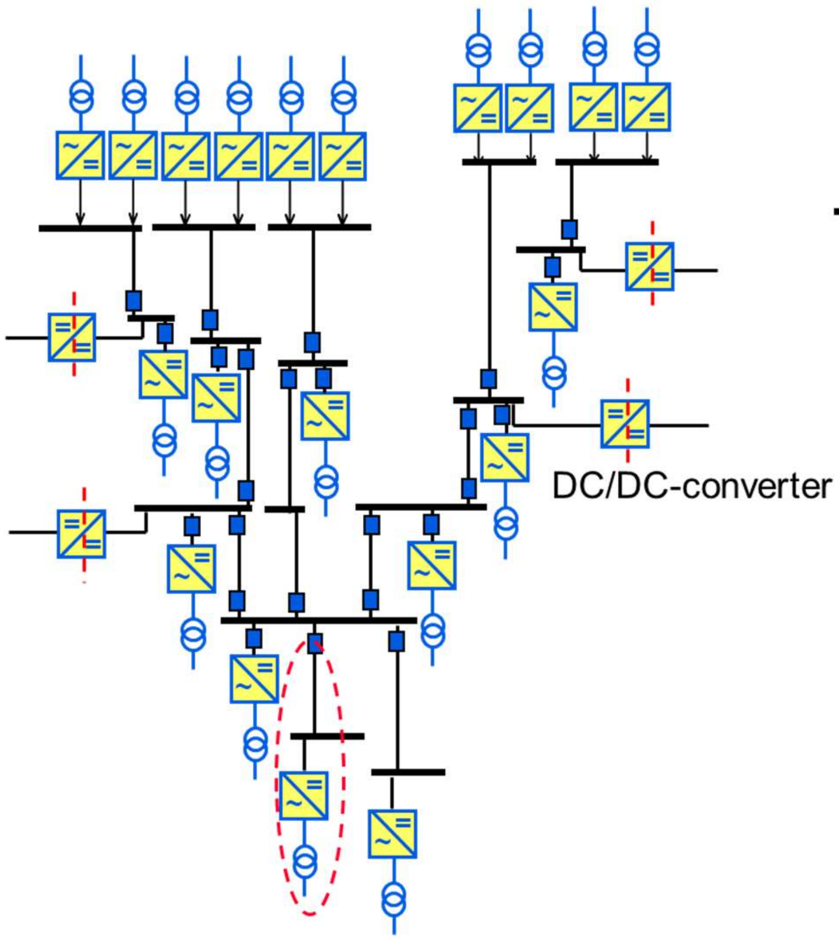
Building a DC Grid – stage wise – Fourth stage



Converter station with different ratings

Cable Transition joint
or
DC switching station

Overhead lines and/or cables

Fault separation/ protective zone

DC switch/DC disconnector

DCCB

DC/DC-converter

First stage
P2P multiterminal ready links

Second stage
P2P and/or radial multi-terminal with sectionalizing disconnectors

Third stage
Connect the different multiterminals through sectionalizing DCCBs

Fourth stage
DC/DC-converters?
and/or
DCCBs protecting each object?

Current blocking function

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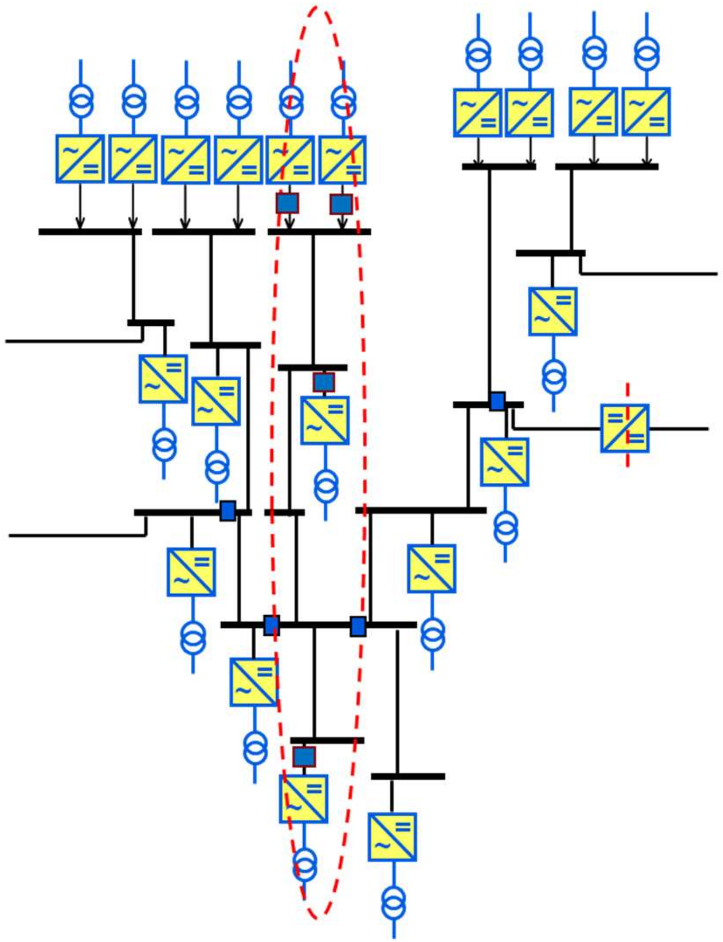

Converter station with different ratings

Cable Transition joint or DC switching station

Overhead lines and/or cables

Fault separation/ protective zone

DC switch/DC disconnector

HHB-DCCB

DC/DC-converter

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P2P multiterminal ready links

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Connect the different multiterminals through sectionalizing DCCBs

Fourth stage
DC/DC-converters?
and/or
DCCBs protecting each object?
and/or
Converter breakers with current blocking/limiting function (HHB-DCCB)?

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Current blocking/limiting function – if required

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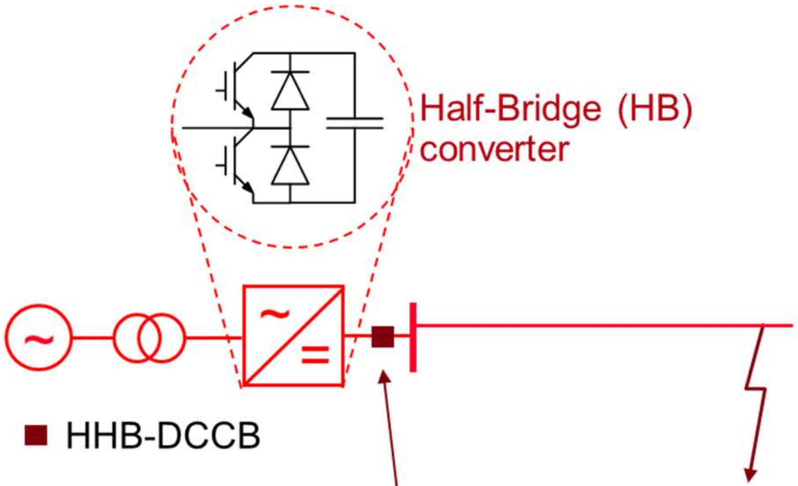
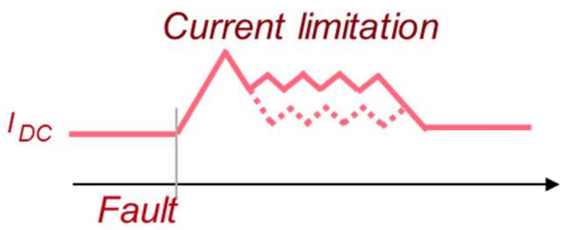
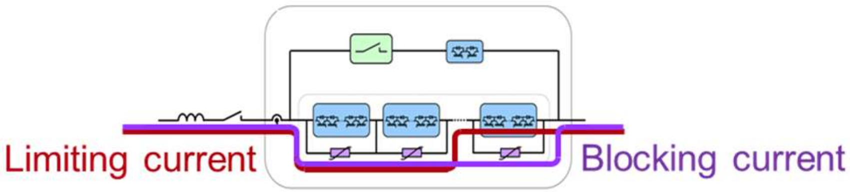






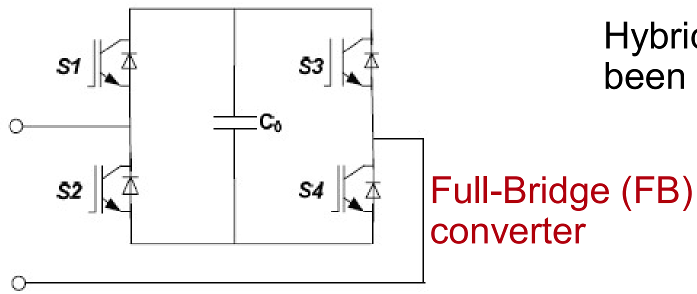
DC earth faults, HB+HHB-DCCB

- The DC breaker limits fault current through converter
- AC breakers will not open
- VSC can provide reactive power support during disturbances

The same functionality can be achieved with:

Full-bridge converters (FB)

Some hybrid converters



Half-Bridge (HB) converter

\+ Lower losses

\+ Lower converter cost

\- External current breaking and/or limitation for converter fault current blocking

Full-Bridge (FB) converter

\- Higher losses

\- Higher cost

\+ Incorporated current limitation

Hybrid combinations have also been proposed

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Internal vs external current blocking

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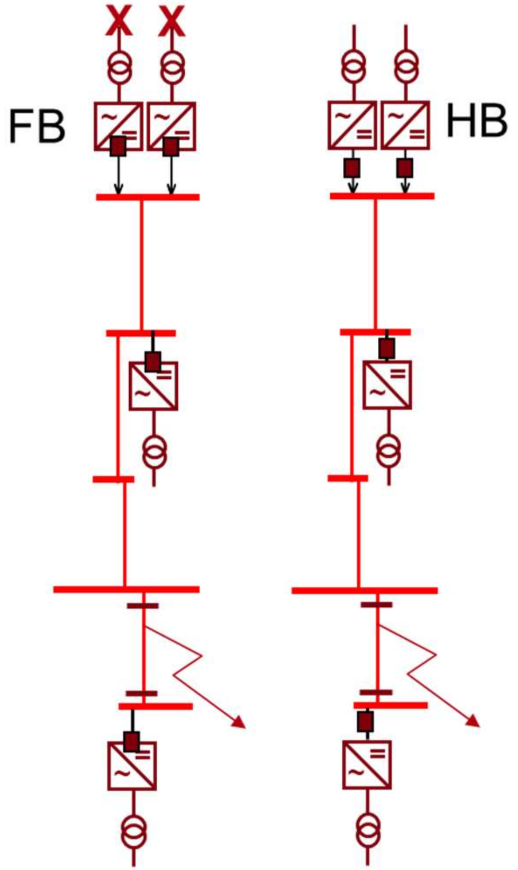

Full-bridge converter (FB):

The on-shore converter stations continues reactive power support of the AC grid

*All off-shore converters trip (**X**)*

Half-bridge converter (HB)+HHB-DCCB, and DC chopper in-between:

The on-shore converter stations continues reactive power support of the AC grid

The off-shore converter DC-chopper supports fault-ride through of the wind farms until opening of the disconnectors

X AC breaker

■ Internal or external current blocking/limitation

However, sectionalizing DCCB is still needed in the DC grid!

FB= Full-bridge converter, HB=Half-bridge converter

Current blocking function without sectionalizing DCCB

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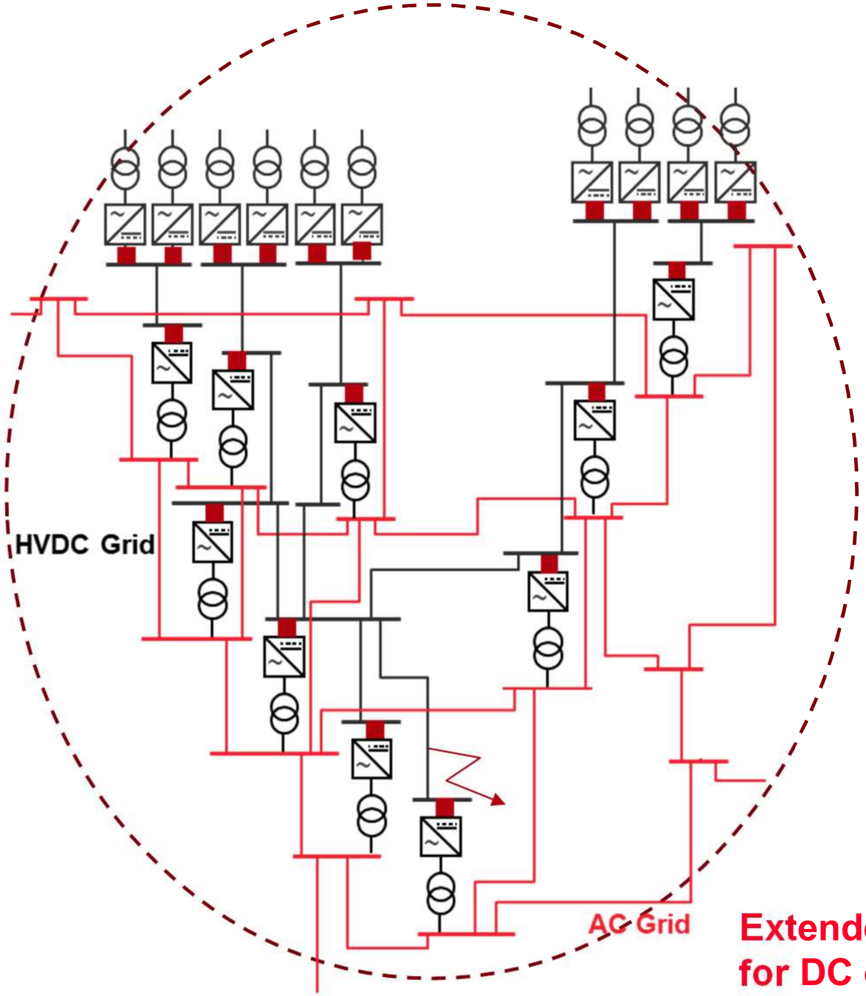

Extended protection zone for DC earth faults!

The whole DC system will now be influenced before the fault is cleared!

Highly likely not acceptable for HVAC Grid Code compliance, since

Large temporary loss of power infeed (RoCoF)

Temporary re-routing of high power on AC lines (Line protection, voltage dip)

DCCB = DC Circuit Breaker, RoCoF = Rate of Change of Frequency

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Probable DC Grid evolution

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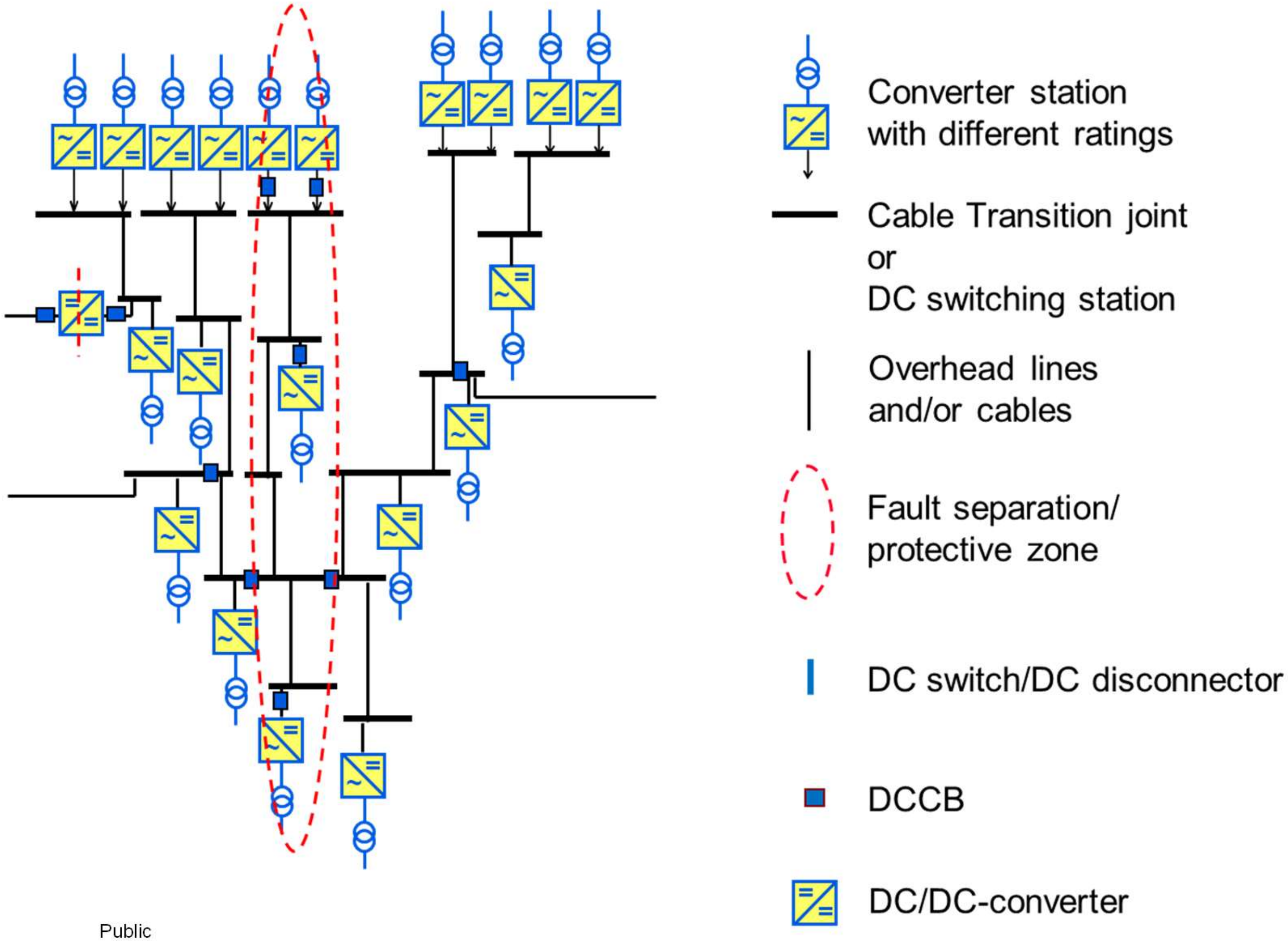

First stage
P2P multiterminal ready links

Second stage
P2P and/or radial multi-terminal with sectionalizing disconnectors

Third stage
Connect the different multiterminals through sectionalizing DCCBs

Fourth stage
Some converter breakers with current limiting/blocking function

Fifth stage
DC/DC-converters with current limiting function

DCCBs protecting each object???

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Evolution of HVAC and HVDC systems

HVAC grids

1) First phase

Single purpose network

Manufacturer doing system studies

2) Intermediate phase

Multi-purpose network

Cooperation between system owner and manufacturer

(Kungliga Vattenfallsstyrelsen and ASEA)

Company standards

3) Final phase

Multi-purpose network

System owner doing system studies (Core competence)

International standards

HVDC grids

Evolution of HVAC and HVDC systems

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HVAC grids

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3) Final phase

Multi-purpose network

System owner doing system studies (Core competence)

International standards

HVDC grids

1) First phase

Single purpose network (mostly P2P)

Manufacturer doing system studies

2) Intermediate phase

3) Final phase

Multi-purpose network

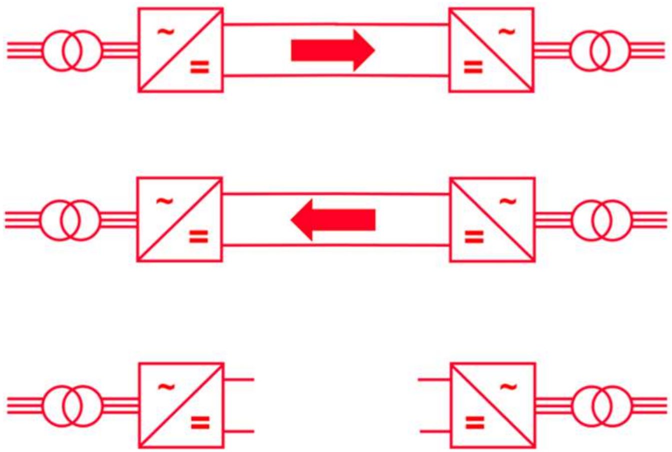
System owner doing system studies

International standards

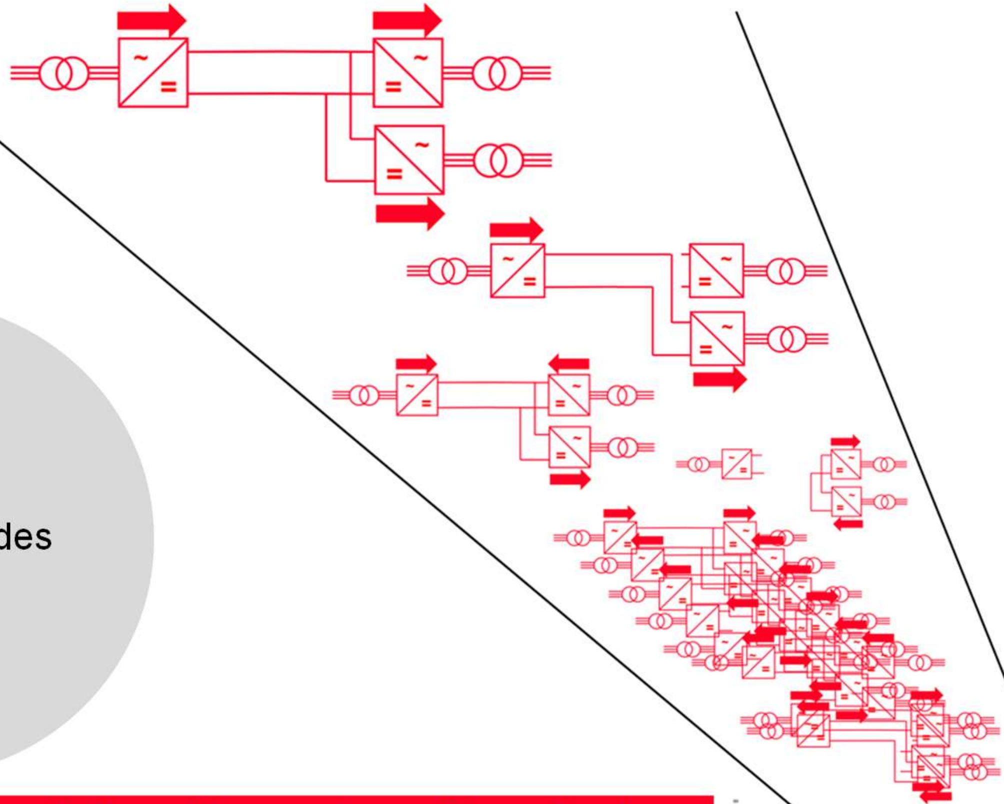
MTDC Intermediate stage – sharing the system studies and verifications?

Engineering challenges - Modes of operation
P2P vs multiterminal

Point-to-point (P2P) – monopole (3)



3-terminal – monopol (13)



- **Inverter**
- **Rectifier**
- **Statcom**
- Control modes
- Reduced voltage
- ...

Operation modes scales exponentially with number of terminals

Example above and next slide only showing operational modes based on Topologies and Power directions. Number of operational modes in parenthesis.

Road-blocker - DC Grid planning studies during HVDC project

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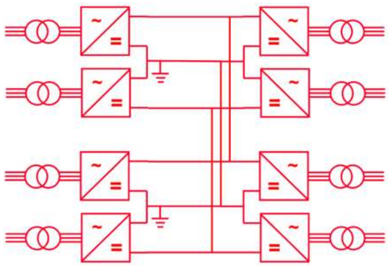
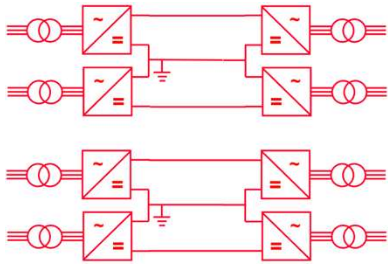
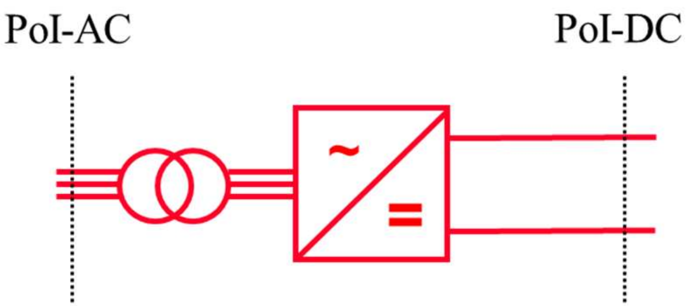
No stations	Bipole			
	All L	2L 1W	1L 2W	2L 2W
2	7			
3	73	34	16	
4	727			160



Four terminal



Two separate bipoles ~7 + 7



Output from pre-project system planning studies - parameters for *both* PoI-AC and PoI-DC!

L=Land HVDC station (rectifier and inverter), W=Wind HVDC station (rectifier), PoI = Point of Interconnection

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