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# High power electronics for HVDC power transmission

## TSTE19 Power Electronics Lecture 14

# Outline

- HVDC Introduction
- Classic HVDC Basic principles
- VSC HVDC Basic principles
- VSC in the power grid - Wind applications
- VSC in the power grid - DC-grid applications

# HVDC Introduction



ABB

# Electric Power Systems

- What is the purpose of the electric power system?
- Why is the system based on AC power?
- When is DC power preferred or needed?

# Market drivers for HVDC transmission
## Environmentally friendly grid expansion

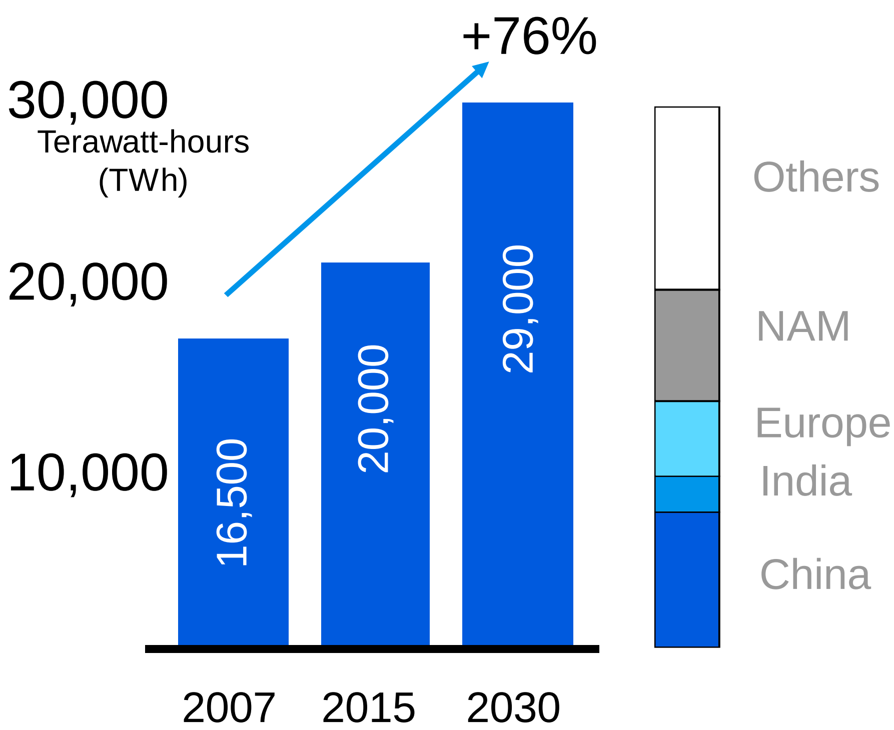


- **Integration of renewable energy**
  - Remote hydro
  - Offshore wind
  - Solar power
- **Grid reinforcement**
  - For increased trading
  - Share spinning reserves
  - To support intermittent renewable energy

# Tackling society's challenges on path to low-carbon era means helping utilities do more using less

Forecast rise in electricity consumption by 2030

- Source: IEA, World Energy Outlook 2009




Solutions are needed for:

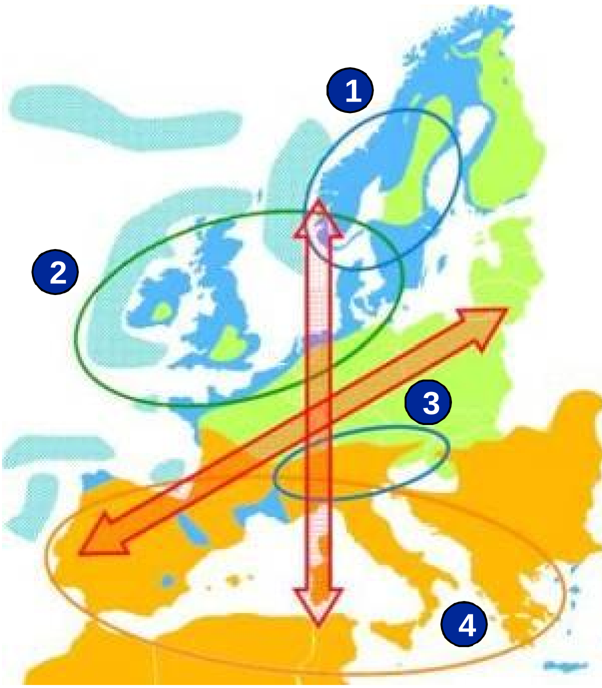
- Rising demand for electricity – more generation
- Increasing energy efficiency - improving capacity of existing network
- Reducing $CO_2$ emissions – Introduce high level of renewable integration

Meeting the rise in demand will mean adding a 1 GW power plant and all related infrastructure every week for the next 20 years

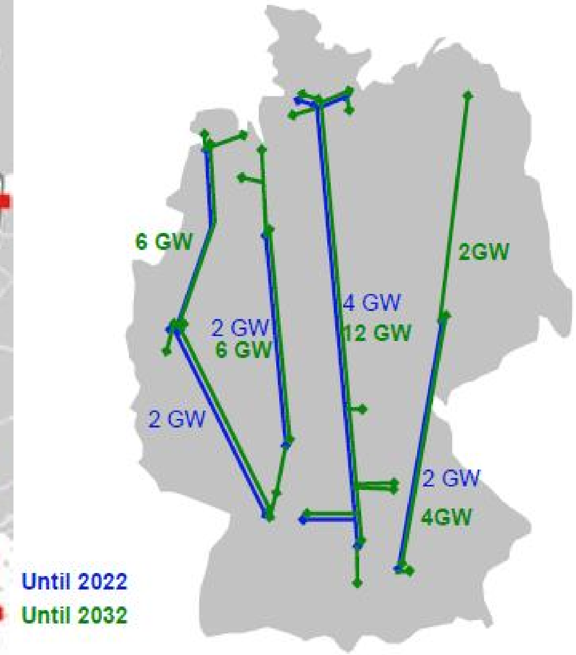
# IEA World Energy Outlook 2012 - 2035

- **5 890 GW of capacity additions (> the total installed capacity in 2011) is required**
- One-third of this is to replace retiring plants; the rest is to meet growing electricity demand.
- Renewables represent half : 3000 GW. Gas 1400 GW.
- The power sector requires investment of $16.9 trillion, ca. half the total energy supply infrastructure investment
- Two-fifths of this investment is for electricity networks, while the rest is for generation capacity.
- Investment in generation capacity, > 60% is for renewables: wind (22%), hydro (16%), solar PV (13%).

# The evolution of grids: Connect remote renewables
## Europe & Germany are planning large scale VSC-HVDC




Source: DG Energy, European Commission



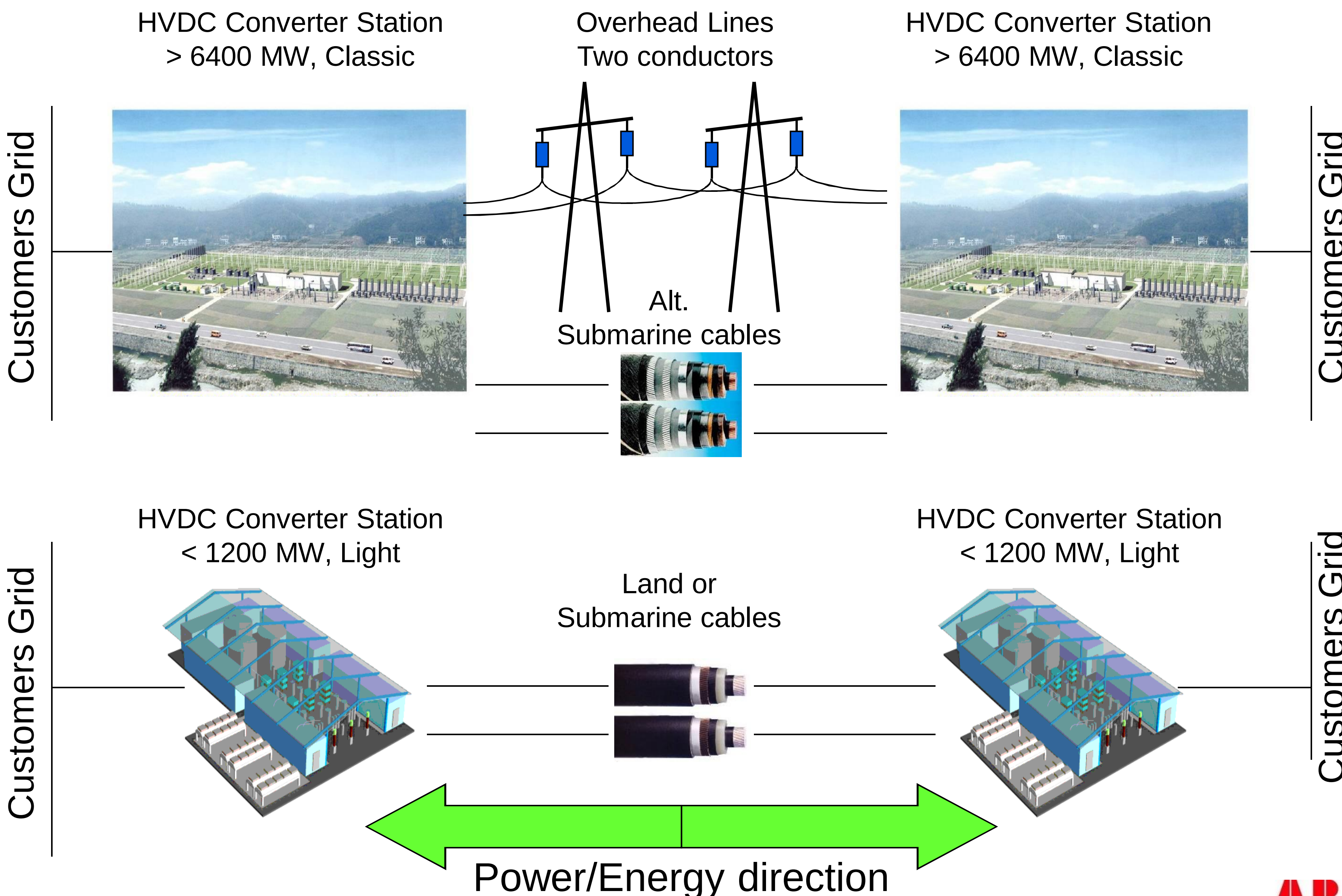

### European Visions

1. Hydro power & pump storage -Scandinavia
2. >50 GW wind power in North Sea and Baltic Sea
3. Hydro power & pump storage plants - Alps
4. Solar power in S.Europe, N.Africa & Middle East

### Germany (draft grid master plan)

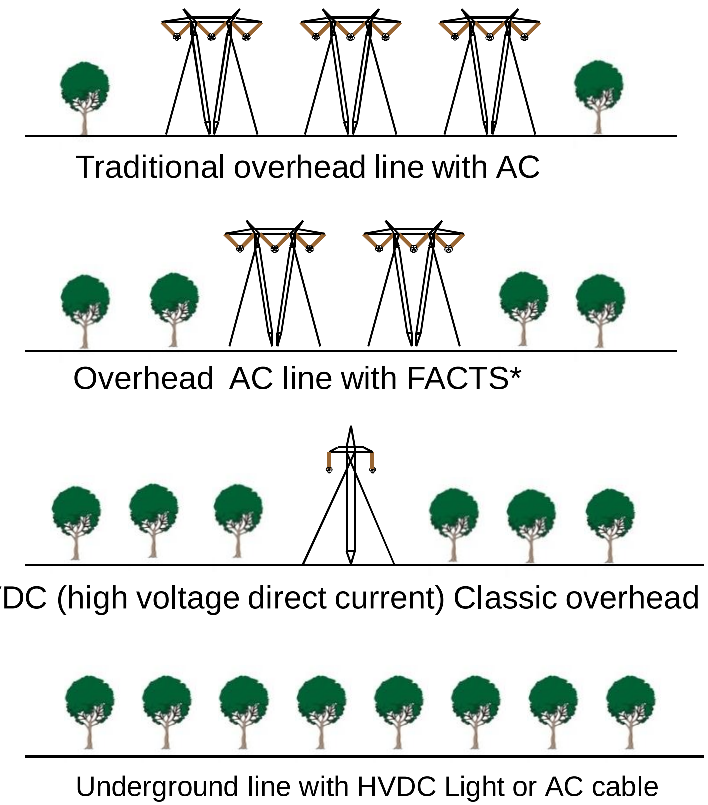
- Alternatives to nuclear-distributed generation
- Role of offshore wind / other renewables
- Political commitment
- Investment demand and conditions
- Need to strengthen existing grid

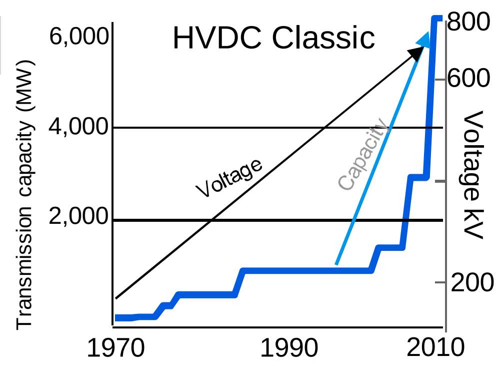
# What is an HVDC Transmission System?



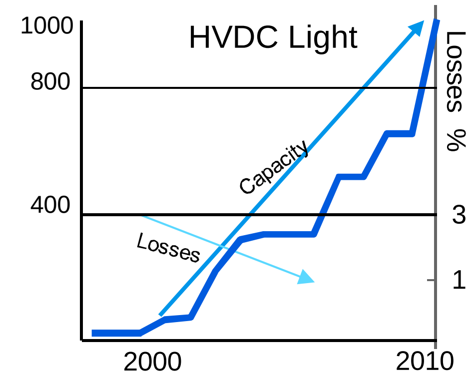
# The transmission grid becomes increasingly important
## Continued development of AC and DC technologies

**Different technologies :Same power transmitted**




Capacity up 6x since 2000; Voltage up from +/- 100kV to +/- 800kV since 1970




- Capacity up 10x ; losses down from 3% to 1% per converter station since 2000

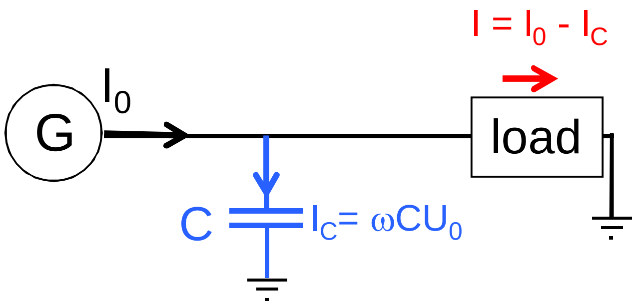
- Longer transmission distances
- More power - lower losses - reduced cost per megawatt (MW)
- Development of power electronics, cable and semiconductor technology



ABB

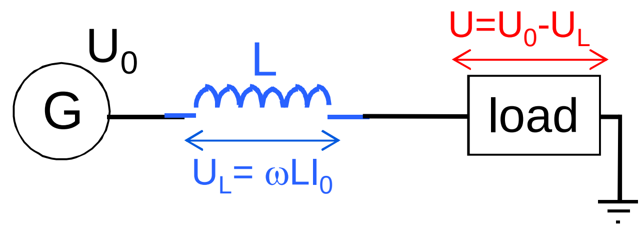
# Why HVDC is ideal for long distance transmission?
## Capacitance and Inductance of power line

### Cable




In cable > 50 km, most of AC current is needed to charge and discharge the “C“ (capacitance) of the cable

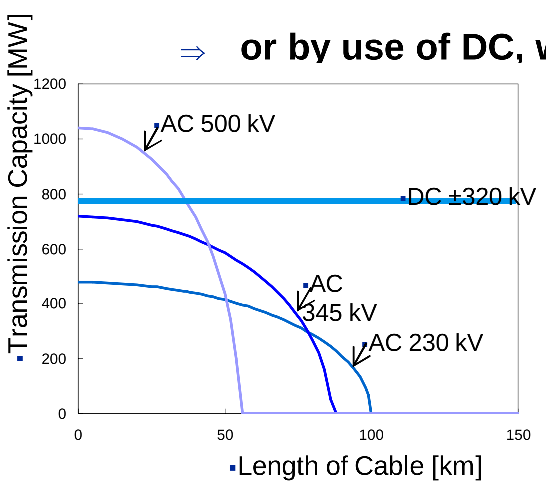
### Overhead Line

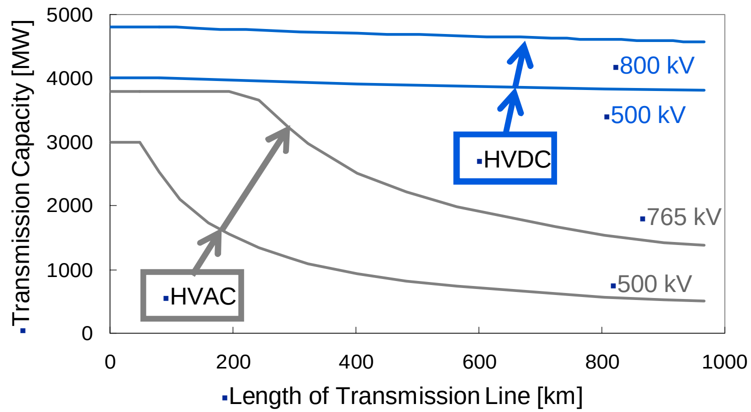



In overhead lines > 200 km, most of AC voltage is needed to overcome the “L” (inductance) of the line

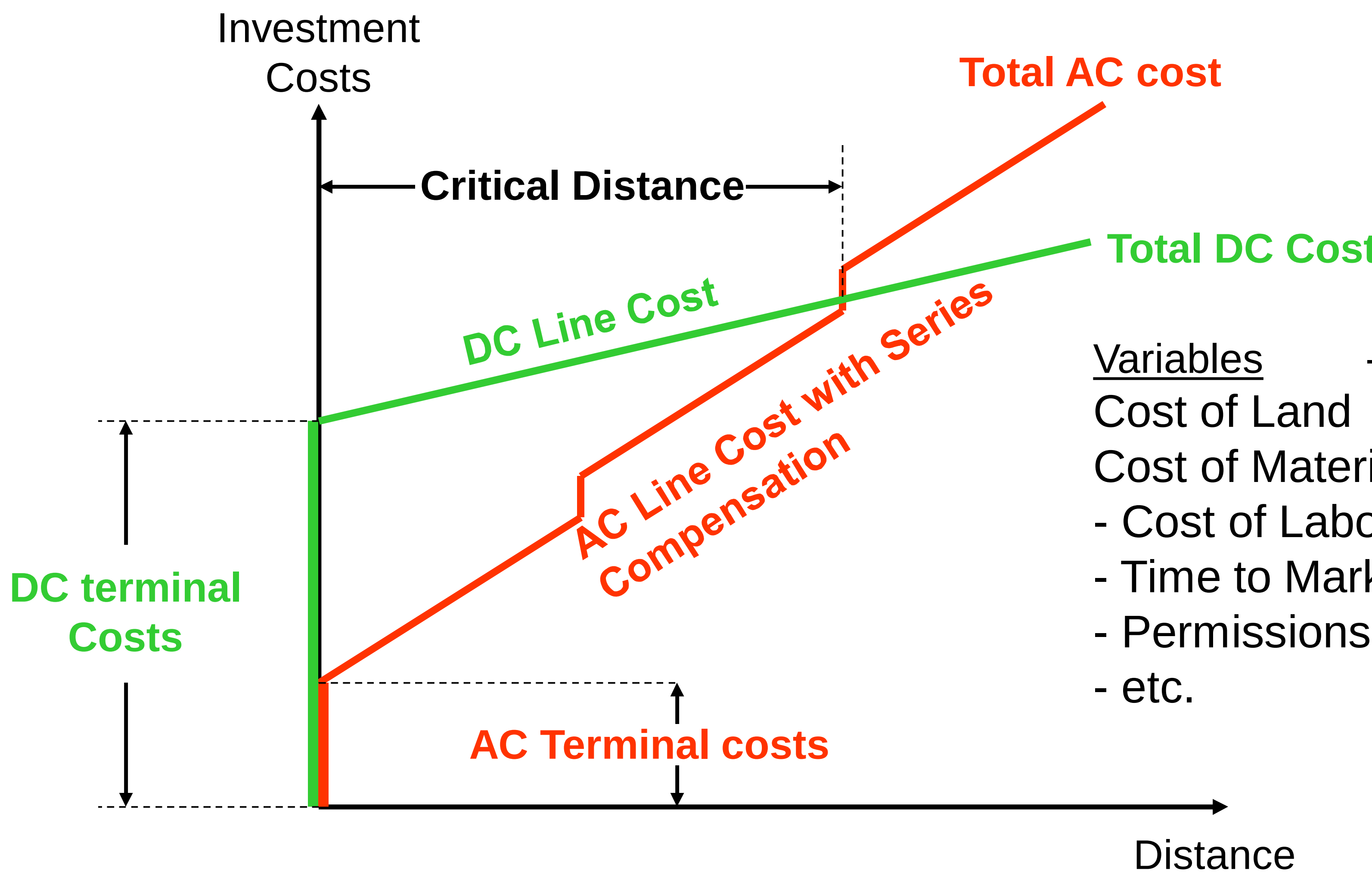
⇒ C& L can be compensated by reactors/capacitors or FACTS

⇒ **or by use of DC, which means $\omega = 2\pi\nu = 0$**



# Investment cost versus distance for HVAC and HVDC



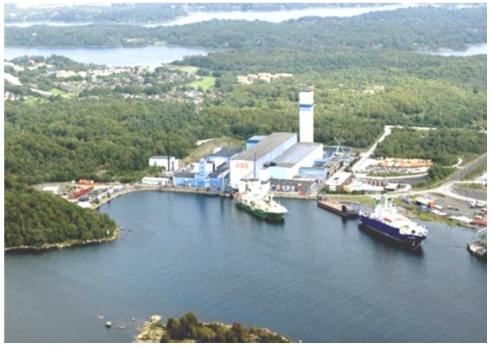
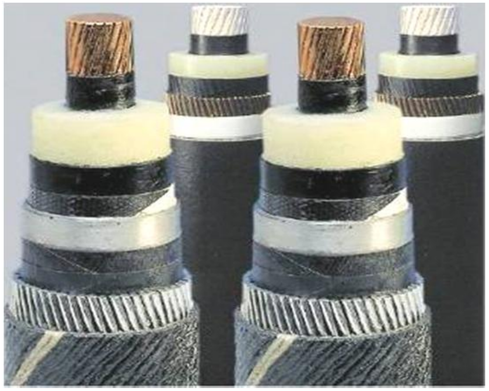

Variables -
Cost of Land -
Cost of Materials
- Cost of Labour
- Time to Market
- Permissions
- etc.

# More than 50 years ago ABB broke the AC/DC barrier
# Gotland 20 MW subsea link 1954

## ▪ABB’s unique position in HVDC

## ▪In-house converters, semiconductors, cables

▪Key components for HVDC transmission systems

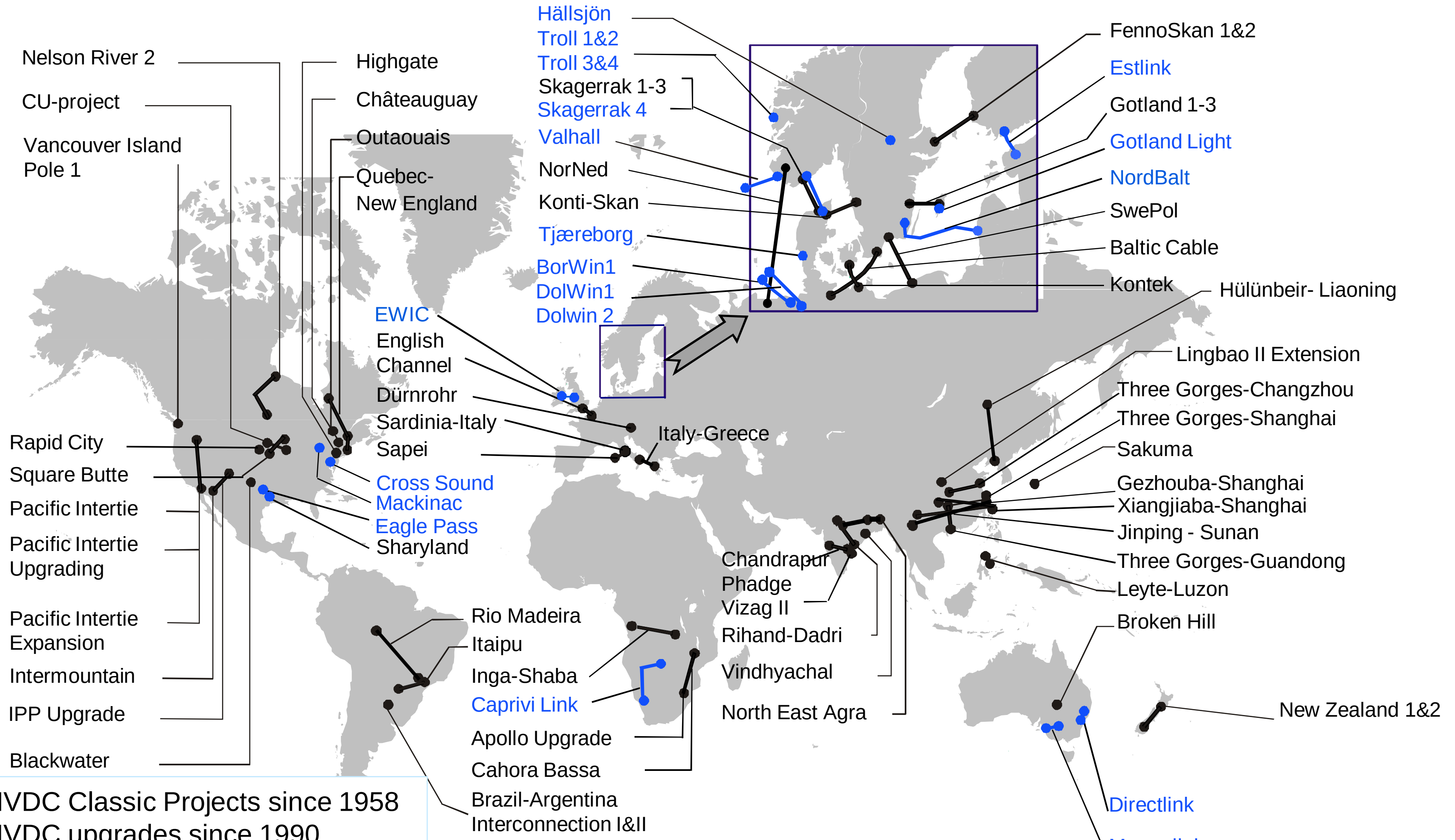
| Converters | High power semiconductors | HV Cables |
| --- | --- | --- |
|  |  |  |
|  |  |  |
| ▪Conversion of AC to DC and vice versa | ▪Silicon based devices for power switching | ▪Transmit large amounts of power- u/ground & subsea |

# 2012: New cable ship AMC Connector




ABB

# ABB has more than half of the 145 HVDC projects
## The track record of a global leader




58 HVDC Classic Projects since 1958
14 HVDC upgrades since 1990
19 HVDC Light Projects since 1997

# Development of HVDC applications

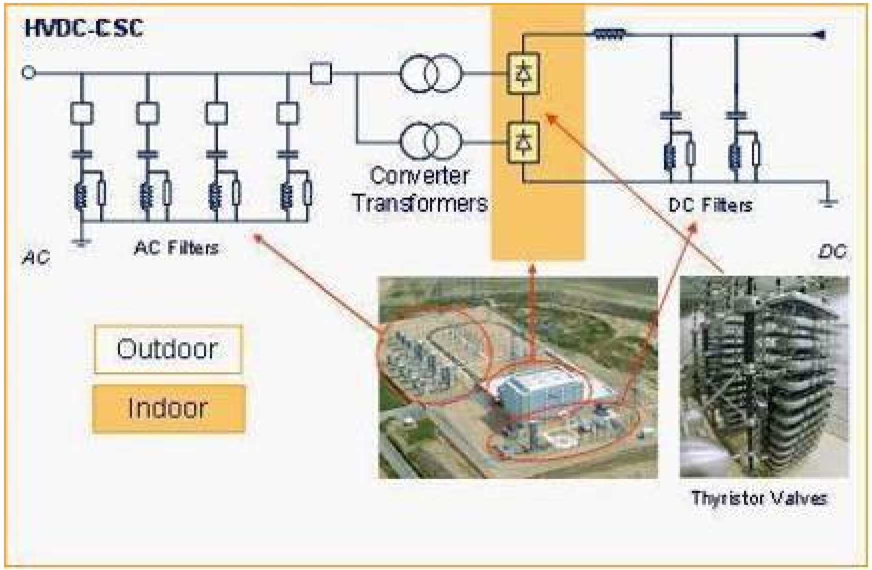

**HVDC Classic**

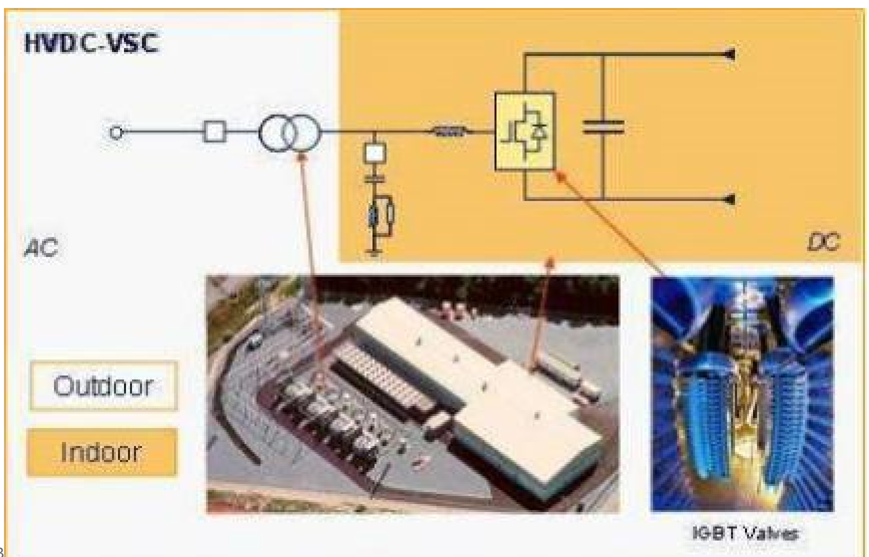
- Very long sub sea transmissions
- Very long overhead line transmissions
- Very high power transmissions

**HVDC Light**

- Offshore power supply
- Wind power integration
- Underground transmission
- DC grids

# HVDC Technologies



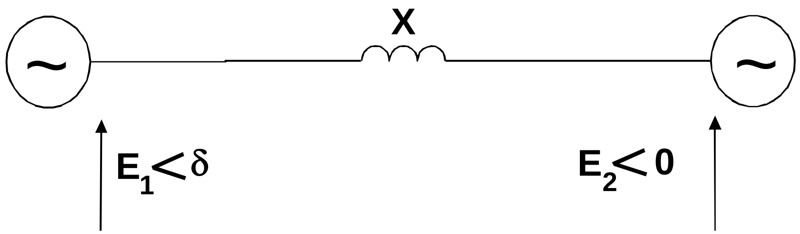

- HVDC Classic
  - Current source converters
  - Line-commutated thyristor valves
  - Requires 50% reactive compensation
  - Converter transformers
  - Minimum short circuit capacity > 2x converter rating
- HVDC Light
  - Voltage source converters
  - Self-commutated IGBT valves
  - Requires no reactive power compensation
  - “Standard” transformers
  - No minimum short circuit capacity, black start

# Classic HVDC basic principles

# AC and DC transmission principles

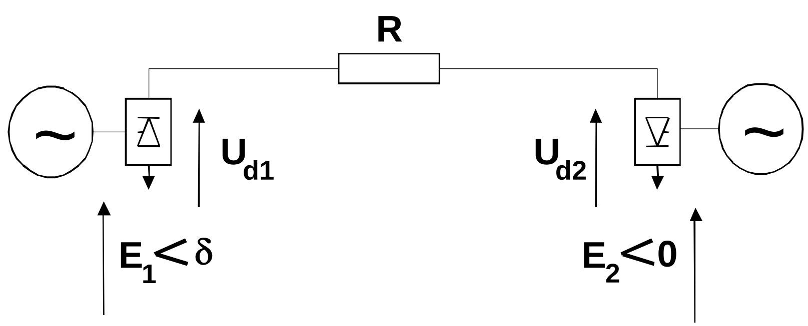
**Power Direction** →

**HVAC**




$$P = \frac{E_1 E_2}{X} sin(\delta)$$

**HVDC**

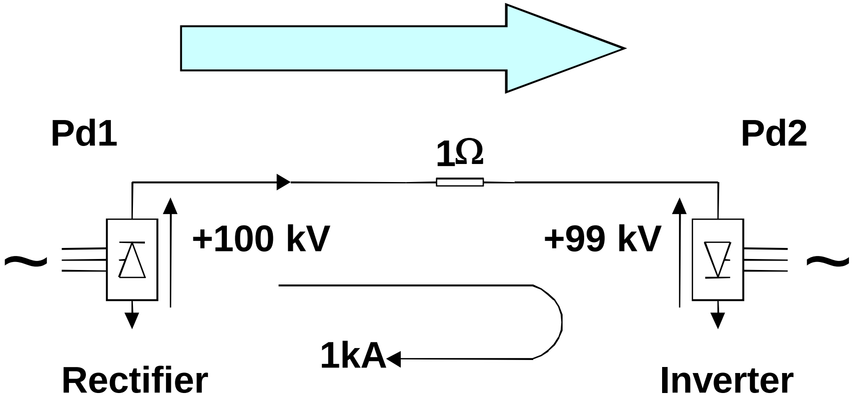



$$P = \frac{U_{d1}(U_{d1} - U_{d2})}{R}$$

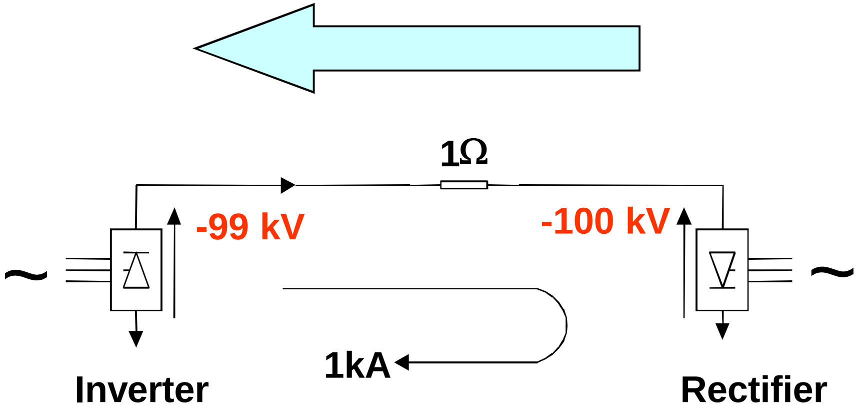
**Power flow independent from system angles**

# HVDC - Controllability of power flow

## Normal Power direction:




## Power reversal:

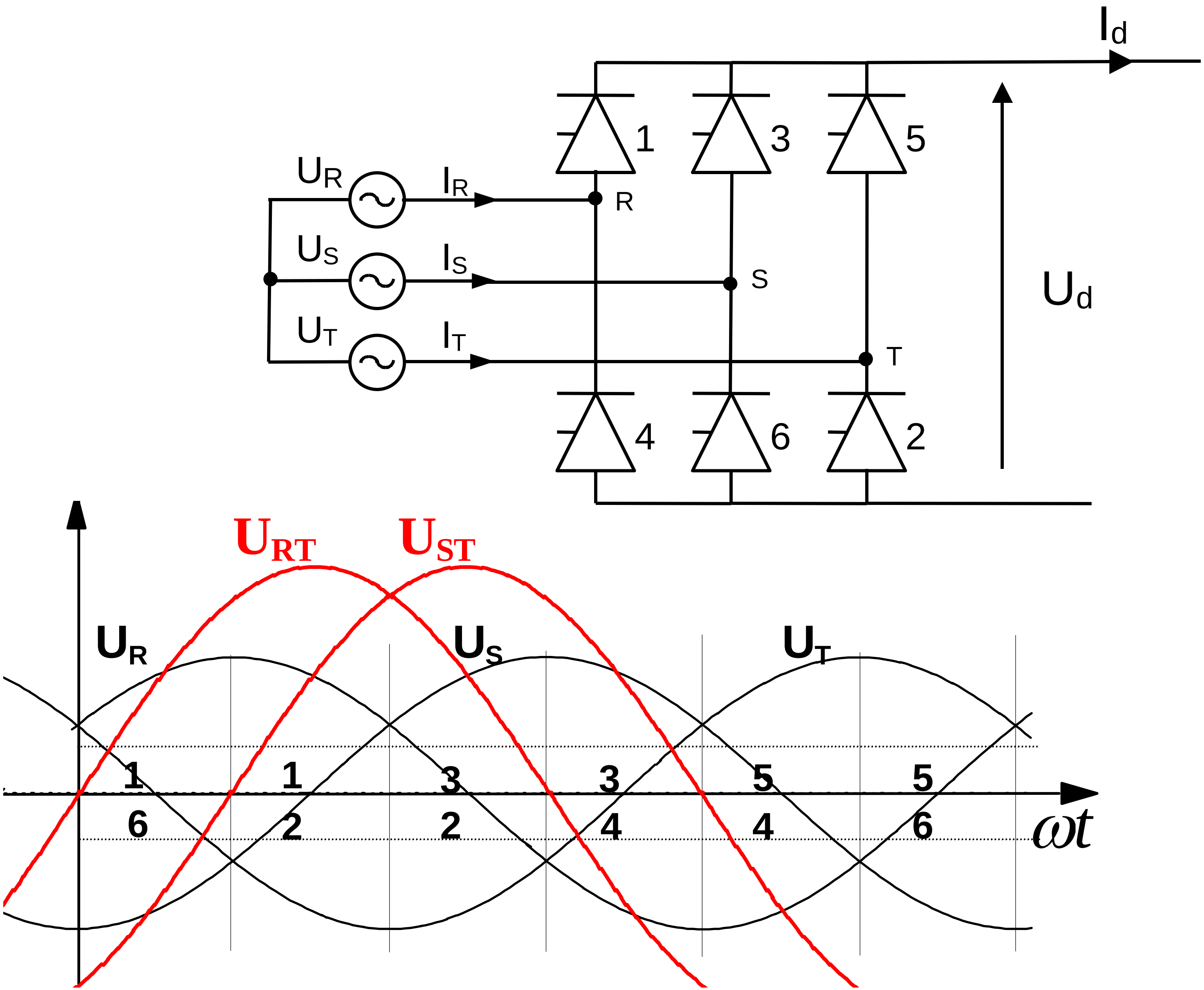



| $U_{d1}$ | $U_{d2}$ | $R_d$ | $I_d$ | $P_{d1}$ | $P_{d2}$ |
|---|---|---|---|---|---|
| 100 | 99 | 1 | 1 | 100 | 99 |
| 101 | 99 | 1 | 2 | 202 | 198 |
| | | | | | |
| -99 | -100 | 1 | 1 | -99 | -100 |

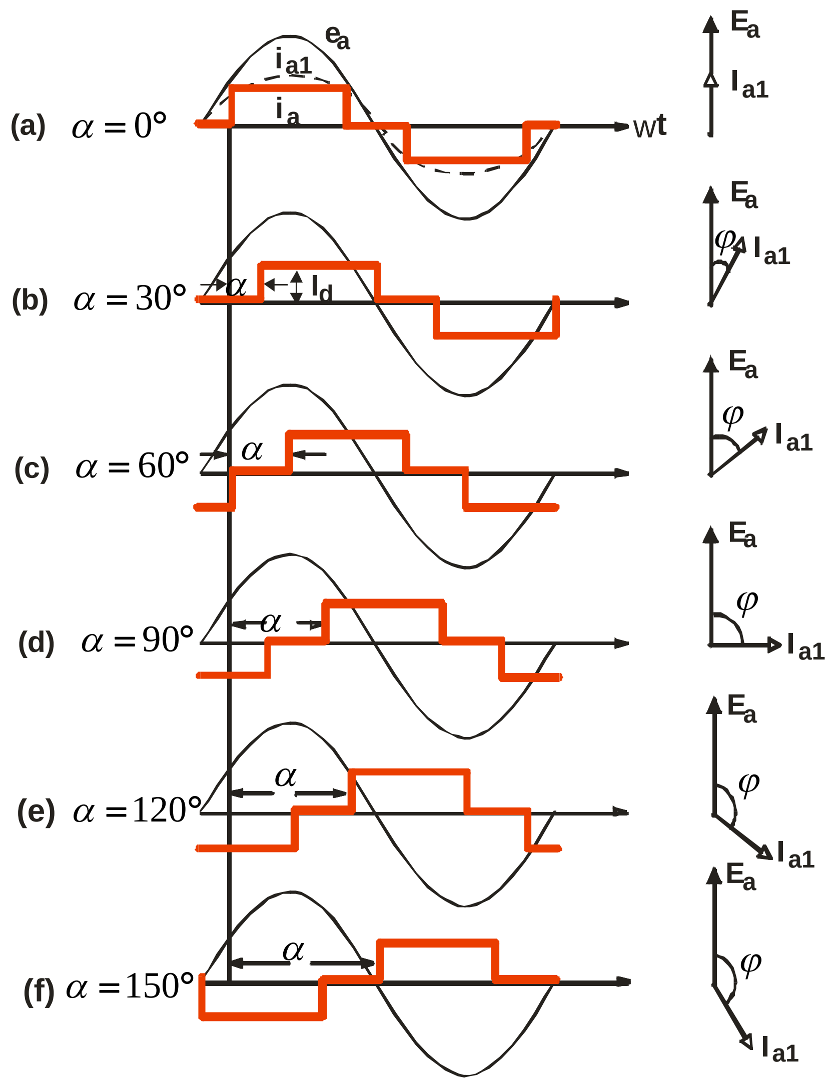
**Fast and stable**

**power flow control**

# Principles of AC/DC conversion, 6-pulse bridge

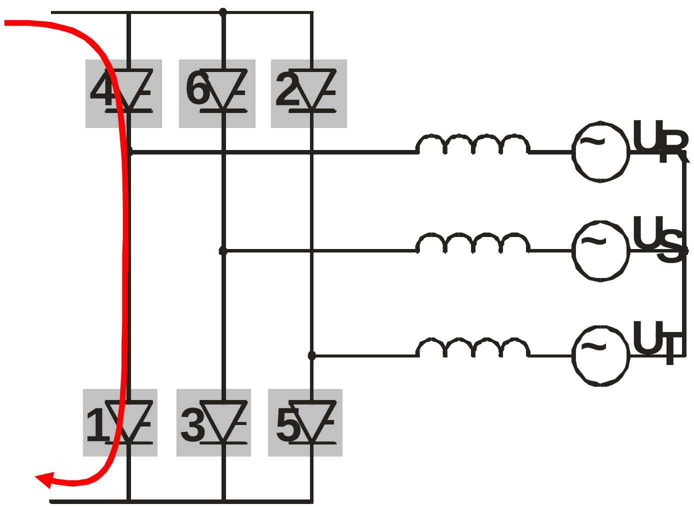


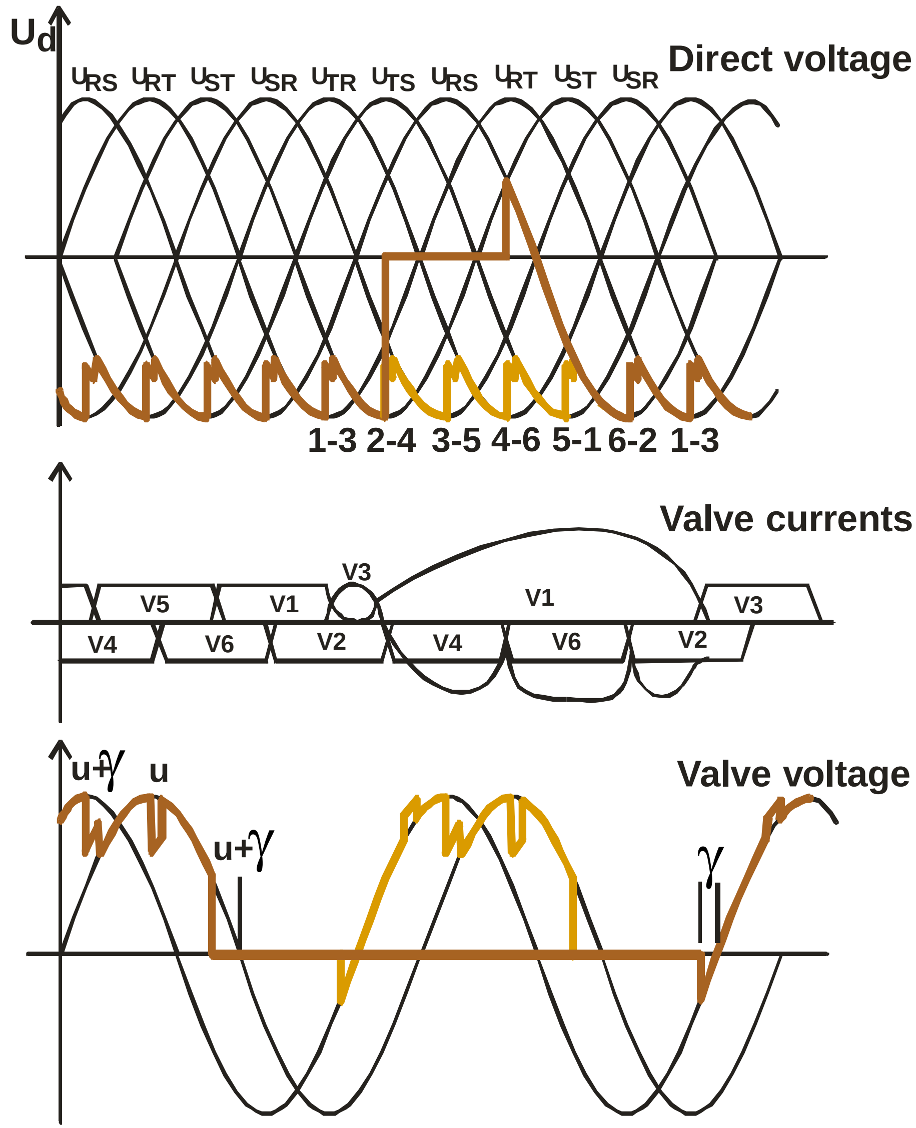
# Relation between firing delay and phase displacement



# Waveshapes during a commutation failure

Normal commutation
Commutation failure



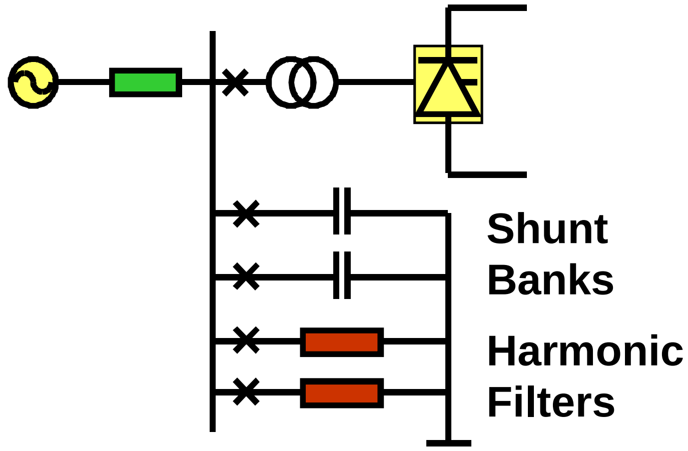

**V1 & V4 conducting simultanously**

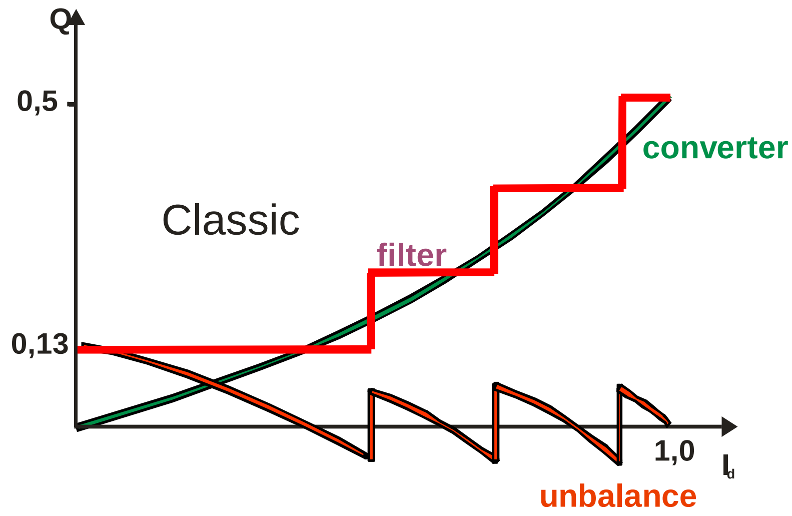
⇓

**DC side short circuit**

# Classic HVDC, Active vs Reactive Power

- **How the Reactive Power Balance varies with the Direct Current for a Classic Converter .............**

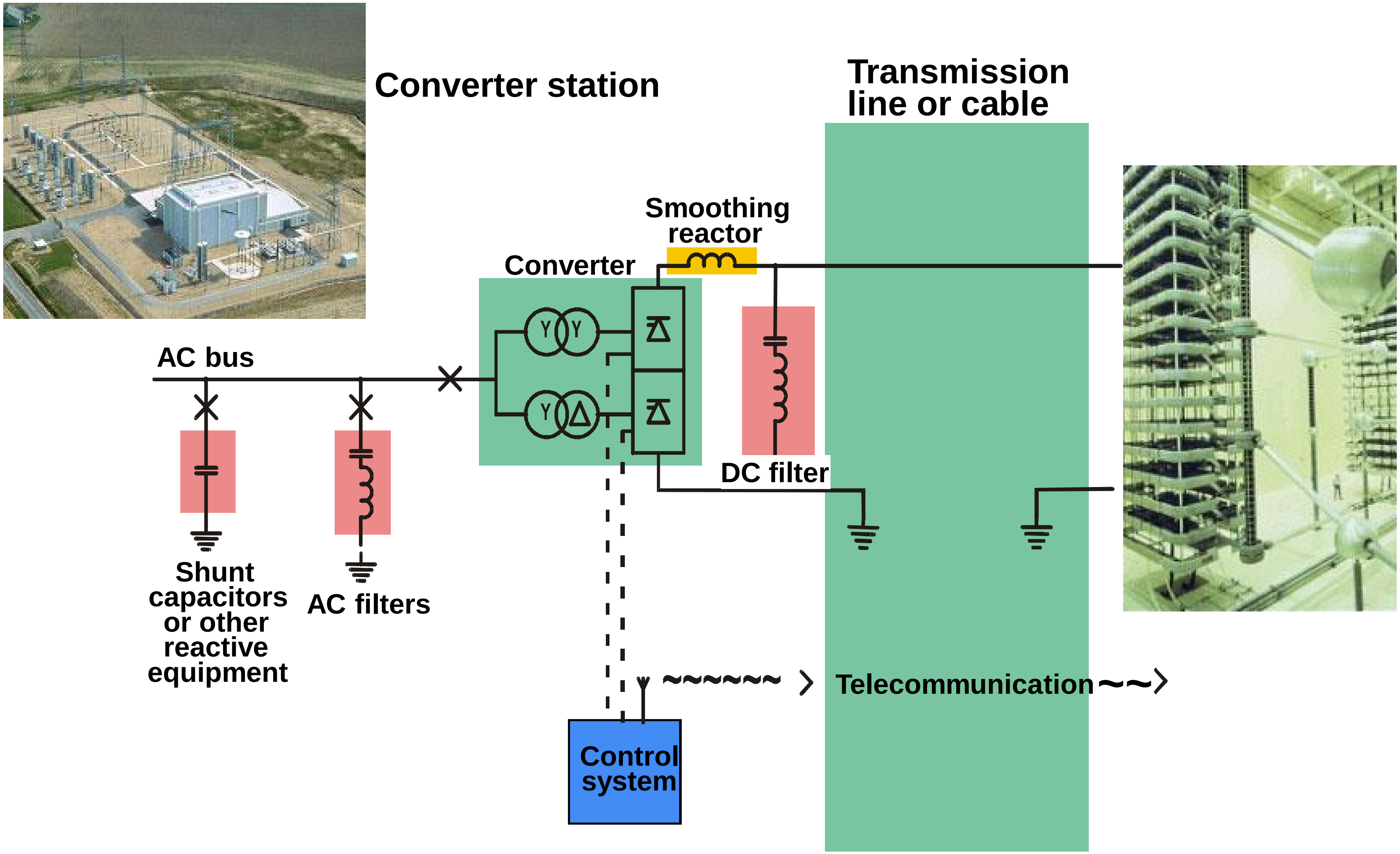


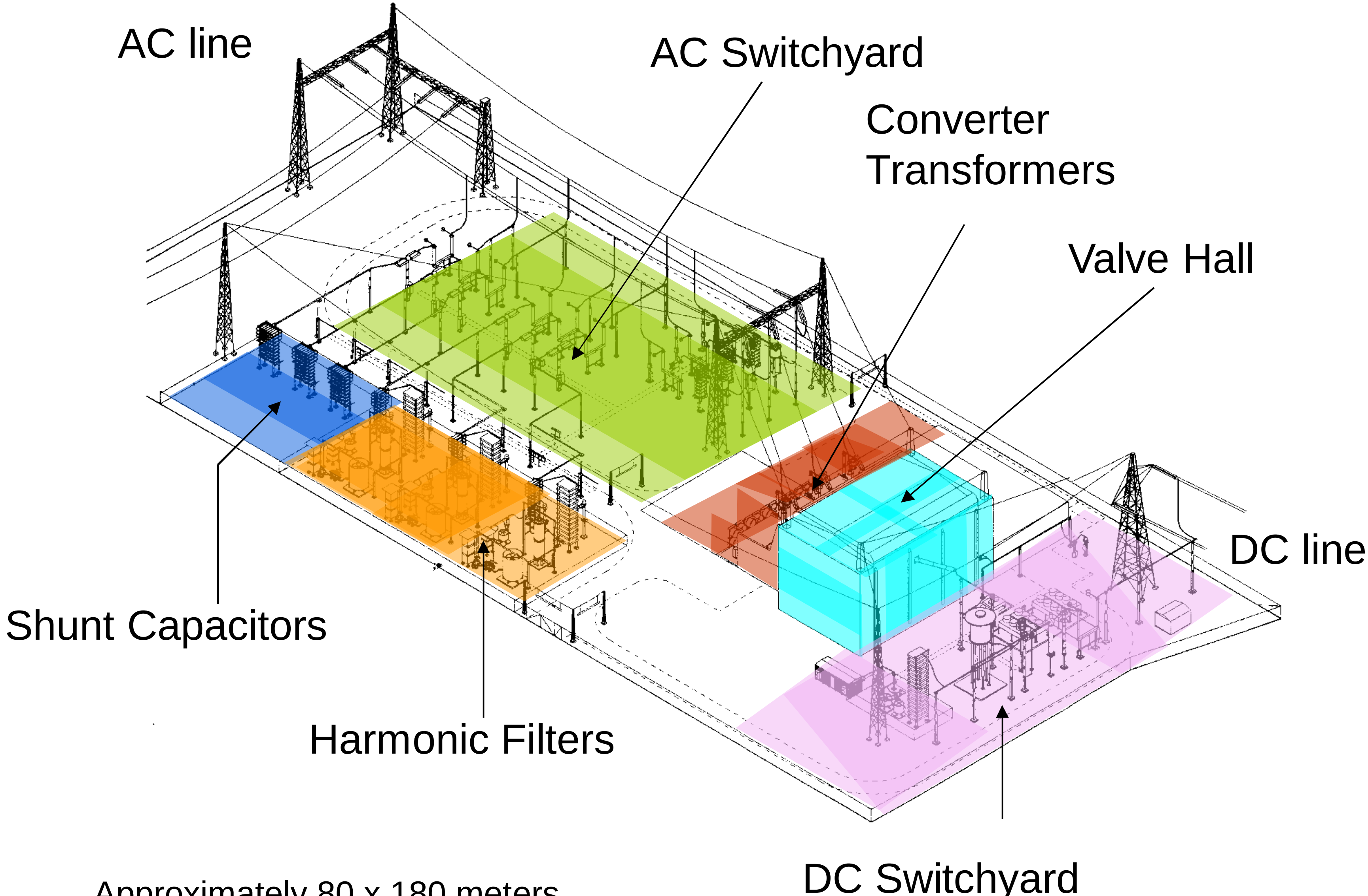
# Baltic Cable 600 MW HVDC link

▪L36994

# The HVDC Classic Monopolar Converter Station



# Monopolar Converter station, 600 MW




Approximately 80 x 180 meters

# Longquan, China
# HVDC Classic

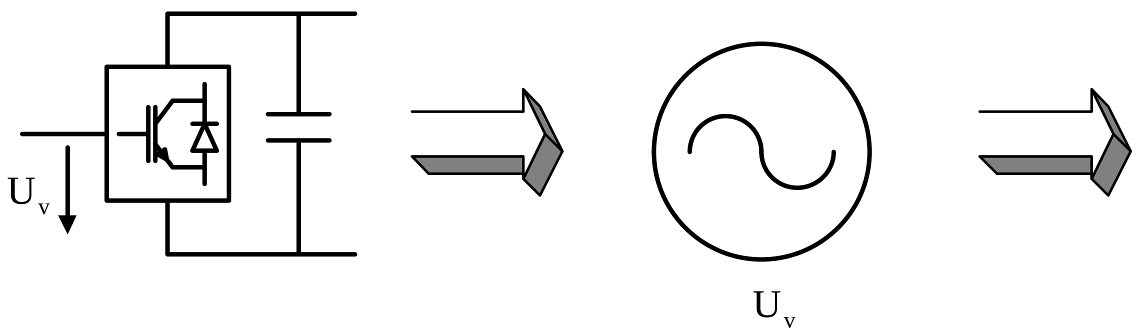
# VSC HVDC
# basic principles

# Introduction

## *1. Why VSC HVDC*

Particular advantages with VSC HVDC

1. Voltage source functionality



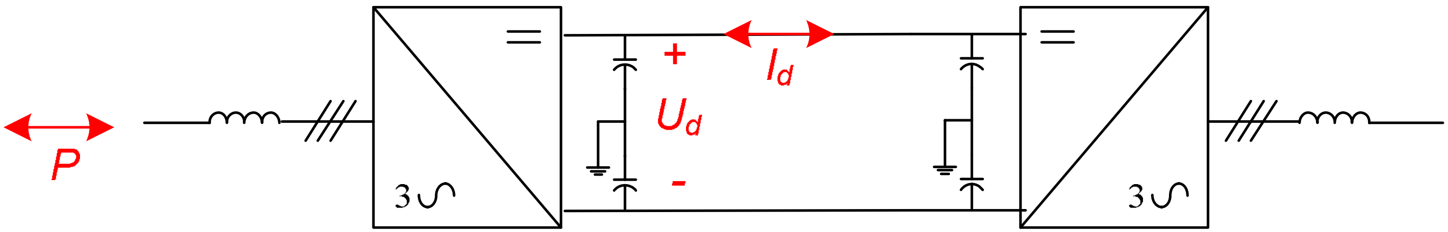

- **Rapid, <u>independent</u> control of active <u>and reactive</u> power**
- **No need for a strong grid**

# Introduction

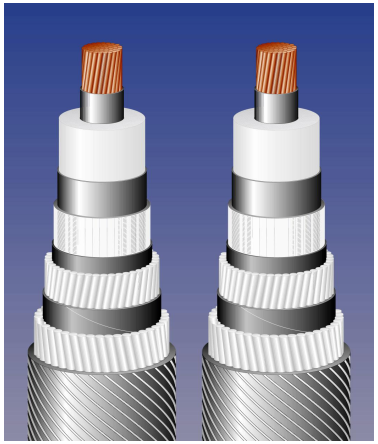
## *1. Why VSC HVDC*

Particular advantages of VSC HVDC

2. Power direction reversal through DC <u>current</u> reversal




**Lightweight, less expensive, <u>extruded polymer DC cables</u> can be used**



Extruded plastic cable

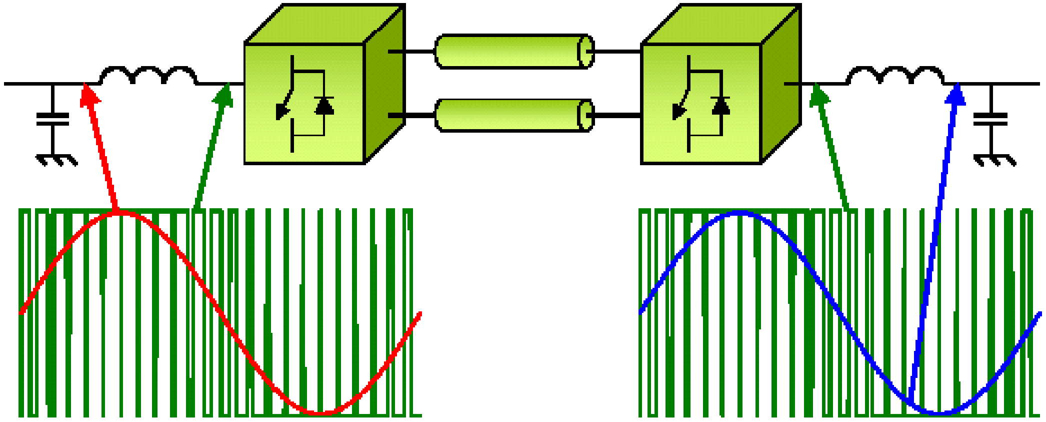
Mass impregnated oil cable

# Introduction

## *1. Why VSC HVDC*

Particular advantages of VSC HVDC

3. Pulse width modulation of  AC voltages

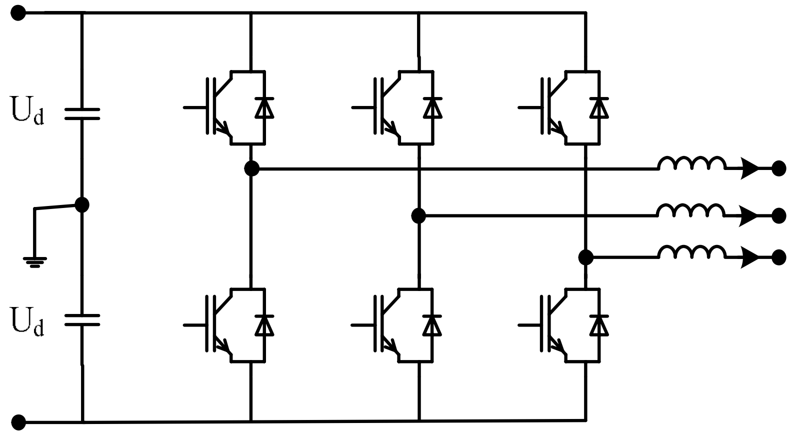


**Small filters, both on AC and DC side**

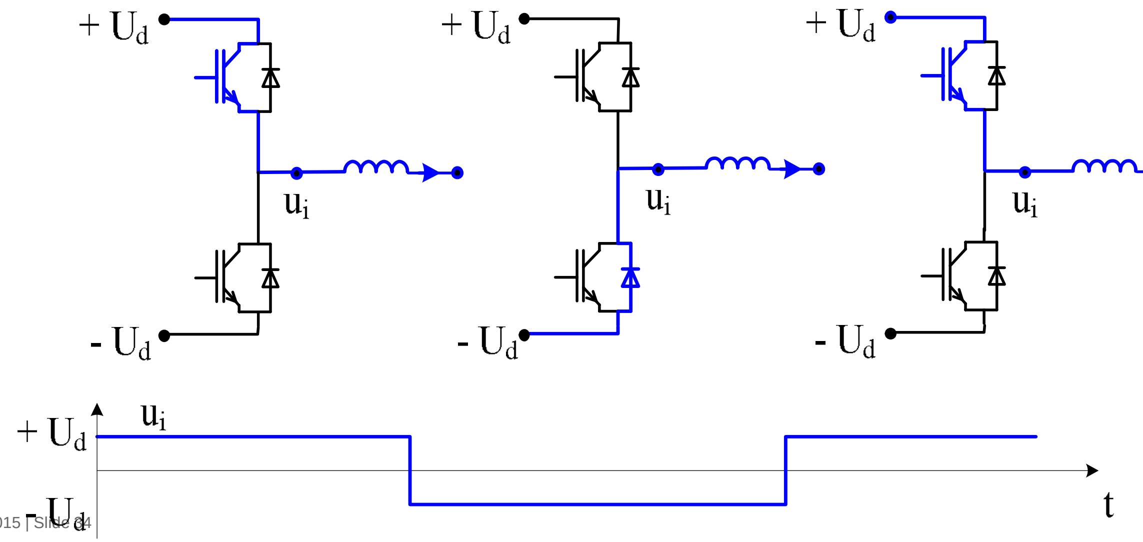
# VSC HVDC basic principles
## *2. VSC converter topologies*

***Two-level voltage source converter.***

*Converts a DC voltage into a three-phase AC voltage by means of switching between **two** voltage levels.*




*Basic operation of a phase leg:*



# VSC HVDC basic principles

## *2. VSC converter topologies*

### Multilevel topologies - basics

**+** Phase voltages **are multi-level (>2).**

**+ Pulse number and switching frequency are** decoupled**.**

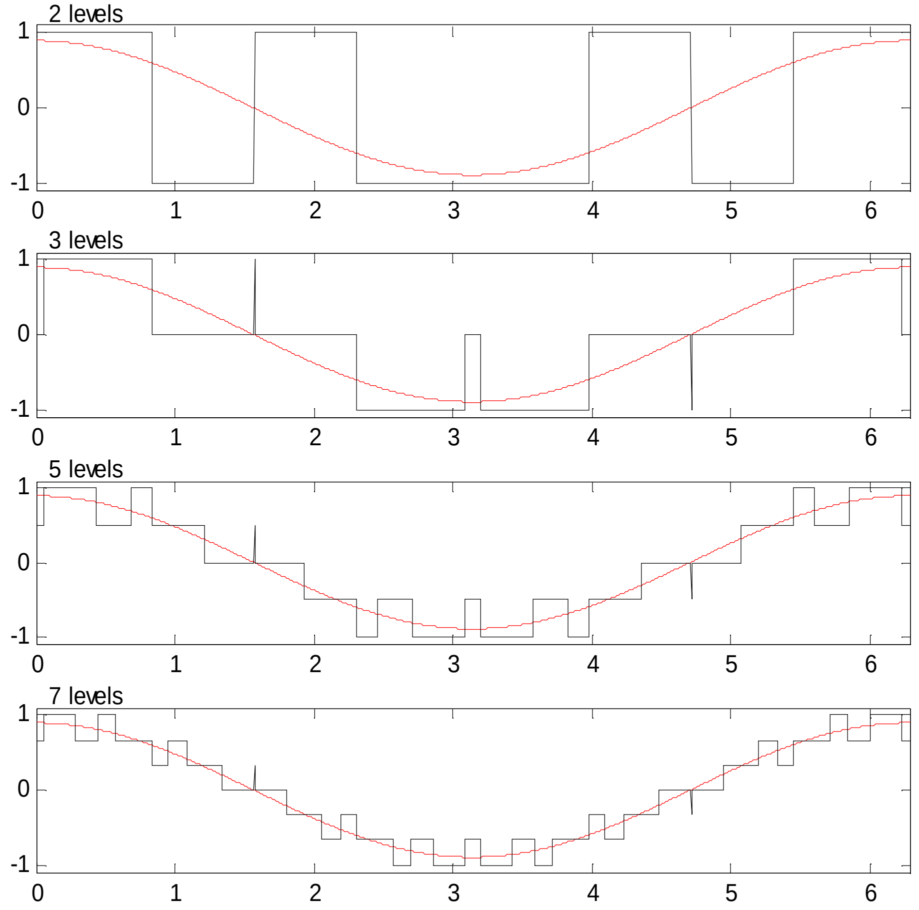
**+ The output** voltage swing is reduced **– less insulation stress**

**+** Series-connected semiconductors **can be avoided for high voltage applications**

**-** More complicated **converter topologies are required**

**- More semiconductors required**

**Typical applications:** high-power converters **operating at medium or high voltage.**

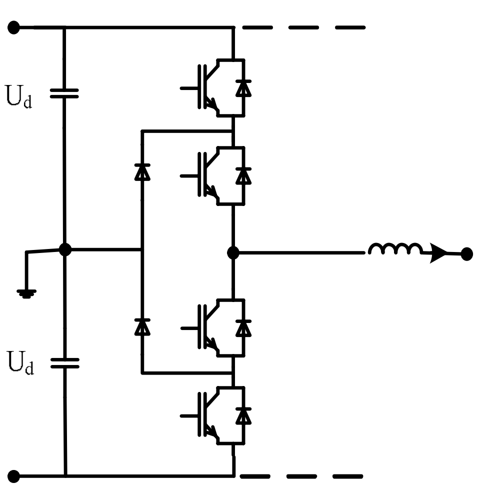


# VSC HVDC basic principles

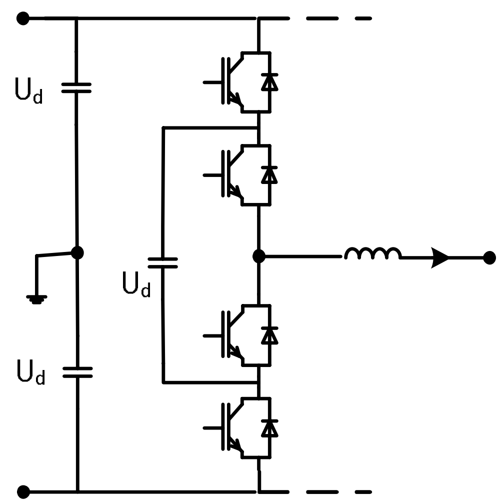
## *2. VSC converter topologies*

### Multilevel converter topologies

*Neutral point clamped (NPC) topologies*



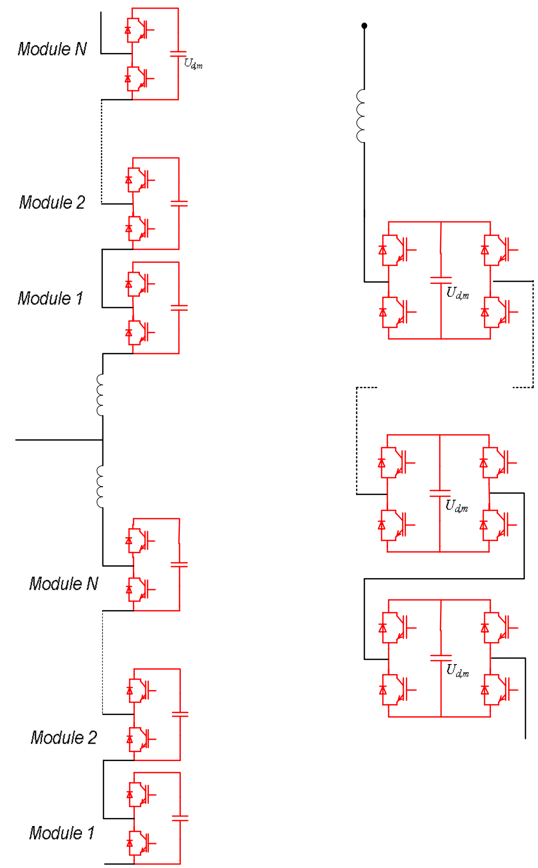

*Flying capacitor topologies*




*Cascaded topologies*

*Modular Multilevel Converters (MMC)*

***Half-bridge and full-bridge variants***




***One phase leg, or equivalent, shown in each case***

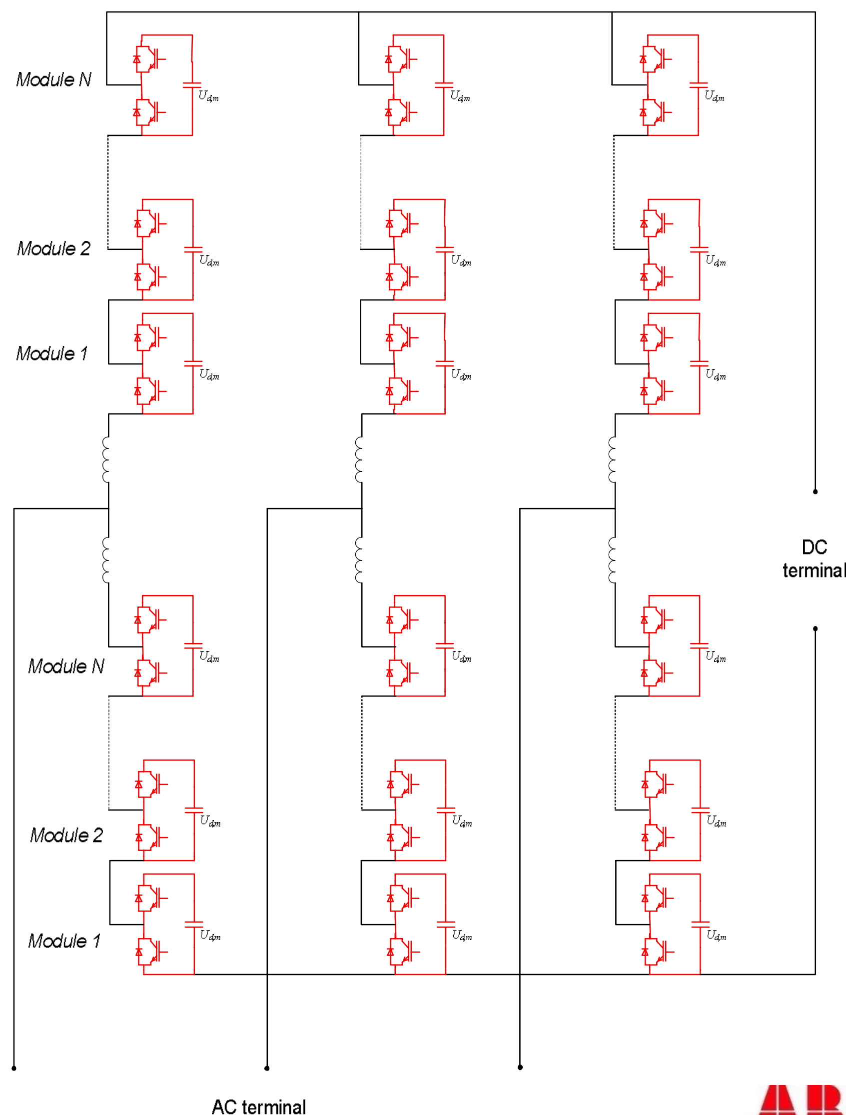
# VSC HVDC basic principles

## Modular multi-level converter *(MMC)*

Modular multi-level converter (MMC)

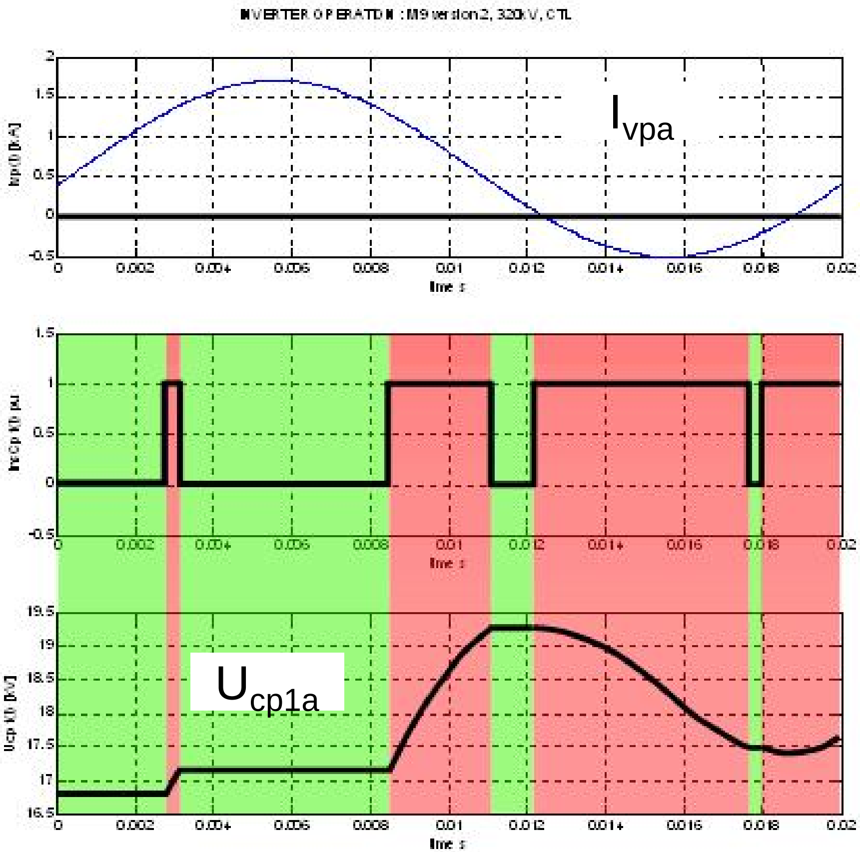
***Prof. Marquardt, Univ. Munich***

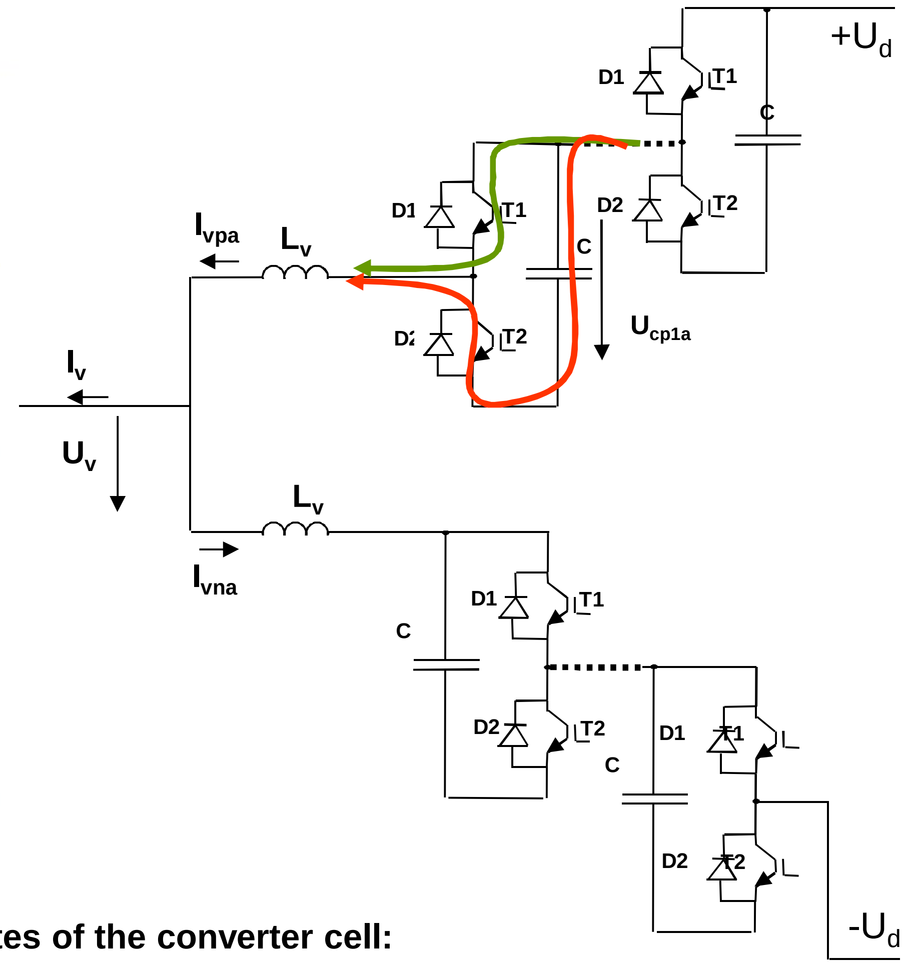
- **DC capacitors distributed in the phase legs**
- **DC capacitors handle fundamental current**
- **Scalable with regard to the number of levels**
- **Twice the total blocking voltage required (twice no of semiconductor devices) compared to two-level converter**
- **Redundancy possible by shorting failing cells**



# VSC HVDC basic principles

## MMC-converter, switching principle



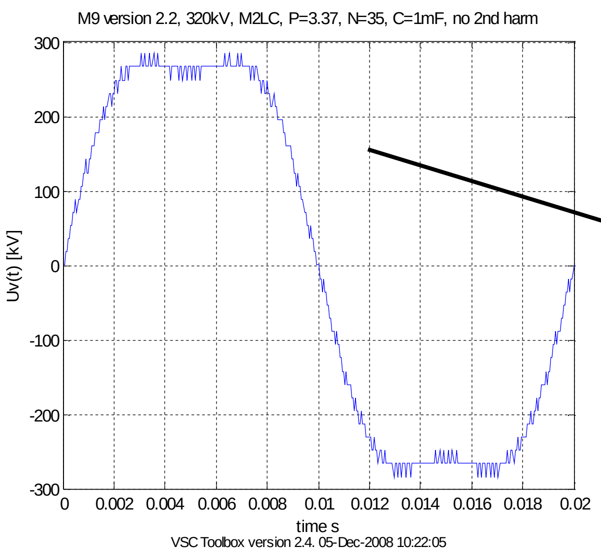

**Three operating states of the converter cell:**

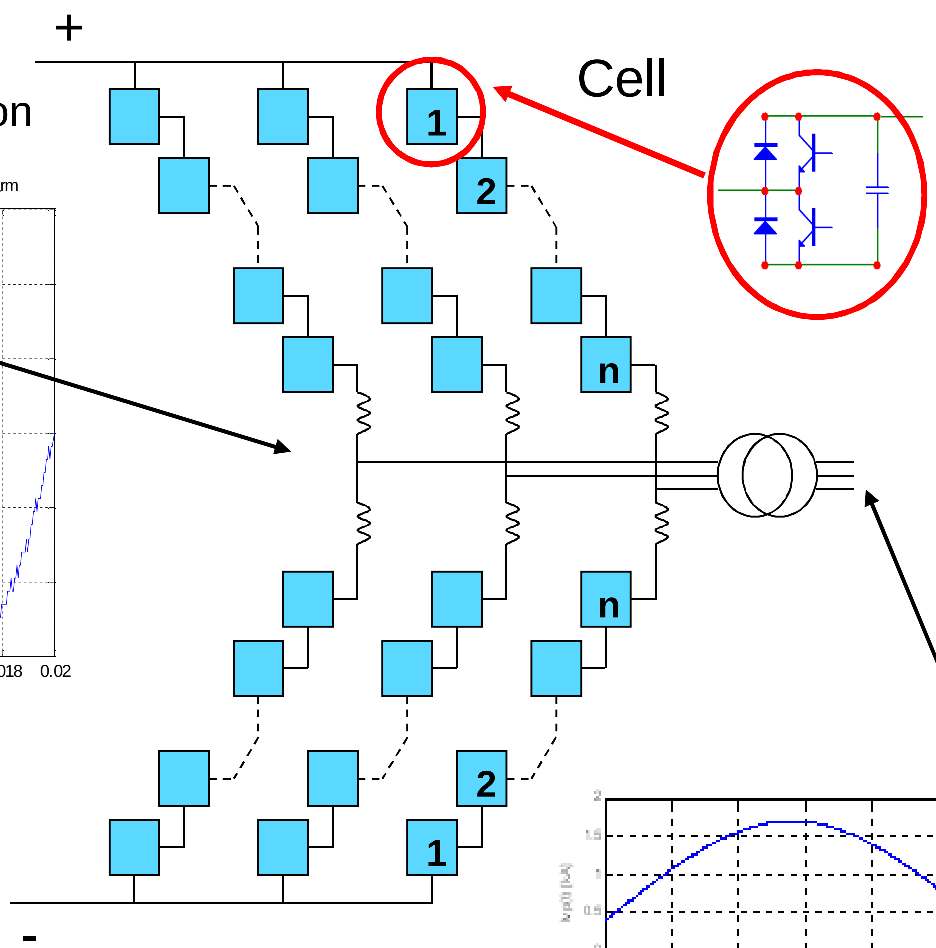
- Bypass mode. Cell capacitor is bypassed. (Green curve)
- Inserted mode. Cell capacitor is inserted and giving contribution to converter output voltage
- Blocked mode. All IGBTs non-conducting

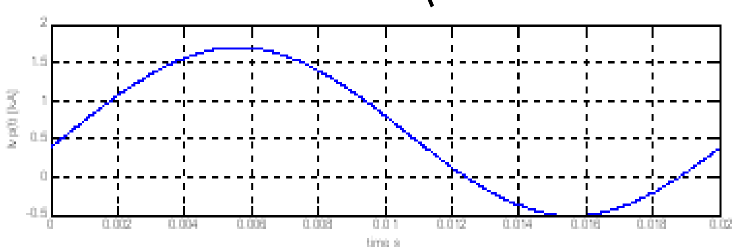
# VSC HVDC basic principles

## MMC-converter, Output voltage

Third harmonic modulation

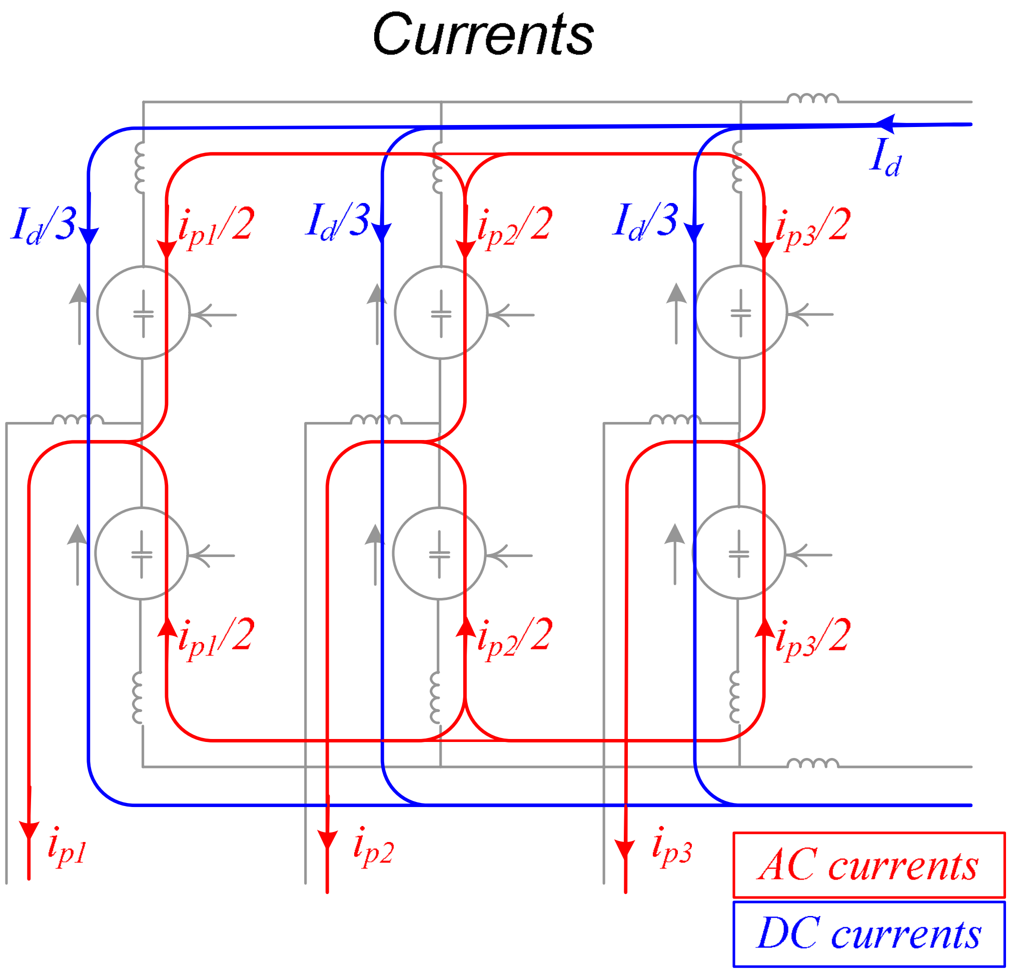


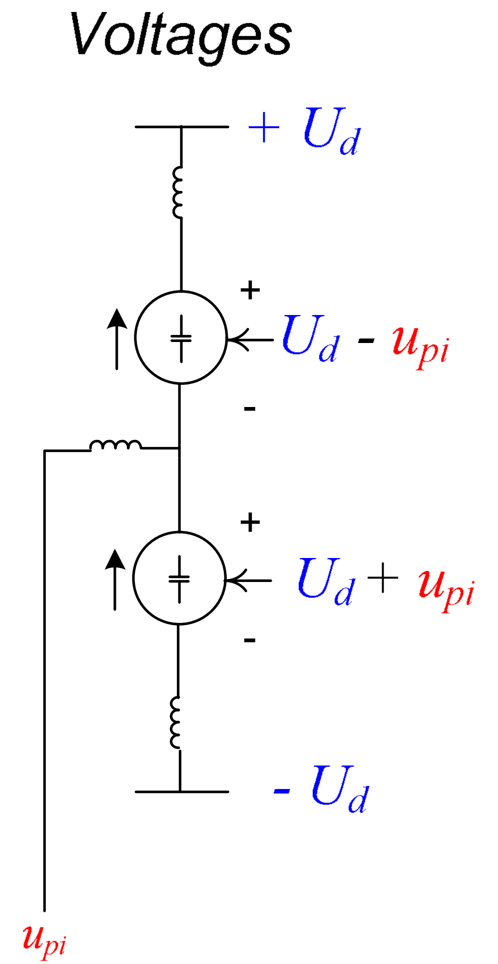



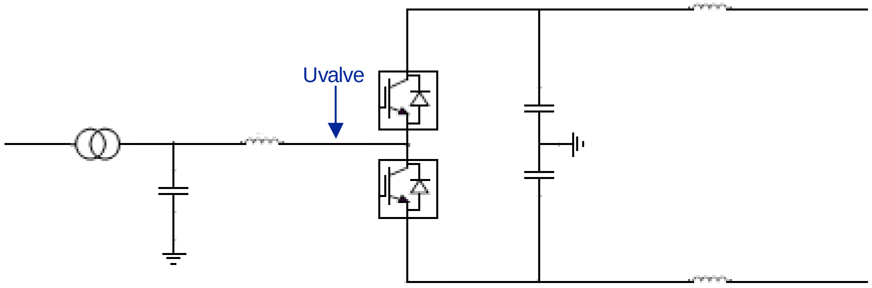
# VSC HVDC basic principles

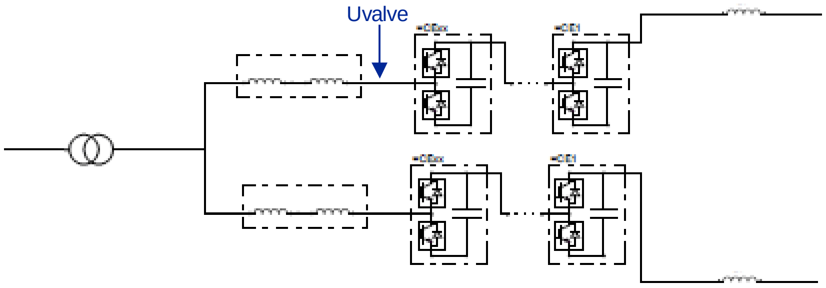
## MMC-converter, basic mode of operation



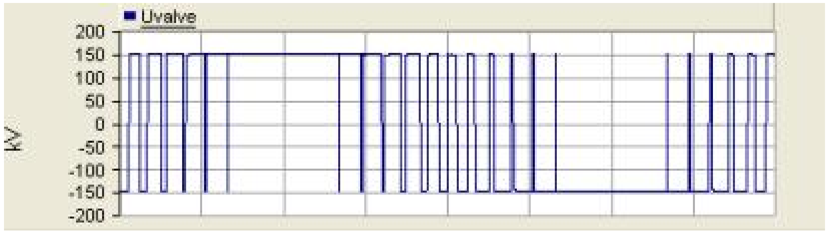



# VSC performance – Switching Principle

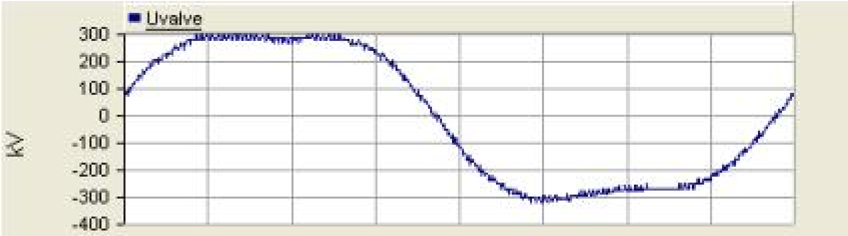


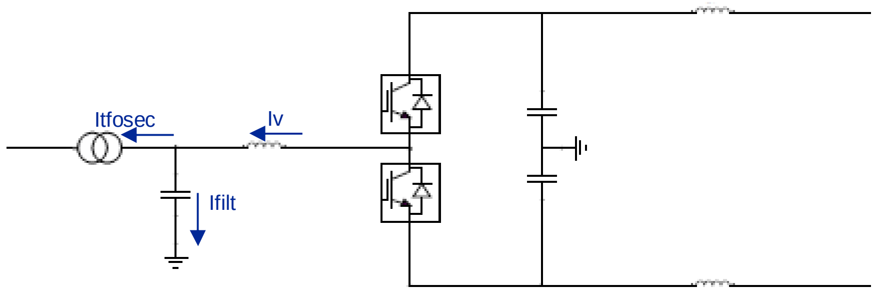

2-level $\pm 150\ kV_{dc}$

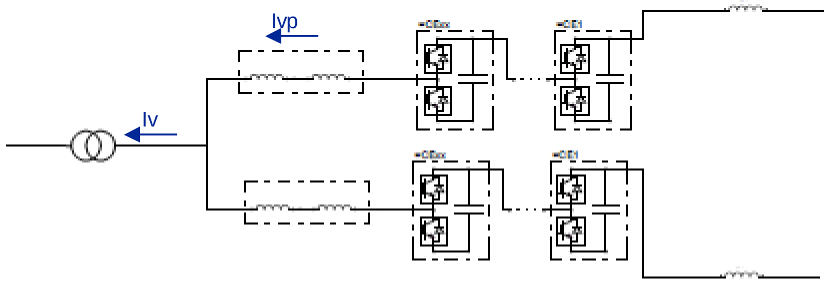



MMC $\pm 320\ kV_{dc}$



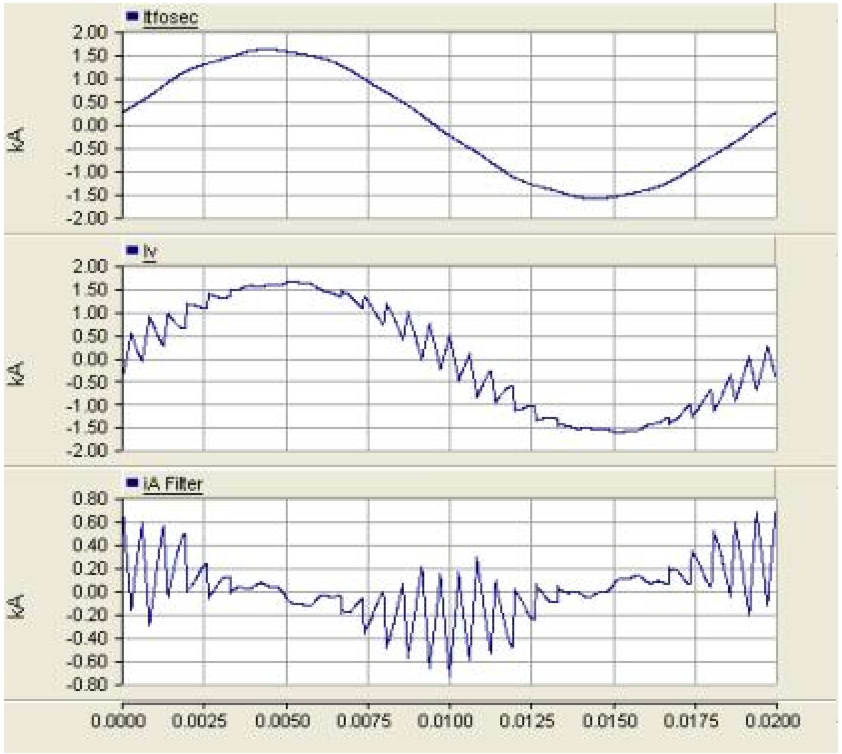
# VSC performance
## – Converter currents

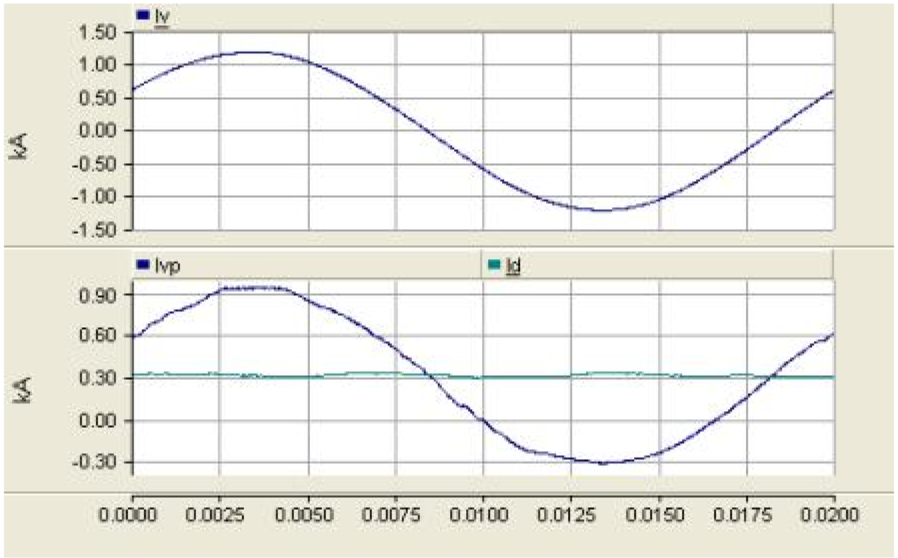



2-level

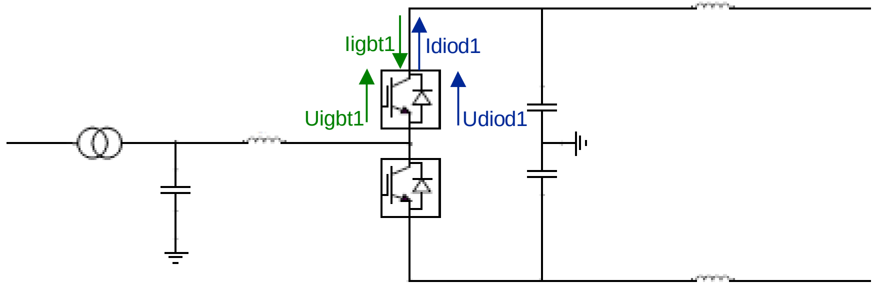
MMC

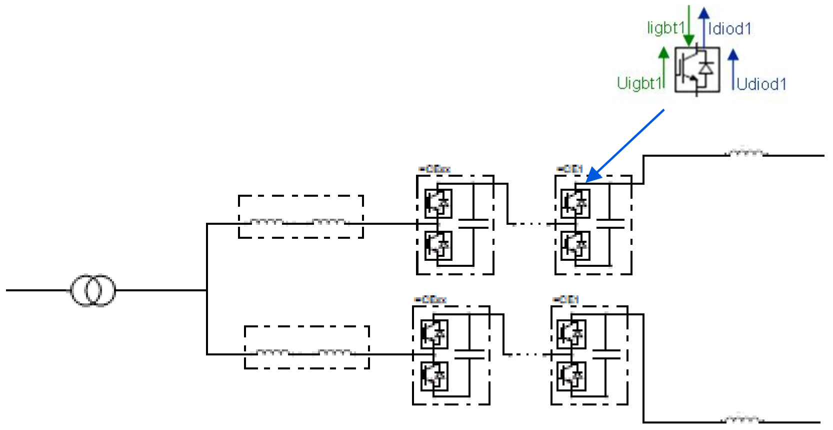



**No filters required**

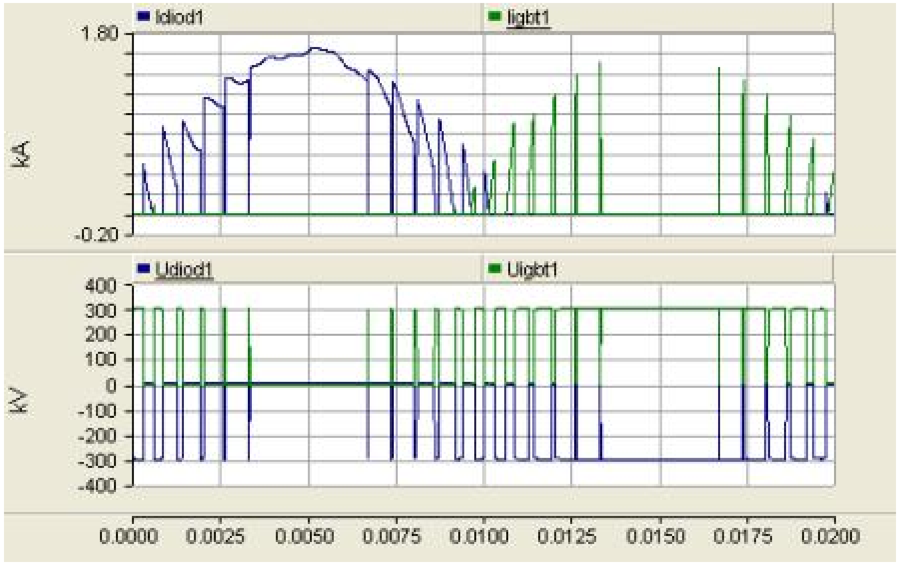
# VSC performance
## – Valve voltages and currents



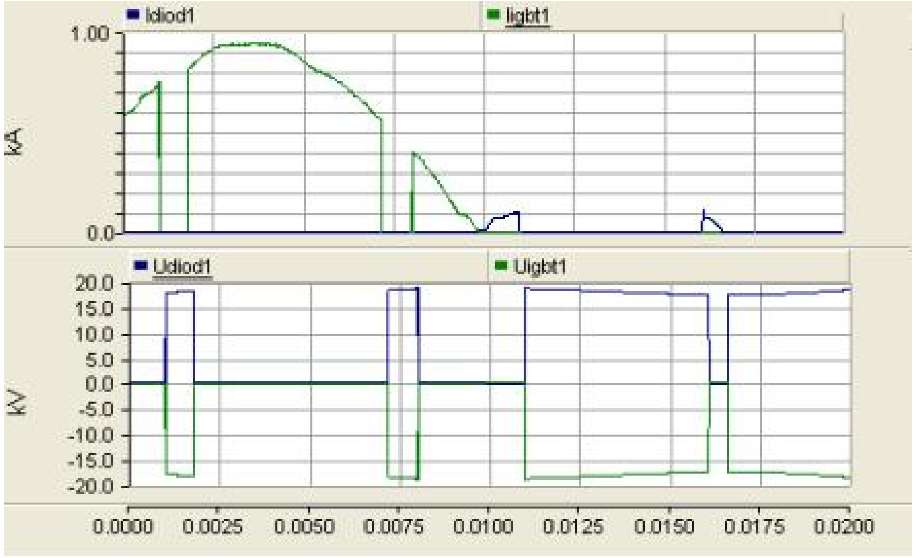




**Reduced losses**

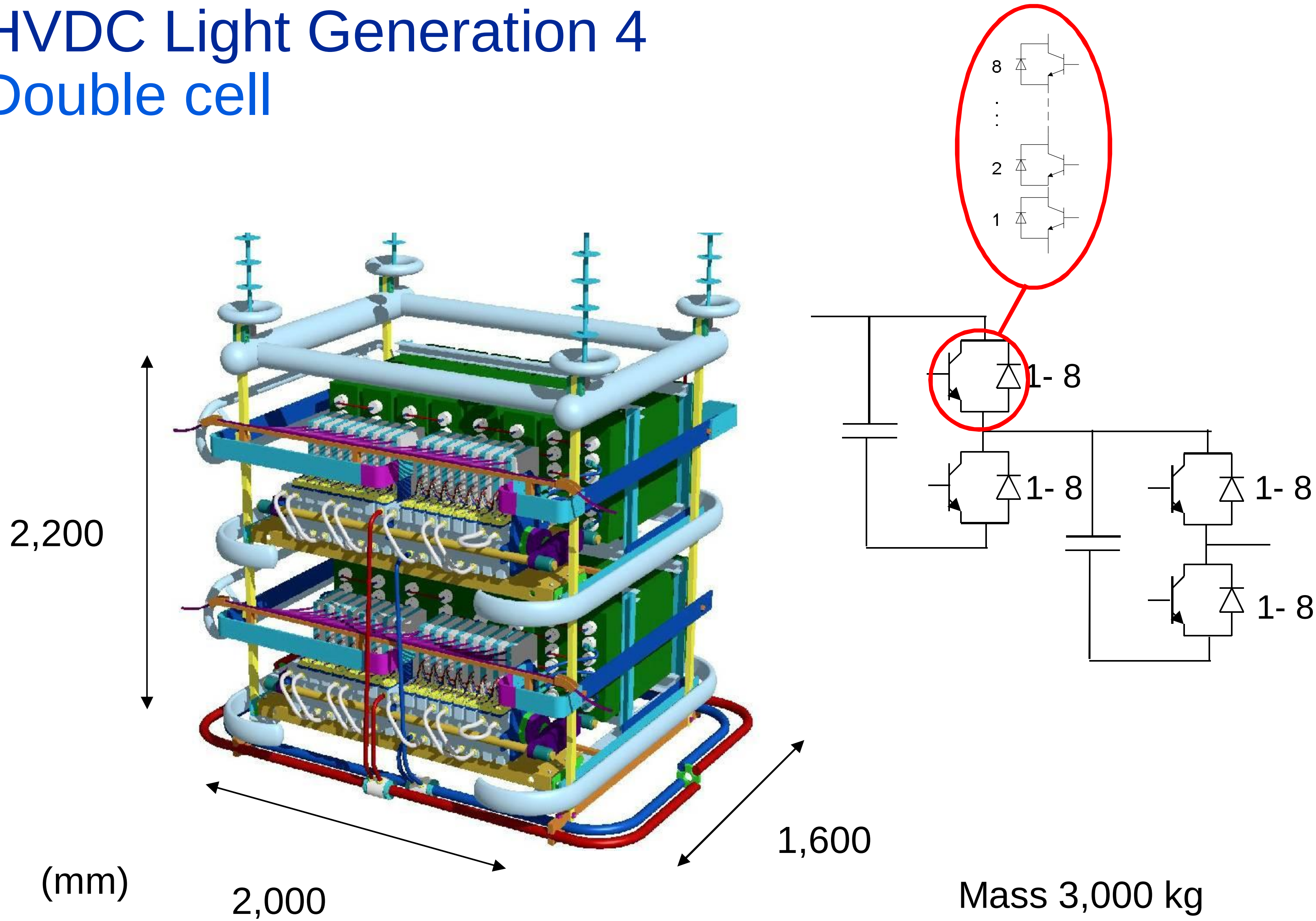
2-level




MMC

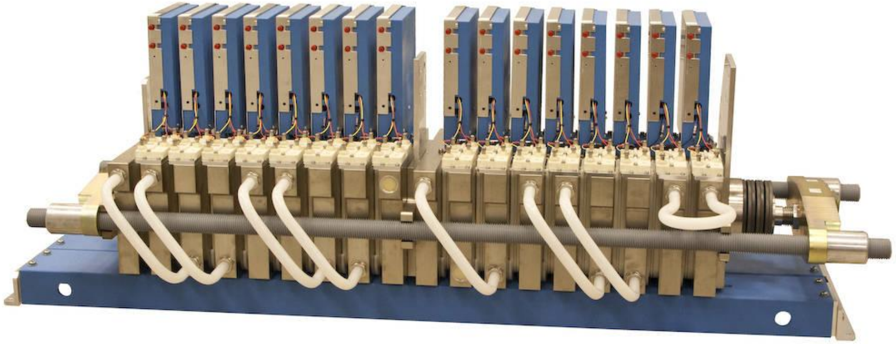


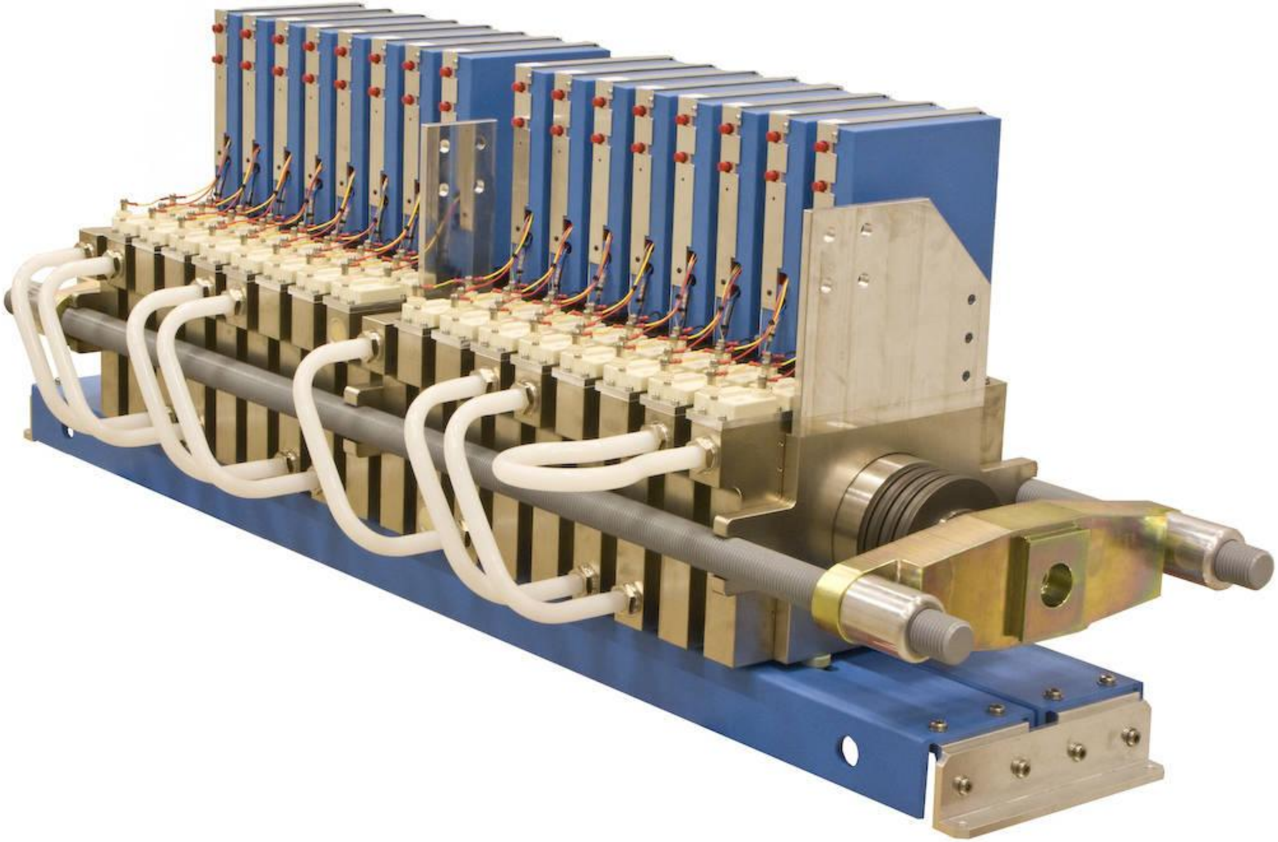
# HVDC Light Generation 4
## Double cell




Mass 3,000 kg

# IGBT Module

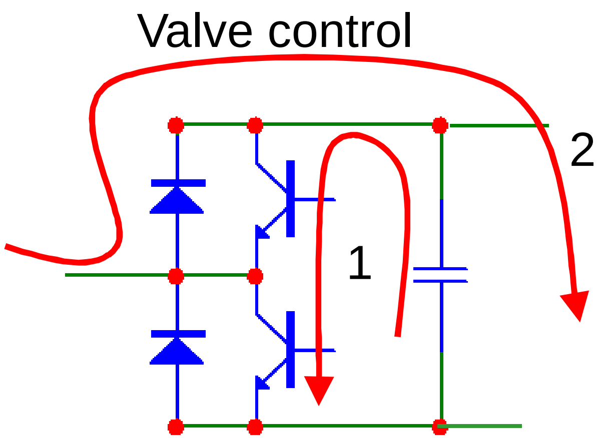


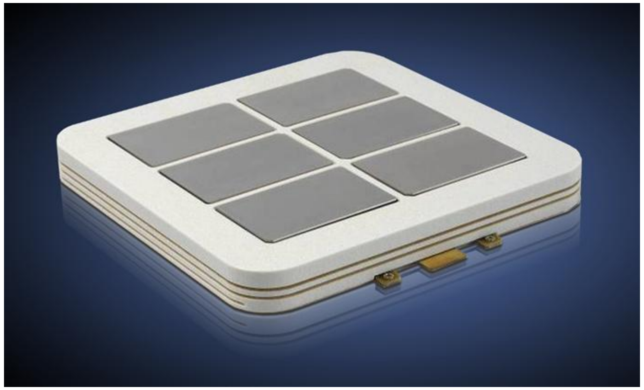


# IGBT inner structure

# HVDC Light - valve design
## Short Circuit Failure Mode (SCFM)

ABB press pack valve design



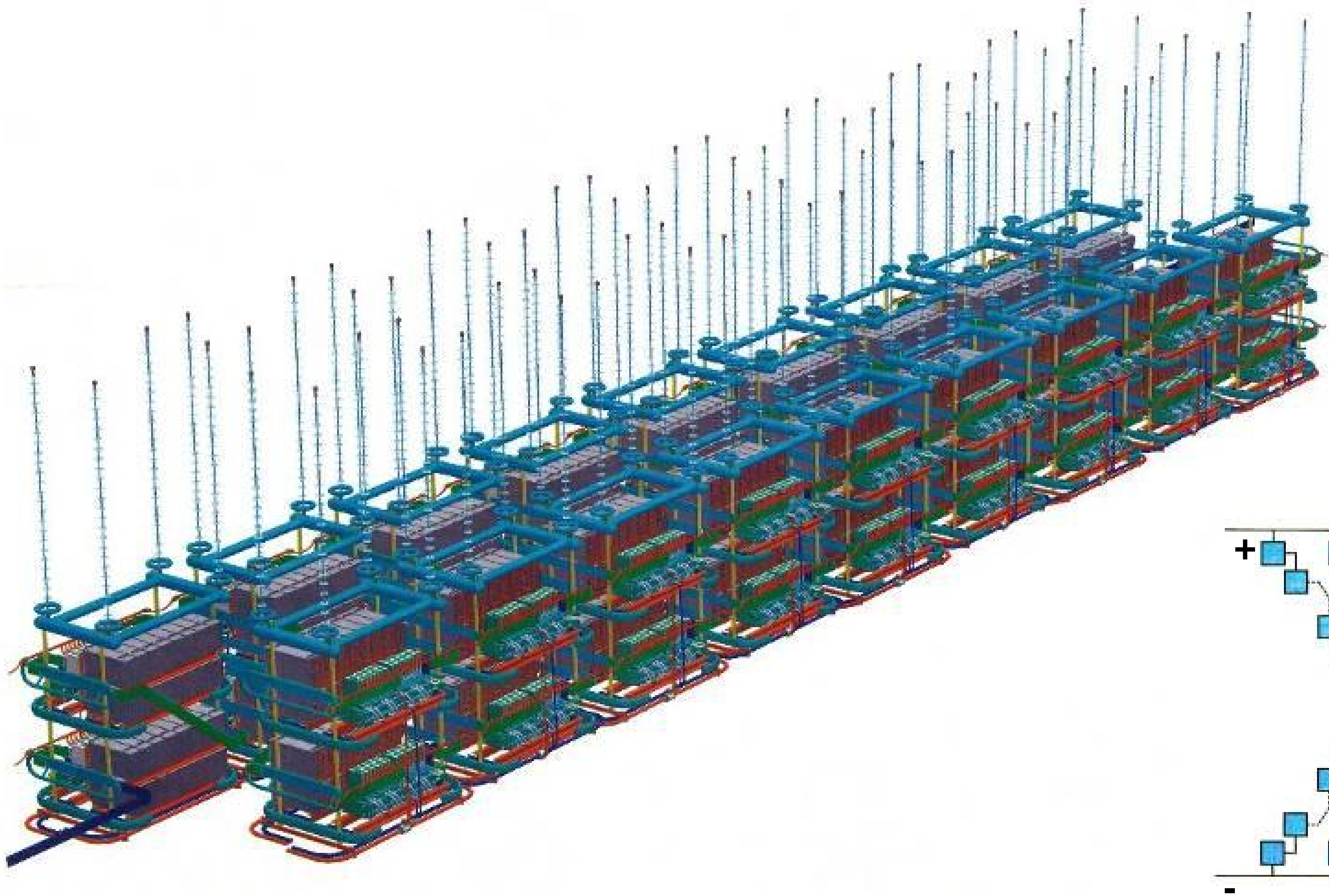



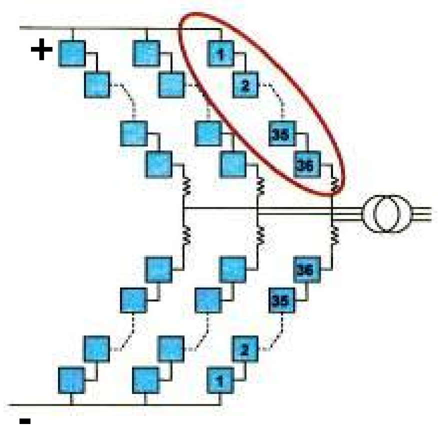
The press-pack IGBTs used by ABB are designed to withstand operation in a short-circuited state. Non press-pack devices that are not designed for transmission applications may fail uncontrollably (explosion resistant housing required).

4,5 kV, 2000 A

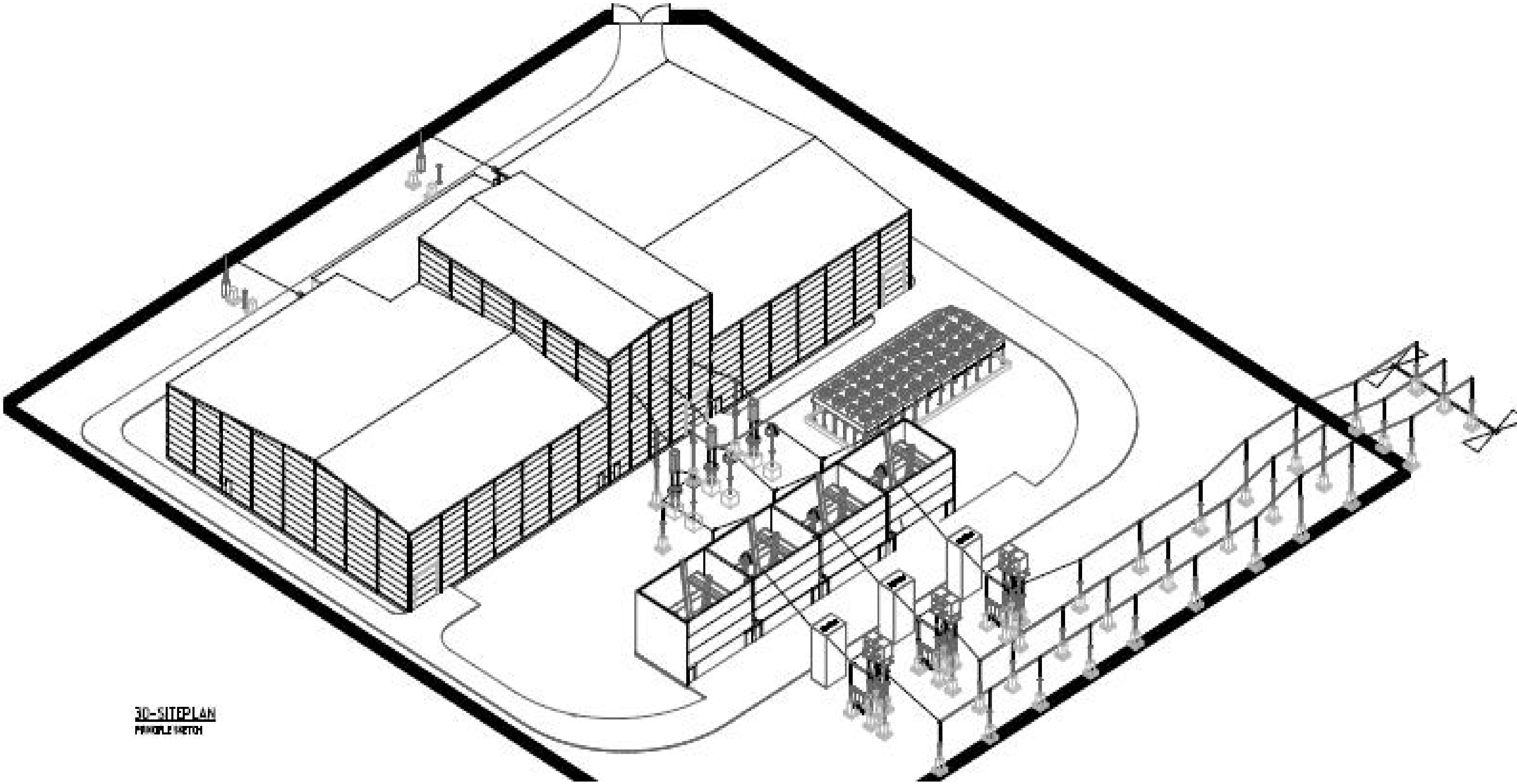
1. Safe short-circuit at single module fault
2. Press-pack IGBT designed to withstand line-to-line DC fault
3. Same short-circuit failure mode as the well-proven press pack for thyristors

# HVDC Light Generation 4
## Valve arm

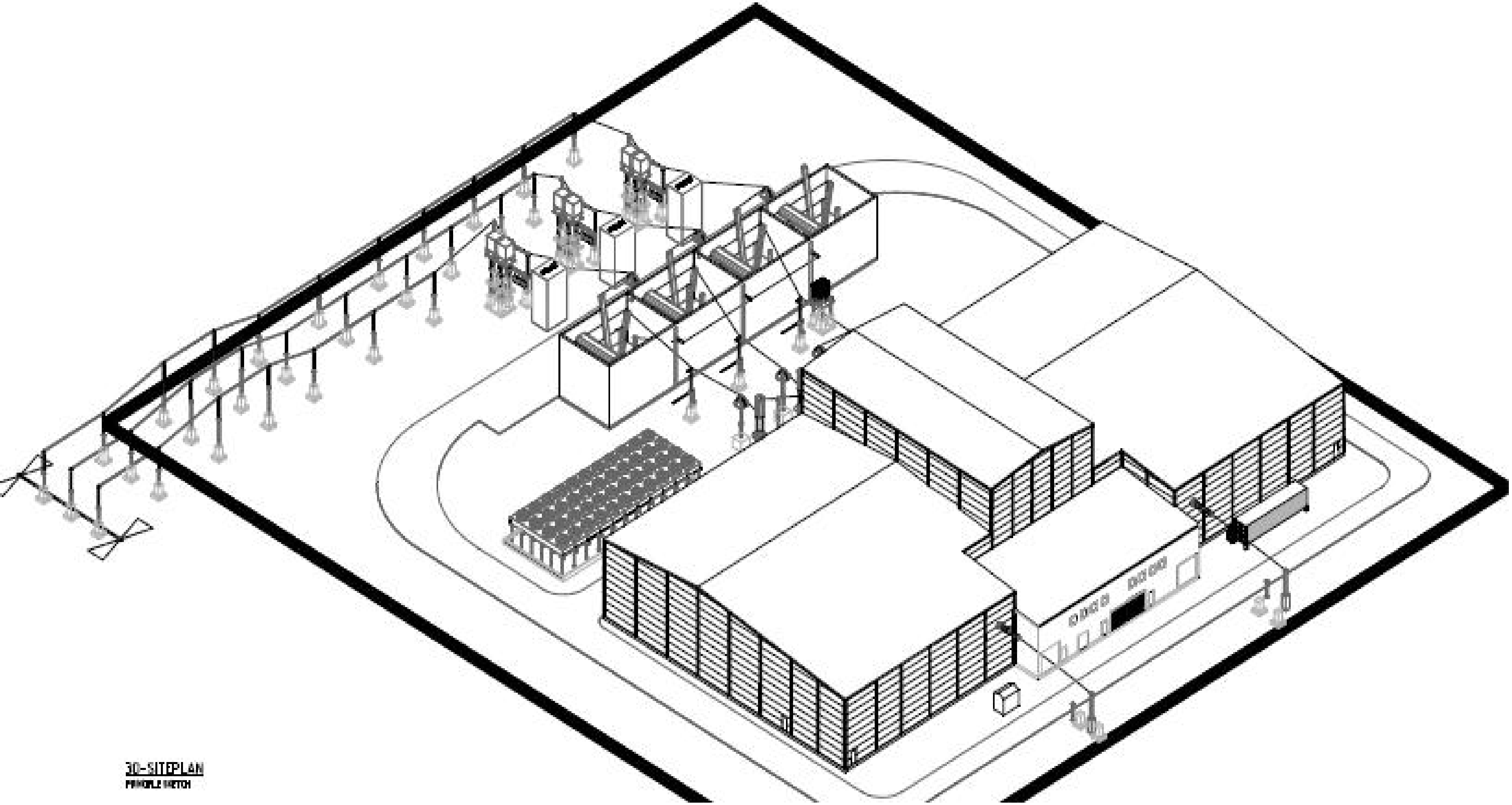




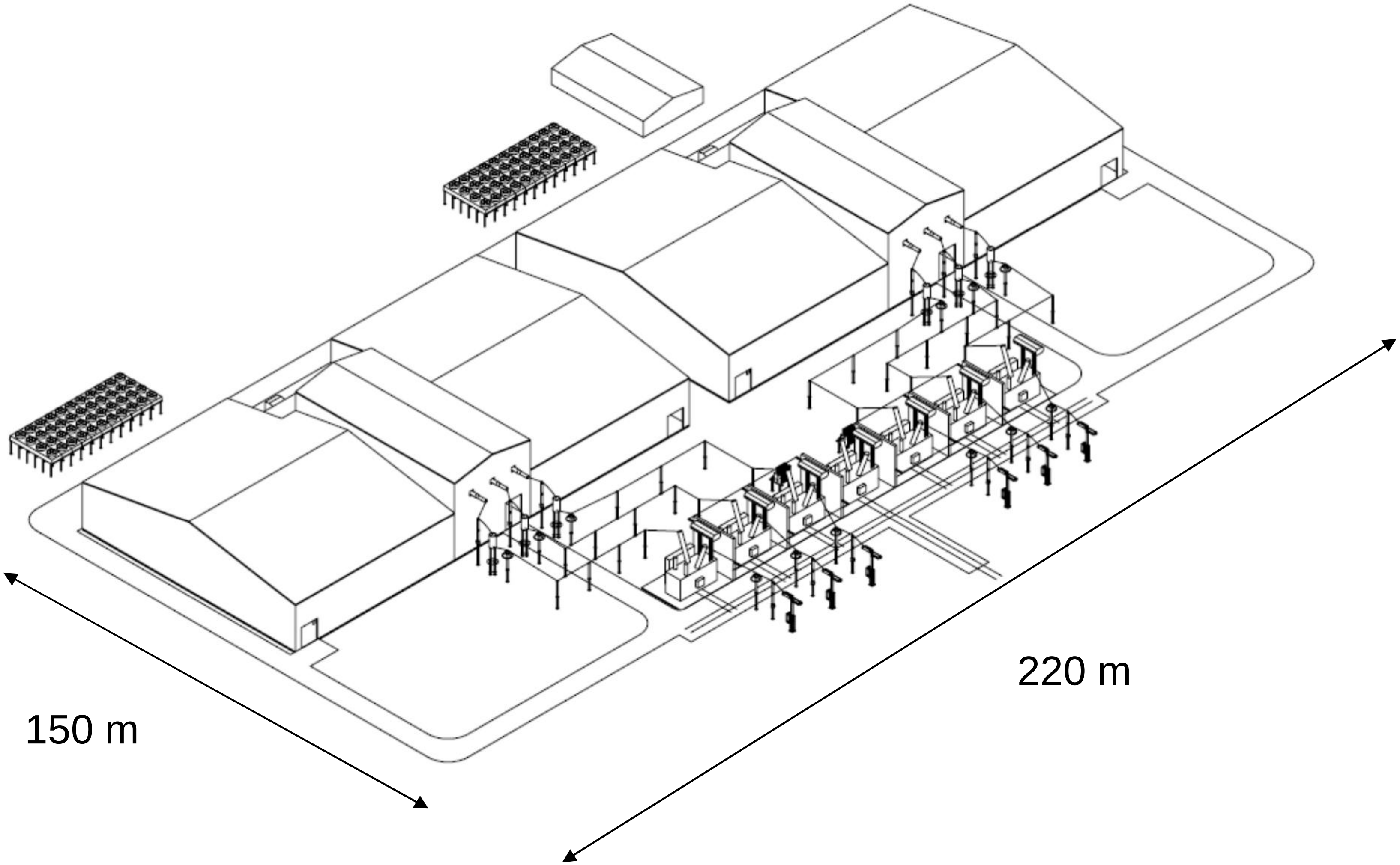
# Typical converter layout – 700 MW



# Typical converter layout – 700 MW

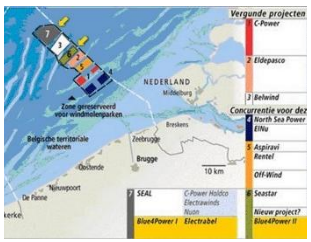


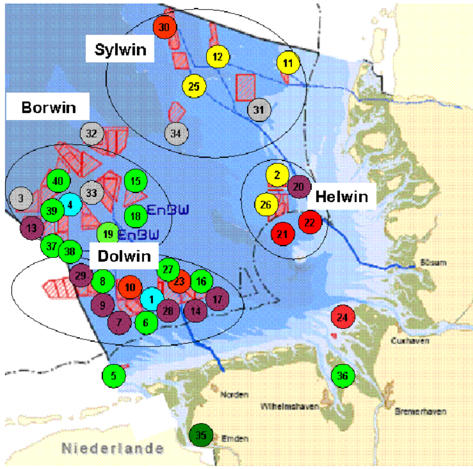
# HVDC Light Generation 4
## Station layout 2 x 1000 MW ± 320 kV

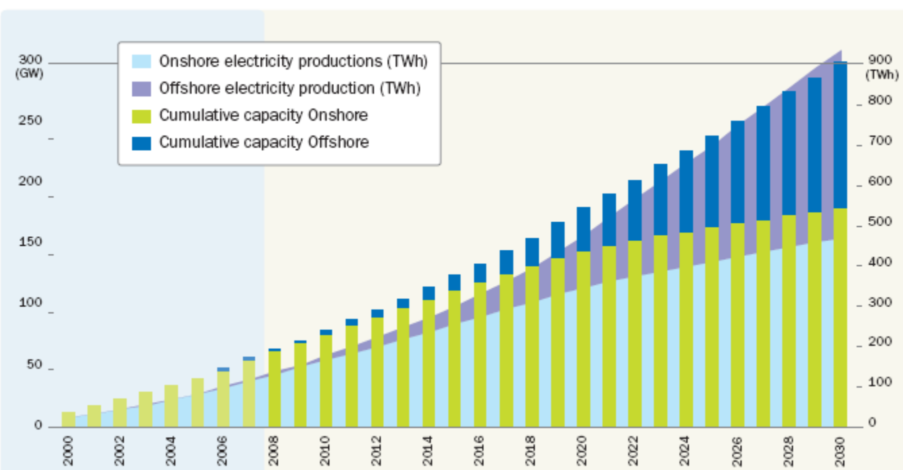


# VSC in the power grid Wind applications

# Offshore Wind Power Connectors
## Planned installations – Europe




Wind farms increase in size.

Most of them above 300 MW.

Larger farms will require massive delivery of AC-cables, both export cables and array cables

Longer distance from shore and increased size favors HVDC connectors (planned up to 1100 MW)

# Offshore Wind Power Connectors
## Technology, AC or DC-connectors

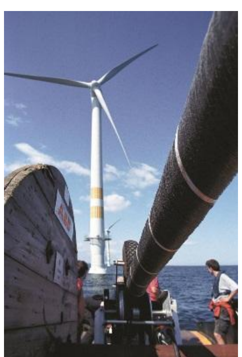
**AC**

**AC** is the “traditional” technology

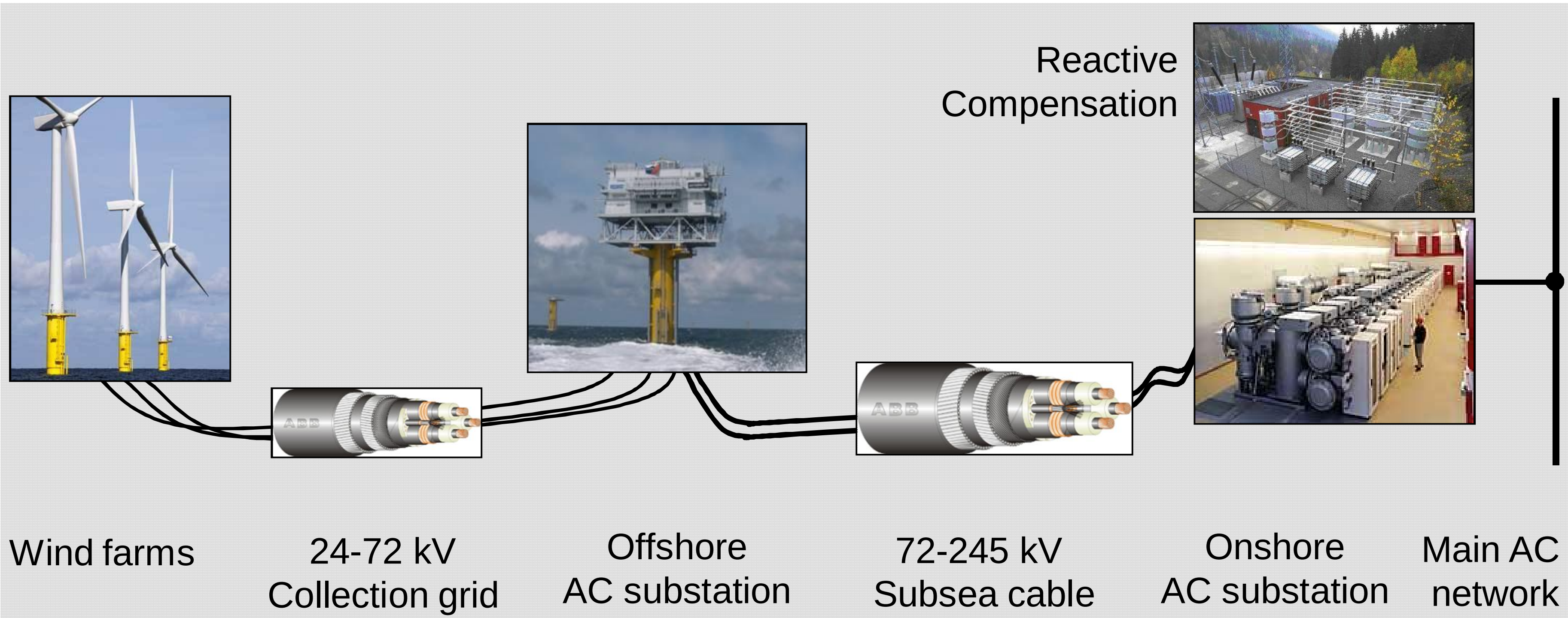
**DC**

**DC** (HVDC) is required for long distances (>50-100 km) or higher power ratings (>300 MW)

- Capex - reduced cable and cable installation cost.
- Opex - reduced power losses over long distances
- Capacity - several wind farms connected to a “plug at sea”
- Reliability - grid code compliance, power control, stability and black start capability
- Flexible - enables long distance underground connection to main AC grid
- Environmental - reduced subsea cable trenching, no magnetical fields, no oil in XLPE cable, no overhead lines



# Overview
## Offshore AC wind power connectors

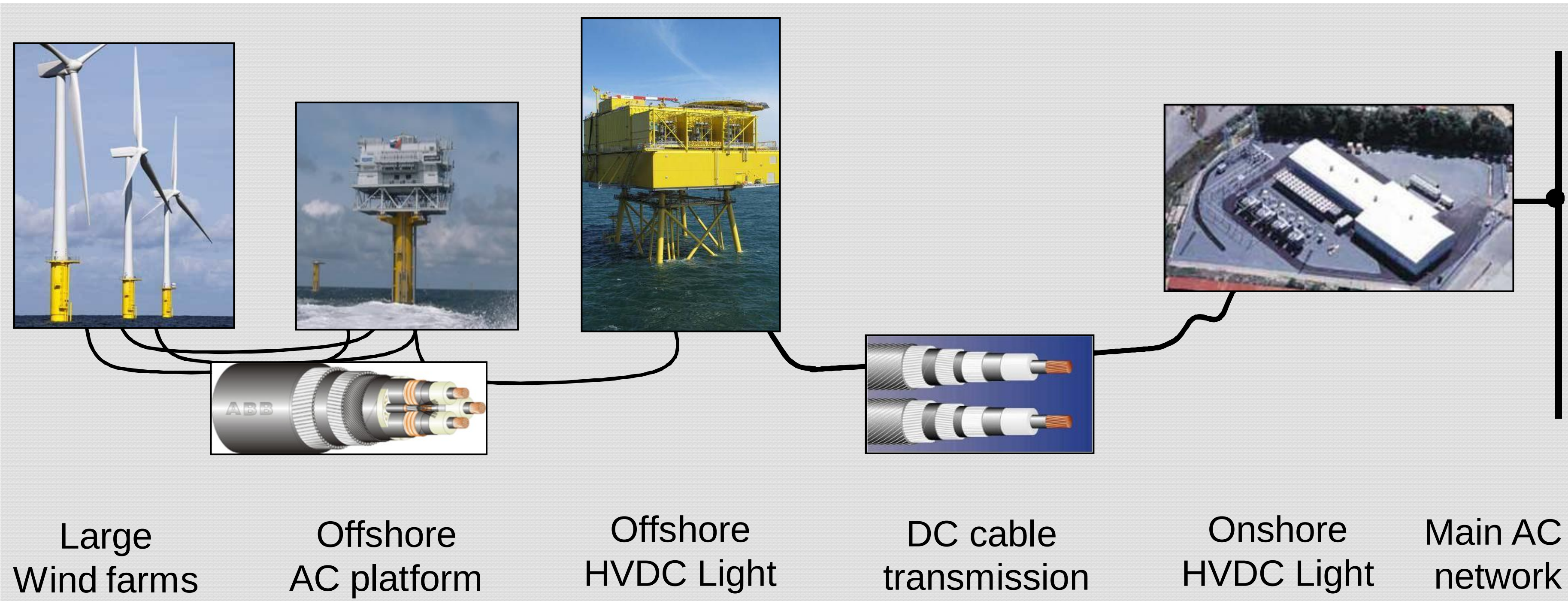



50 – 300 MW: 72-150 kV
200 – 500 MW: 150-245 kV

Traditional AC-substations located off-shore
Key issue is to fulfill grid code compliance

(Longest AC subsea cable is the Isle of Man connector – 104 km, 90kV / 40 MW)

# Overview
## Offshore HVDC wind power connectors




100 – 300 MW: ± 80 kV HVDC Light (VSC)
300 – 500 MW: ± 150 kV HVDC Light
500 – 1000 MW: ± 320 kV HVDC Light

VSC technology for compact solutions. ABB with 10 years experience ( 13 references)

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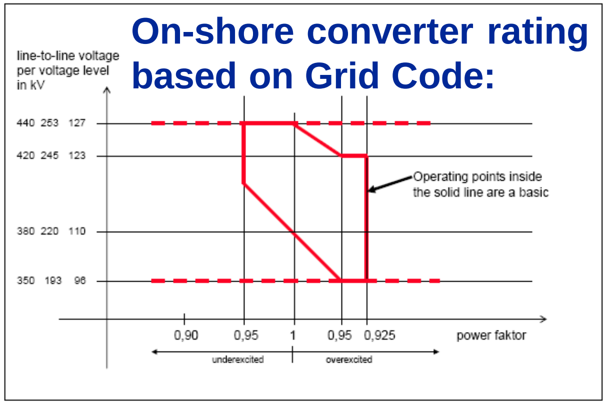
# Overview, 400 MW HVDC Light System, BorWin 1

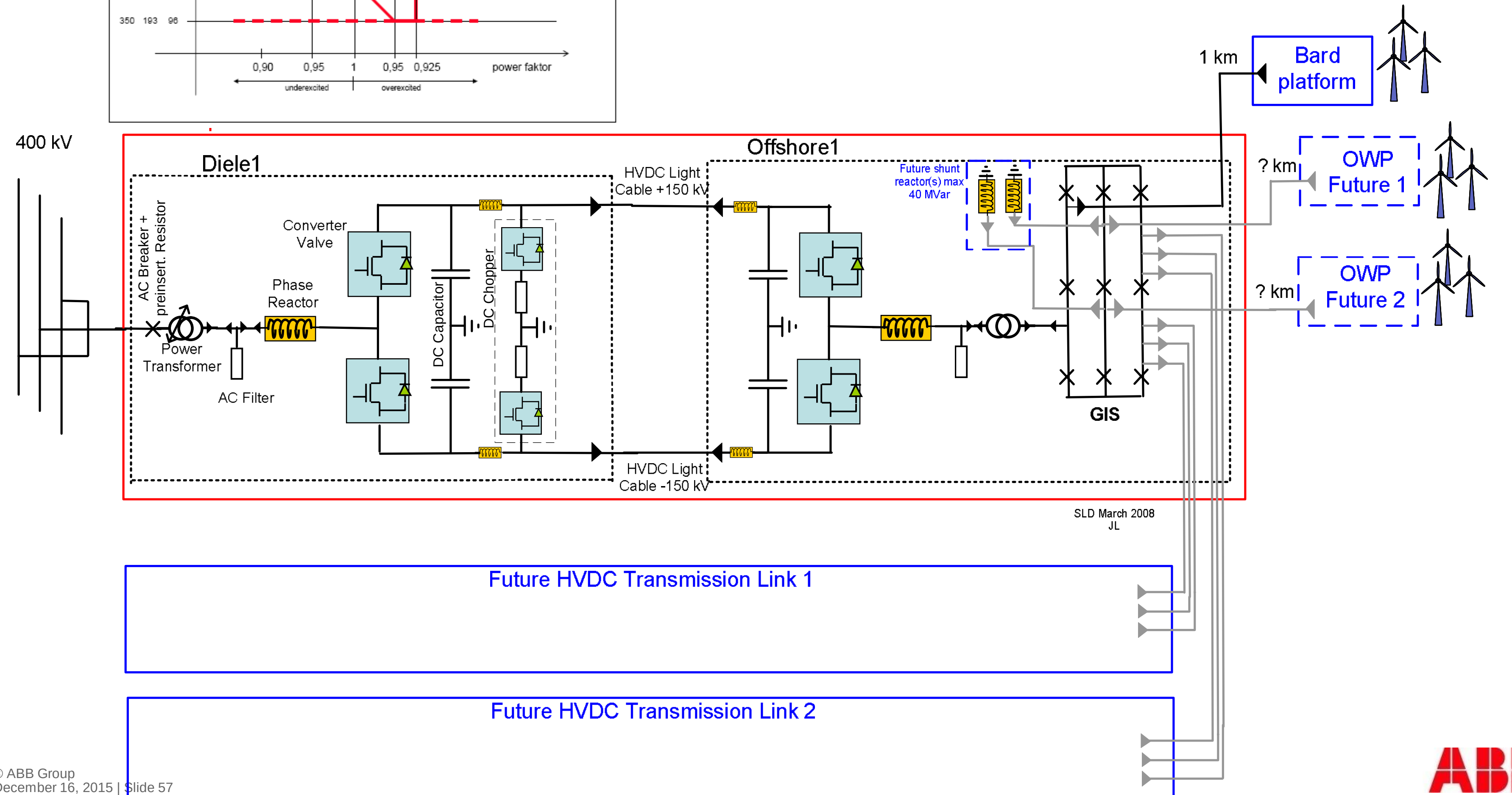



**Offshore rating conditions**

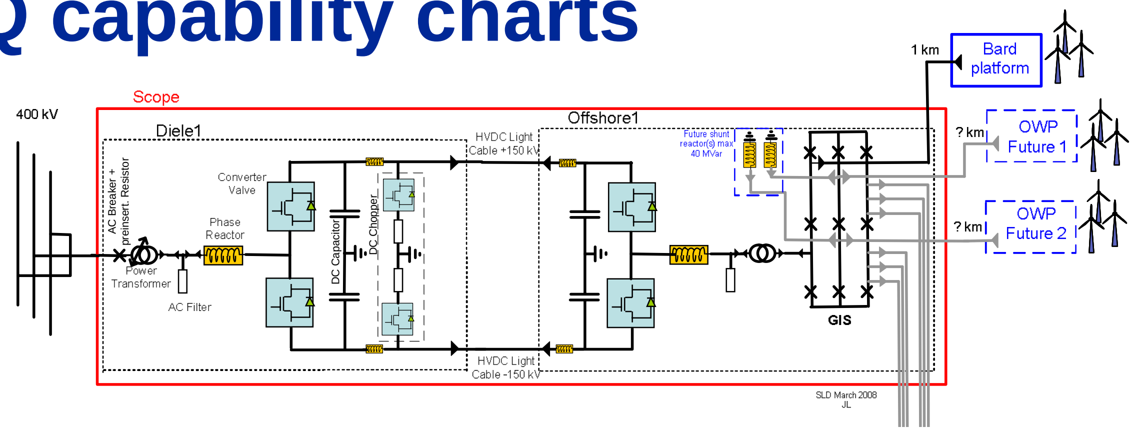
Wind park Q

Cable grid Q

No tap-changer needed through converter ac-voltage control



# Main Circuit – PQ capability charts

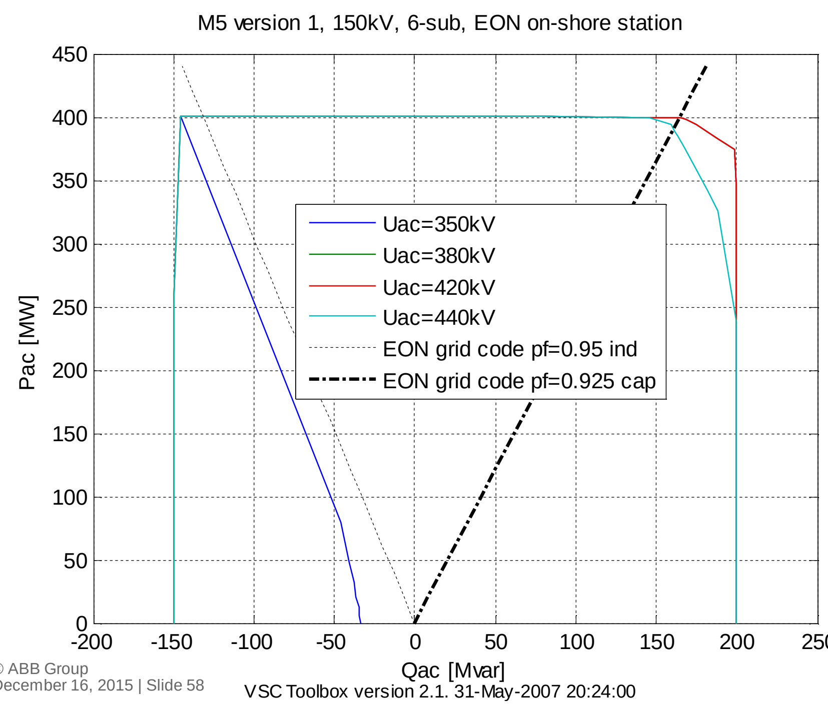


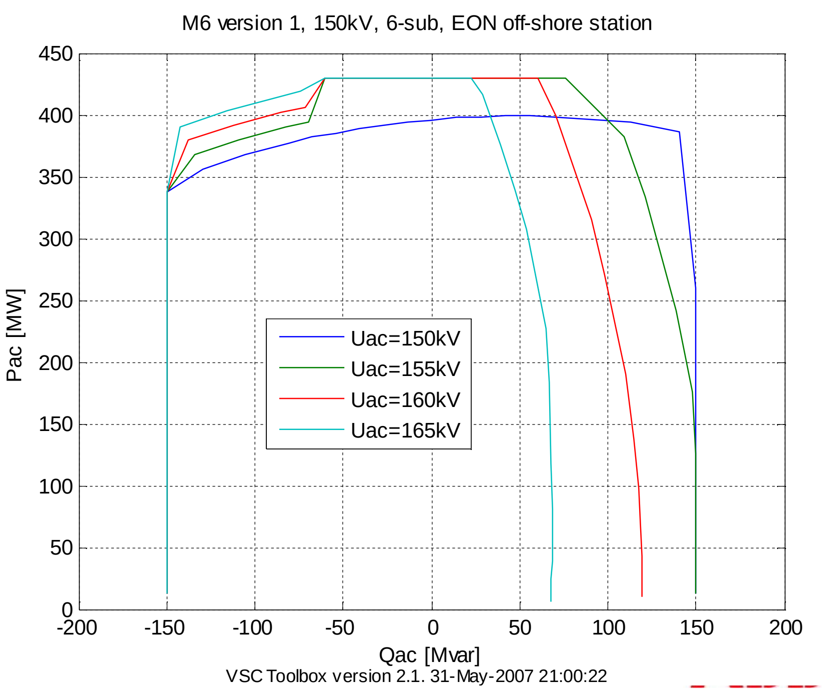

**Onshore**

- 350-420 kV

**Offshore**

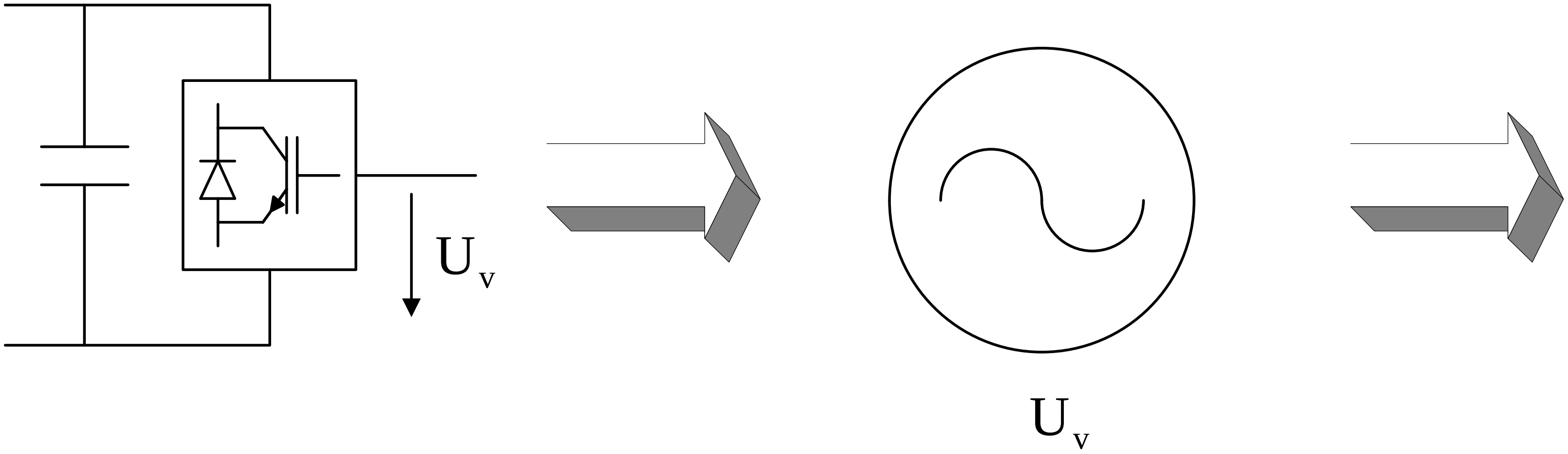
- 155 -165 kV



# Windpower Control Aspects

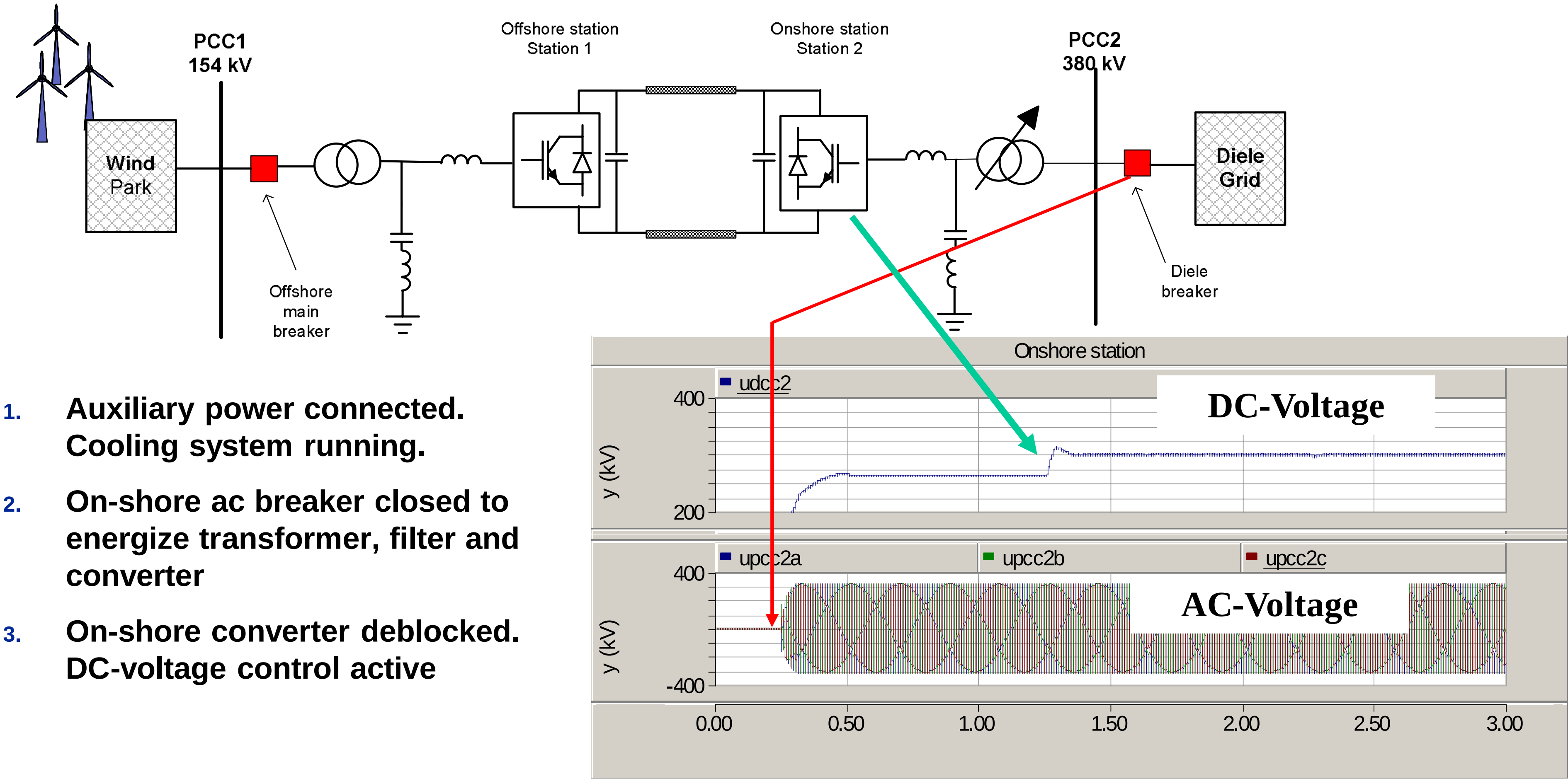
# Basic Control Principle.
# Voltage Source Converter




**adjustable**

- amplitude
- phase angle
- frequency

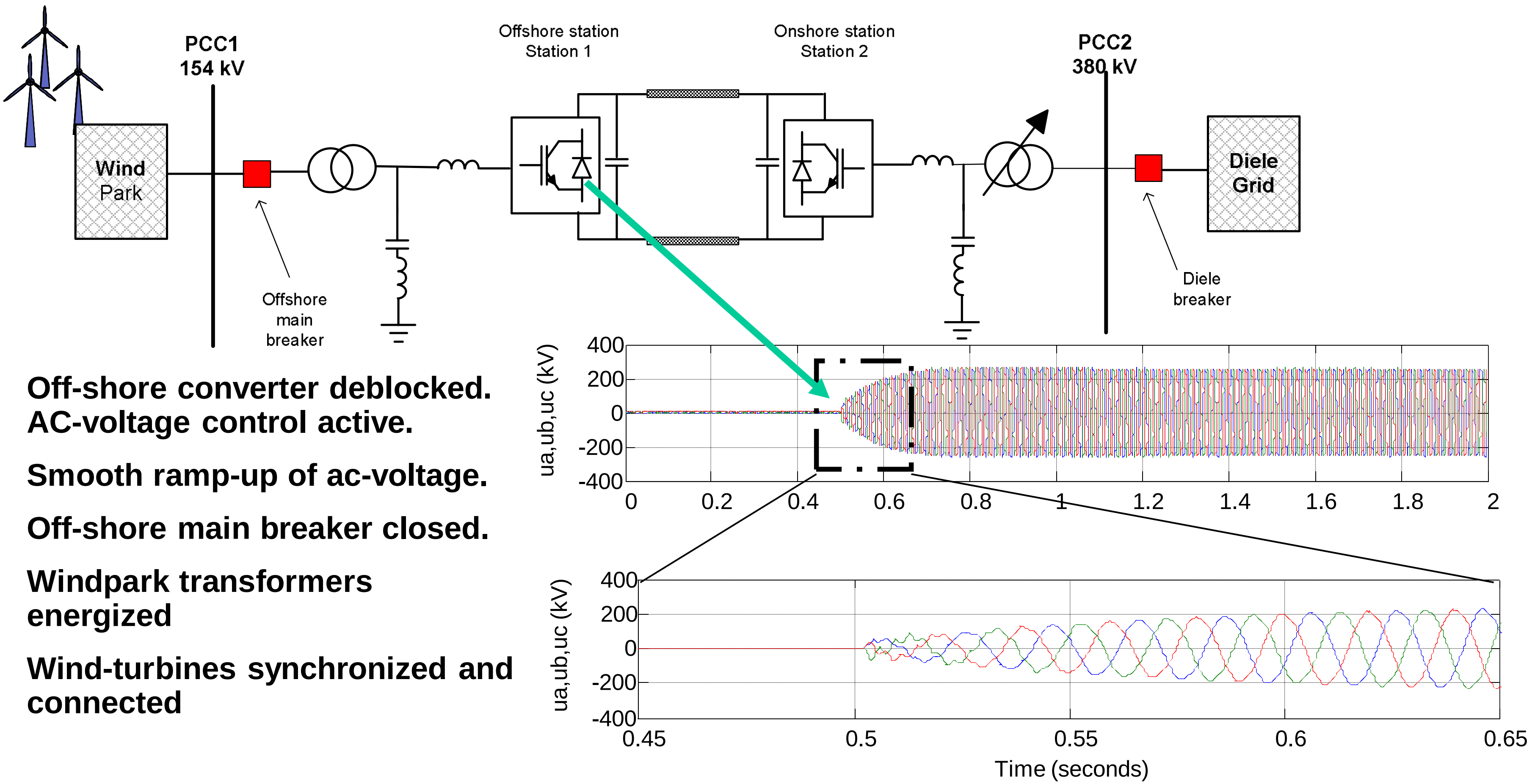
# VSC HVDC basic principles
## Converter energization




1. **Auxiliary power connected. Cooling system running.**
2. **On-shore ac breaker closed to energize transformer, filter and converter**
3. **On-shore converter deblocked. DC-voltage control active**

# VSC HVDC basic principles

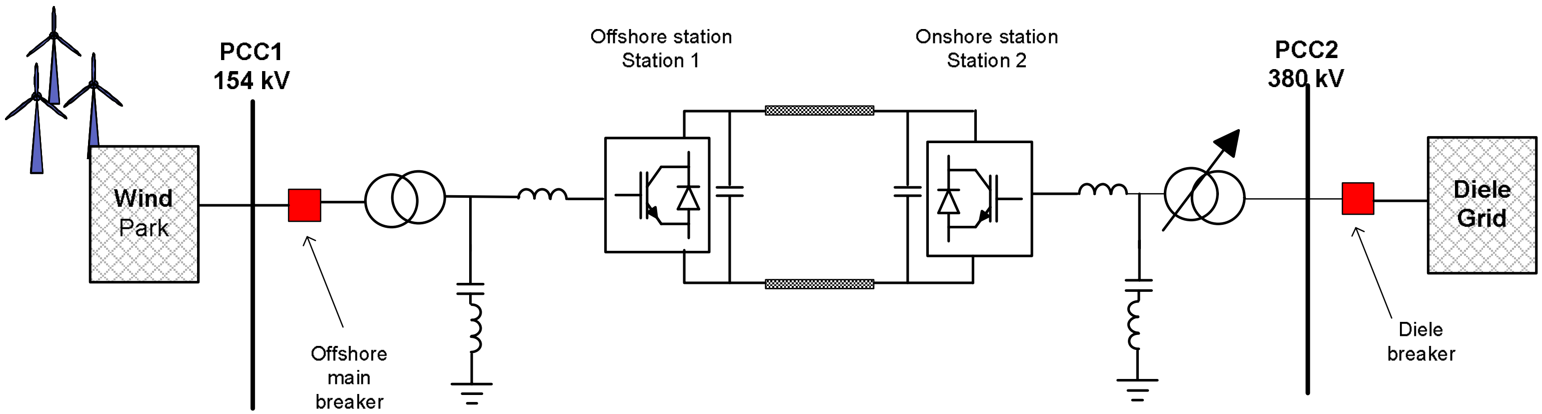
## Off-shore grid energization



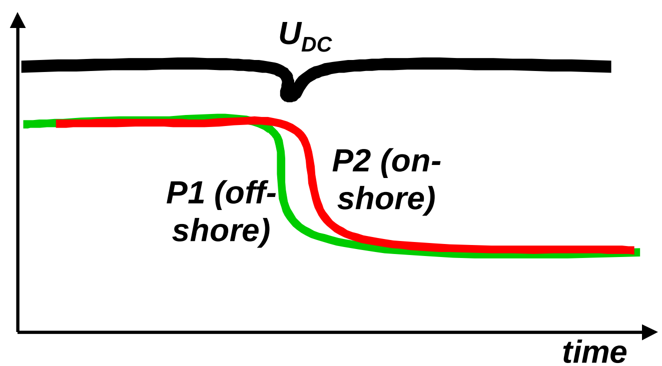

1. **Off-shore converter deblocked. AC-voltage control active.**
2. **Smooth ramp-up of ac-voltage.**
3. **Off-shore main breaker closed.**
4. **Windpark transformers energized**
5. **Wind-turbines synchronized and connected**

# VSC HVDC basic principles

## Normal operation

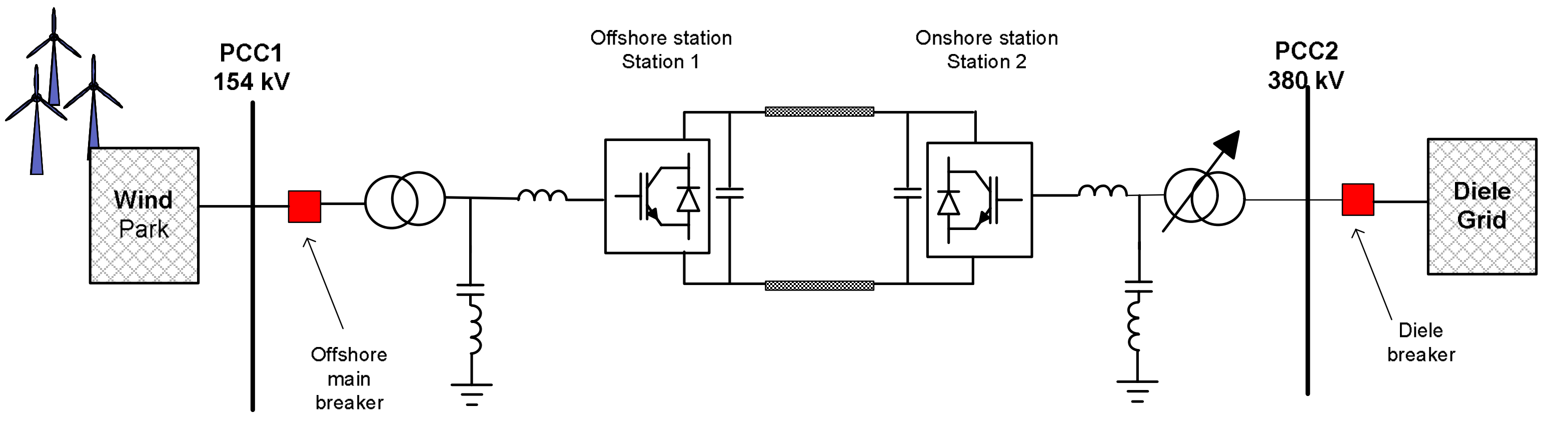



1. **Off-shore converter in voltage and frequency control.**
2. **On-shore converter in dc-voltage and reactive power control.**
3. **Windpark power reduction,**
4. **Off-shore converter power (P1) drops, since ac-voltage control results in power tracking**
5. **Instantaneous dc-power unbalance (P1-P2) < 0 $\Rightarrow$ dc-voltage drop**
6. **On-shore dc-voltage control quickly reduces power (P2) to restore nominal dc-voltage and power balance.**

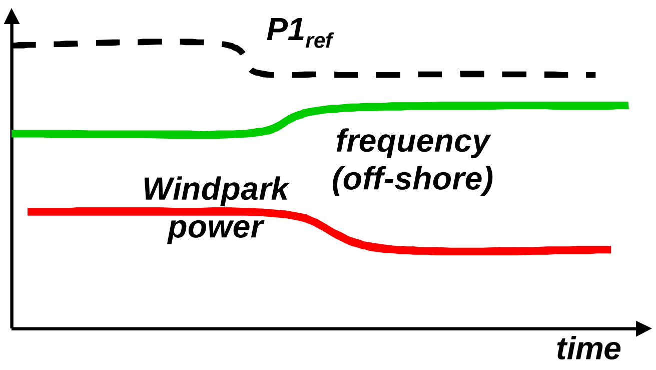


# VSC HVDC basic principles

## Automatic windpower dispatch

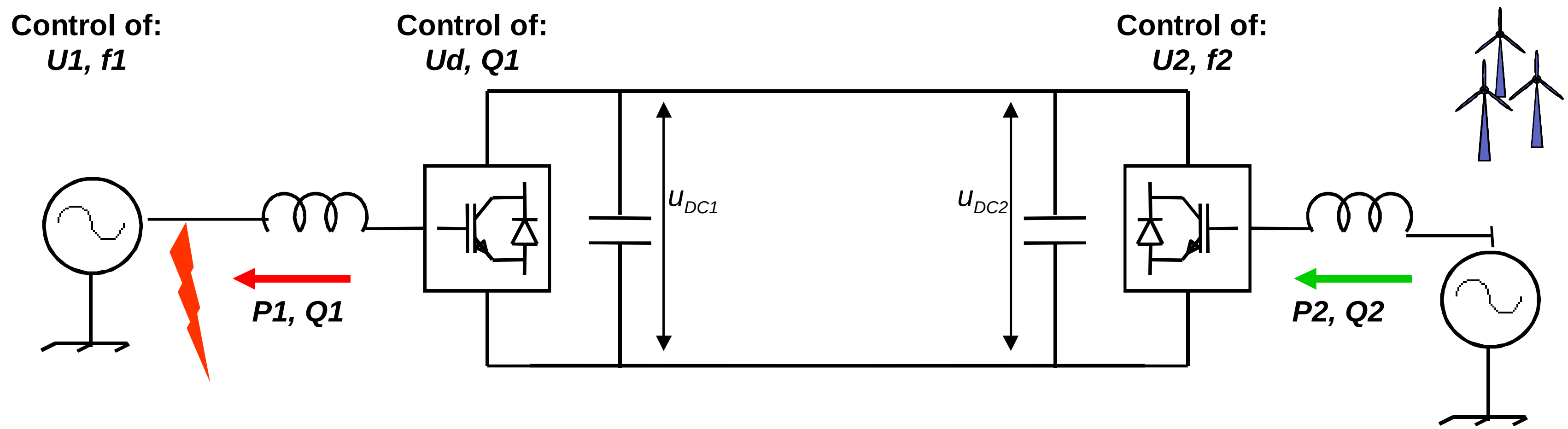


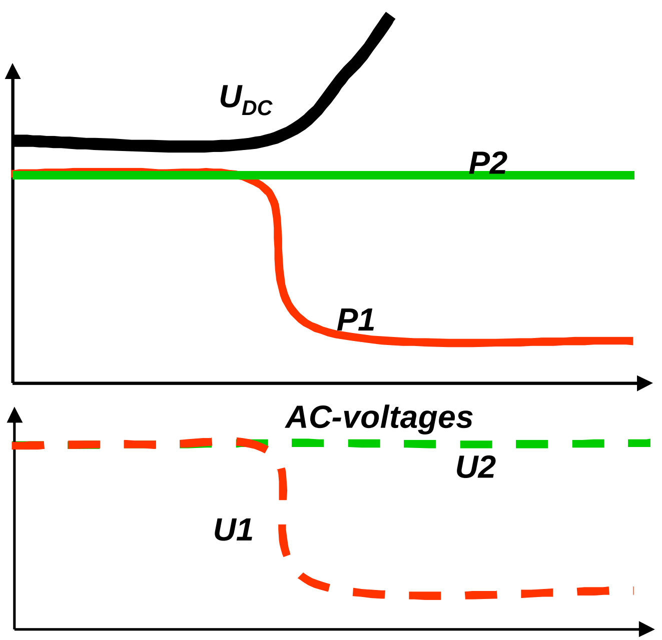

1. **Off-shore converter in voltage and frequency control.**
2. **Power reduction ordered by on-shore grid operator (or frequency control)**
3. **Off-shore converter increases off-shore grid frequency**
4. **Wind turbine control responds to the frequency increase by power reduction (98% per Hz)**
5. **Off-shore converter power (P1) drops, since ac-voltage control results in power tracking**
6. **On-shore dc-voltage control quickly reduces P2 to restore nominal dc-voltage and power balance.**



# VSC HVDC basic principles

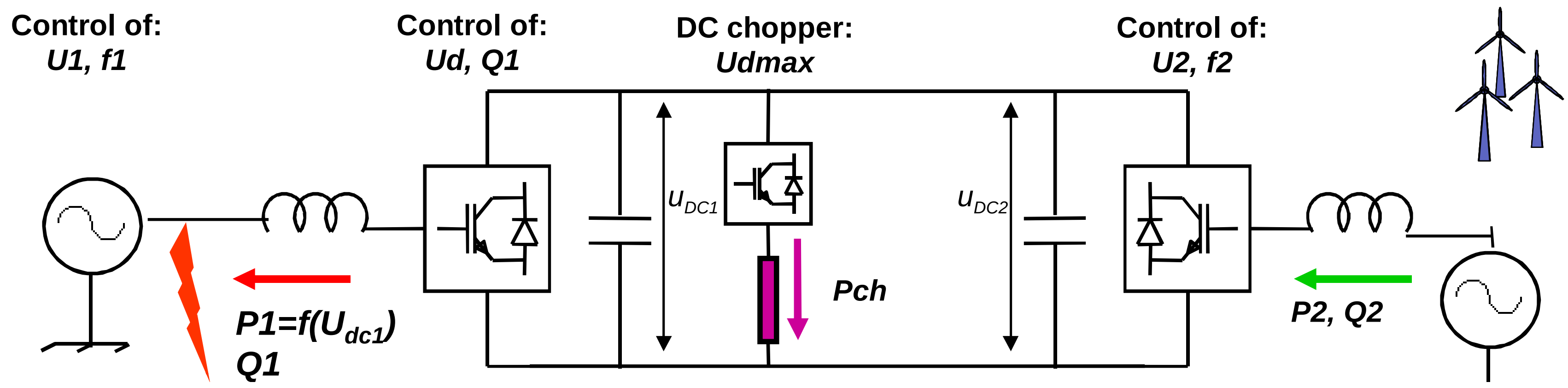
## Isolated generation, grid fault without fault ride through



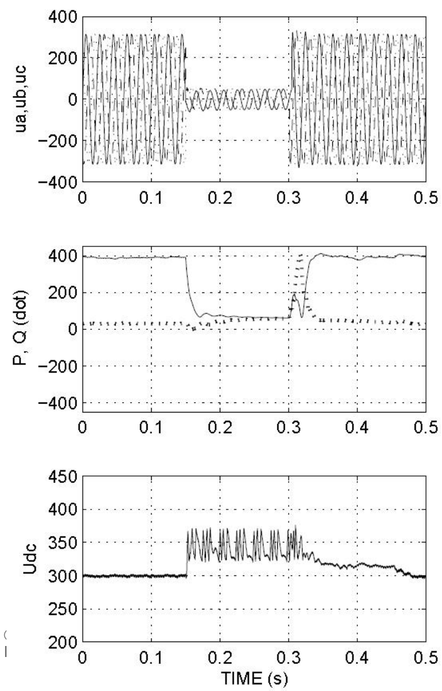



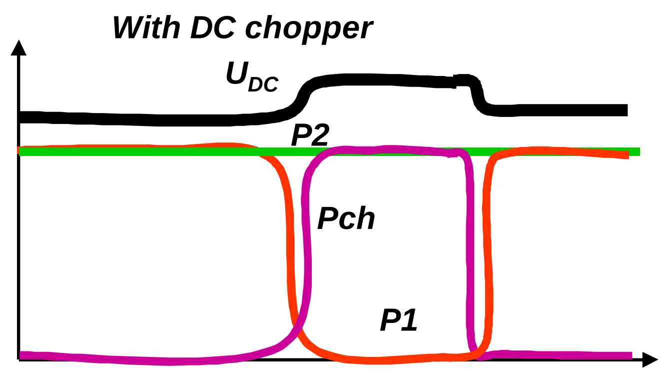
# VSC HVDC basic principles

## Fault ride through with chopper

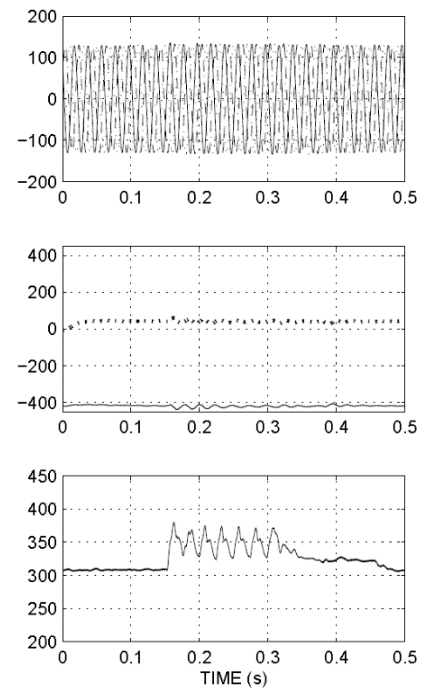



**On-shore**




**Off-shore**




- **DC-chopper decouples windpark from on-shore grid**
- **Minimum impact on wind production during on-shore grid faults**

# Chopper resistors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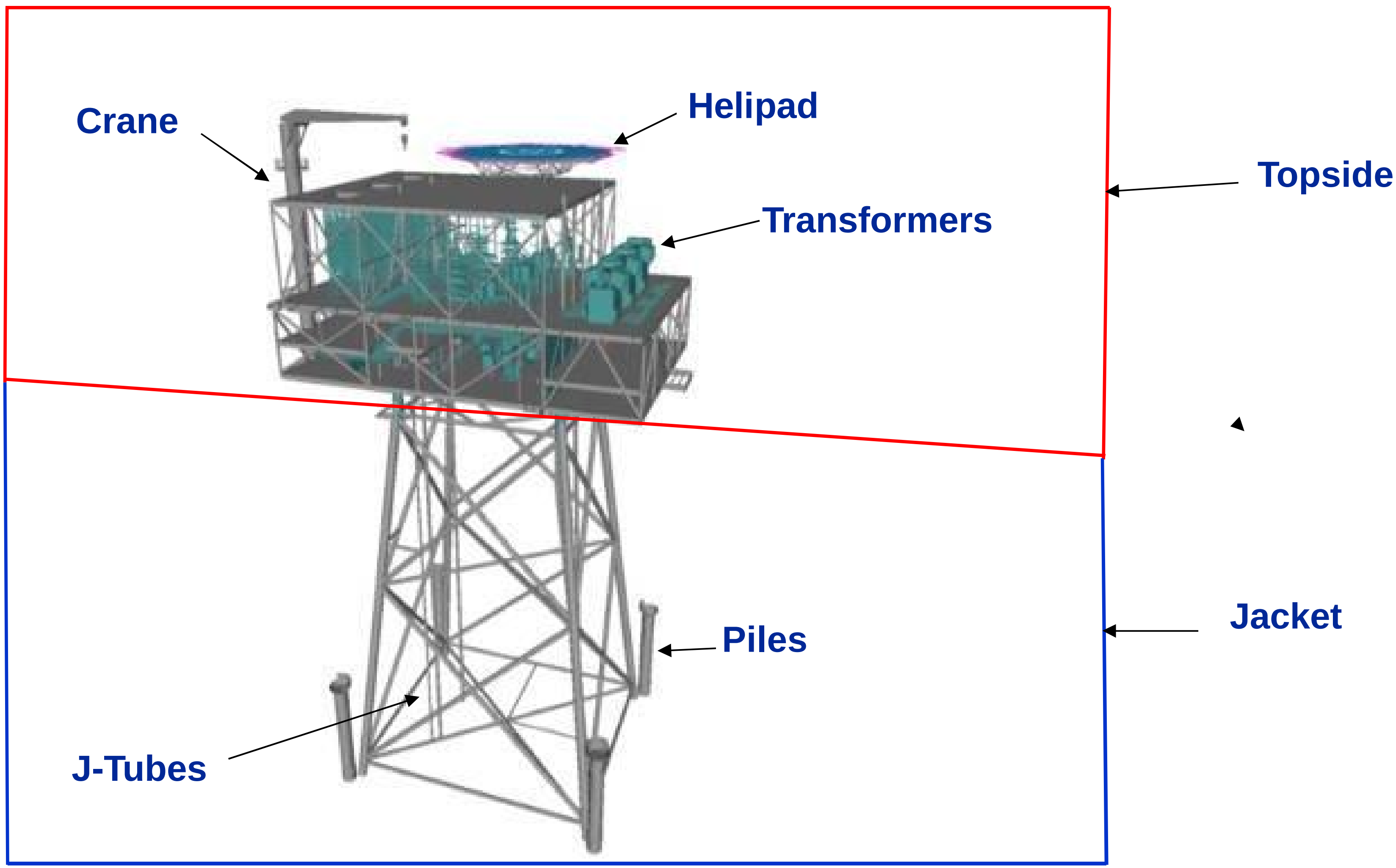
Document id

# Example of offshore platform layout



# Jacket

# Topside




Slide 70
Document ID

# Transport of Jacket + Topside

# Jacket installation

# Topside placed on jacket

# Final platform

# Borwin 1, Dolwin 1 & 2 Offshore Point-to-Point

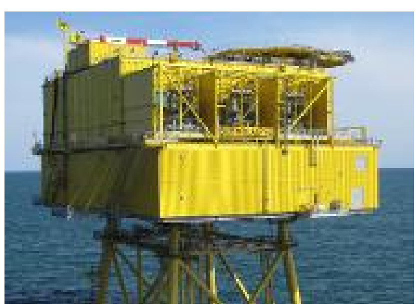
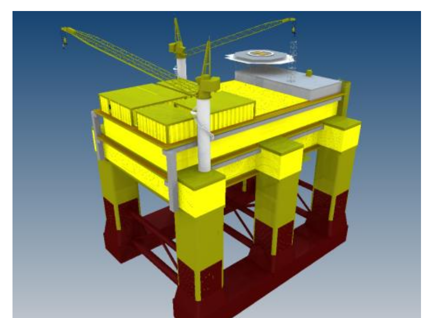
## Why HVDC Light: Length of land and sea cable

| Main data | Borwin 1 | Dolwin 1 | Dolwin 2 |
|---|---|---|---|
| In operation: | 2010 | 2013 | 2015 |
| Power rating: | 400 MW | 800 MW | 900 MW |
| AC Voltage Platform:<br>Onshore | 170 kV<br>380 kV | 155 kV<br>380 kV | 155 kV<br>380 kV |
| DC Voltage: | ±150 kV | ±320 kV | ±320 kV |
| DC underground cable:<br>DC submarine cable: | 2 x 75 km<br>2 x 125 km | 2 x 75 km<br>2 x 90 km | 2 x 45 km<br>2 x 90 km |

DOLWIN1: efficiently integrating power from offshore wind

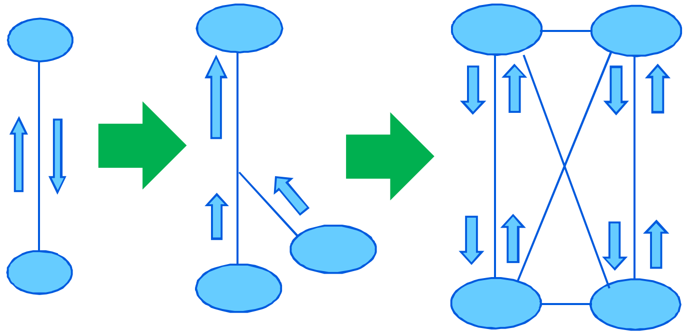
DOLWIN alpha platform loadout

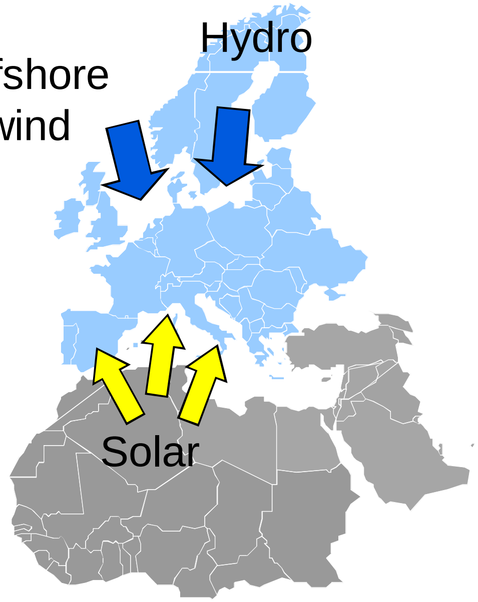


# VSC in the power grid DC-grid applications

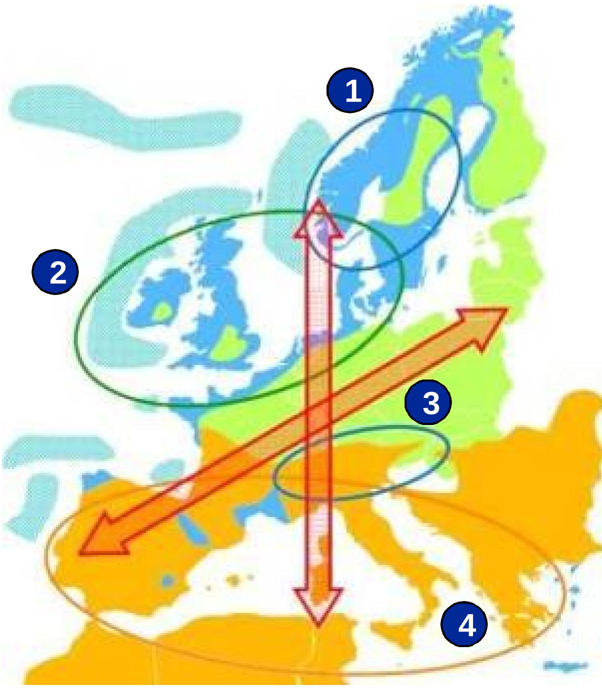
# HVDC Grids – Why?
## Regional to continental HVDC Grids

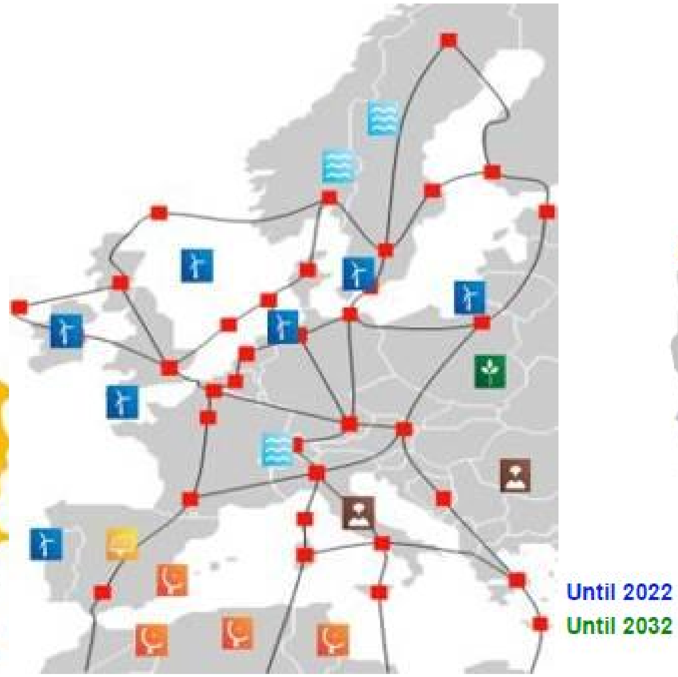


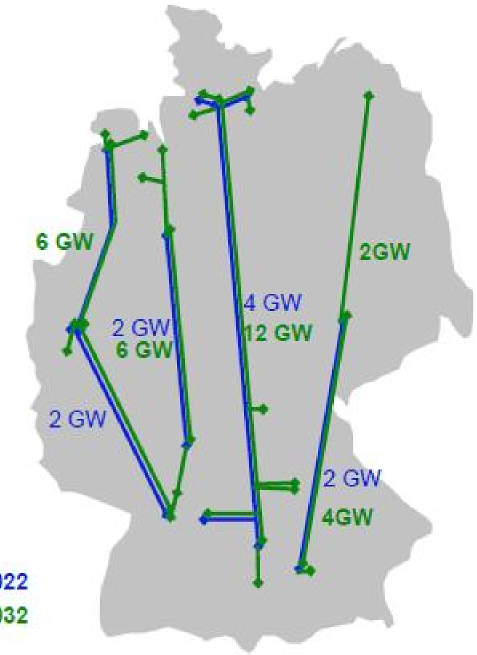



- Why HVDC Grids *vs* HVDC single links
  - Only relevant offshore solution (DC-cables)
  - Loss reduction
  - Increased power capacity & availability combined with the AC-system
  - Less visual impact & easier permitting (DC-cables)
- Why now:
  - Offshore wind, remote solar, grid constraints
  - HVDC Light systems and components mature
- Challenges:
  - DC-fault clearing strategies
  - DC overhead lines
  - Regulatory framework

# The evolution of grids: Connect remote renewables
## Europe & Germany are planning large scale VSC-HVDC




Source: DG Energy, European Commission

### European Visions

1. Hydro power & pump storage -Scandinavia
2. >50 GW wind power in North Sea and Baltic Sea
3. Hydro power & pump storage plants - Alps
4. Solar power in S.Europe, N.Africa & Middle East

### Germany (draft grid master plan)

- Alternatives to nuclear-distributed generation
- Role of offshore wind / other renewables
- Political commitment
- Investment demand and conditions
- Need to strengthen existing grid



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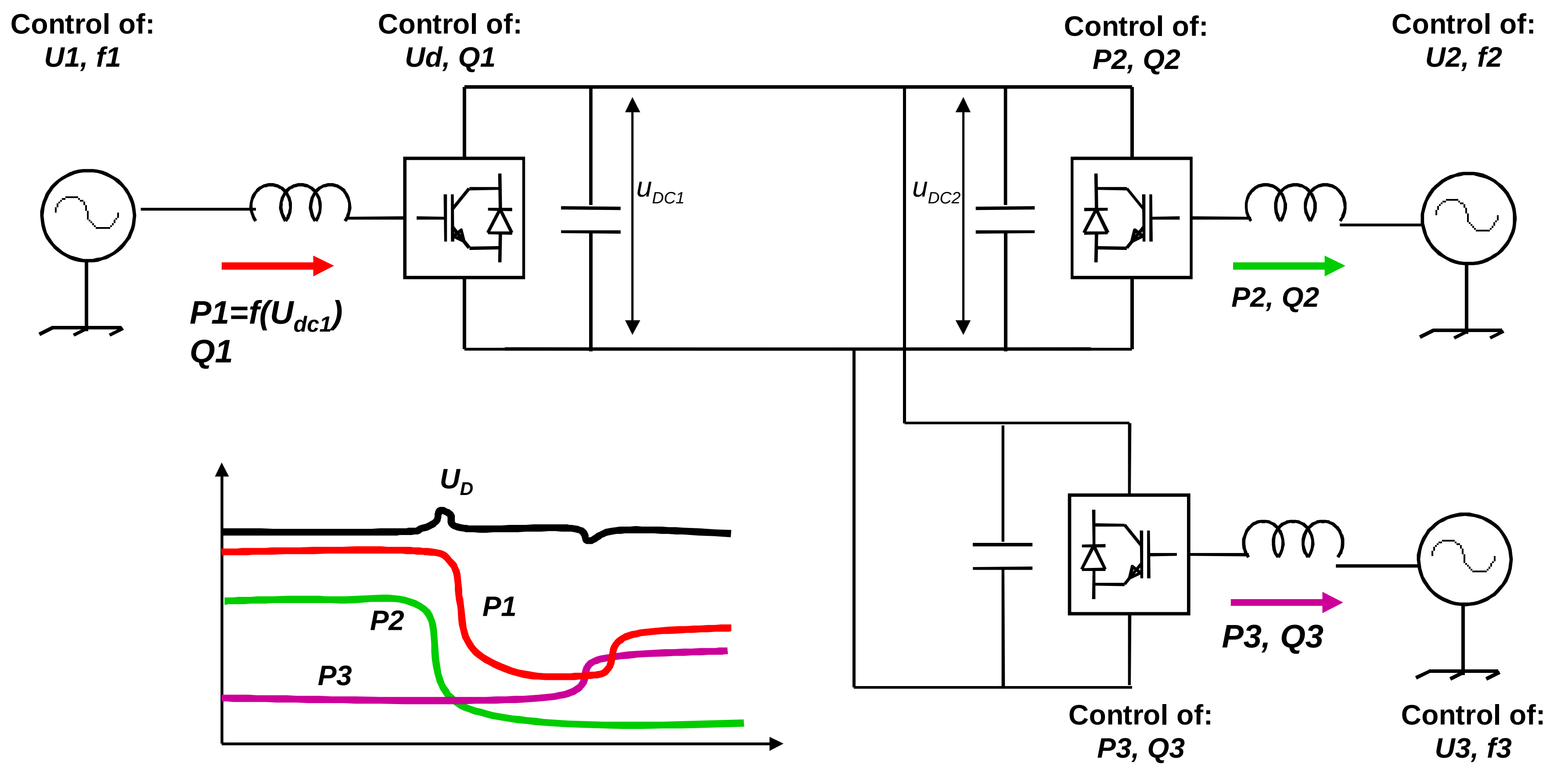
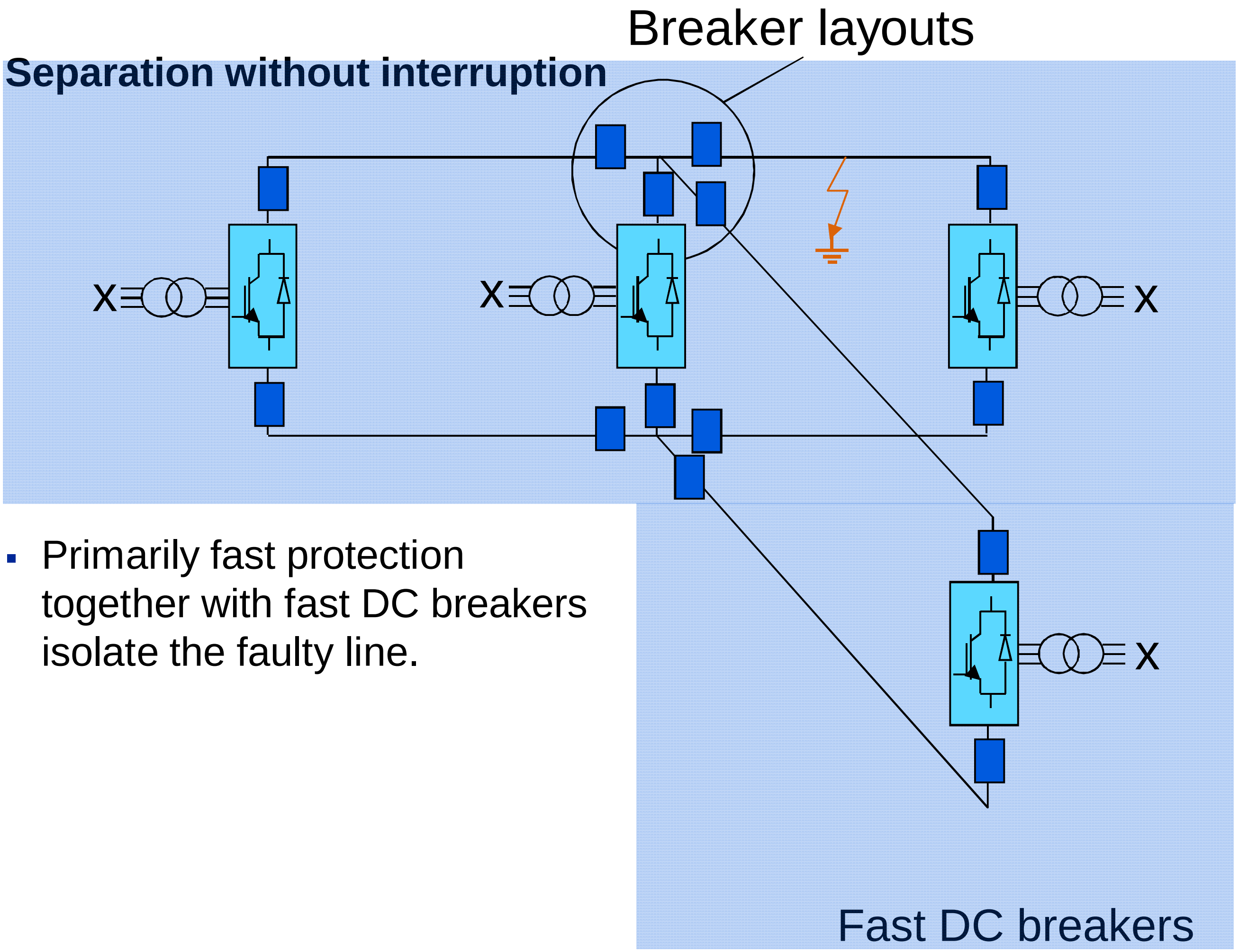
# VSC HVDC basic principles
## Multi-terminal operation



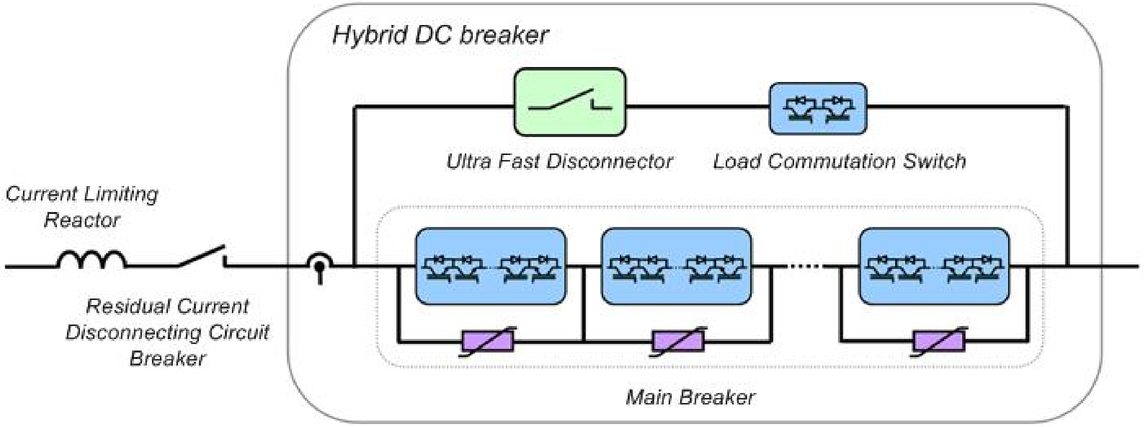

- **One converter station maintains a constant dc voltage (left), while the other two (right) converter operates at independant power reference given by system operator.**

# Protection philosophy
## Line fault handling




- Primarily fast protection together with fast DC breakers isolate the faulty line.

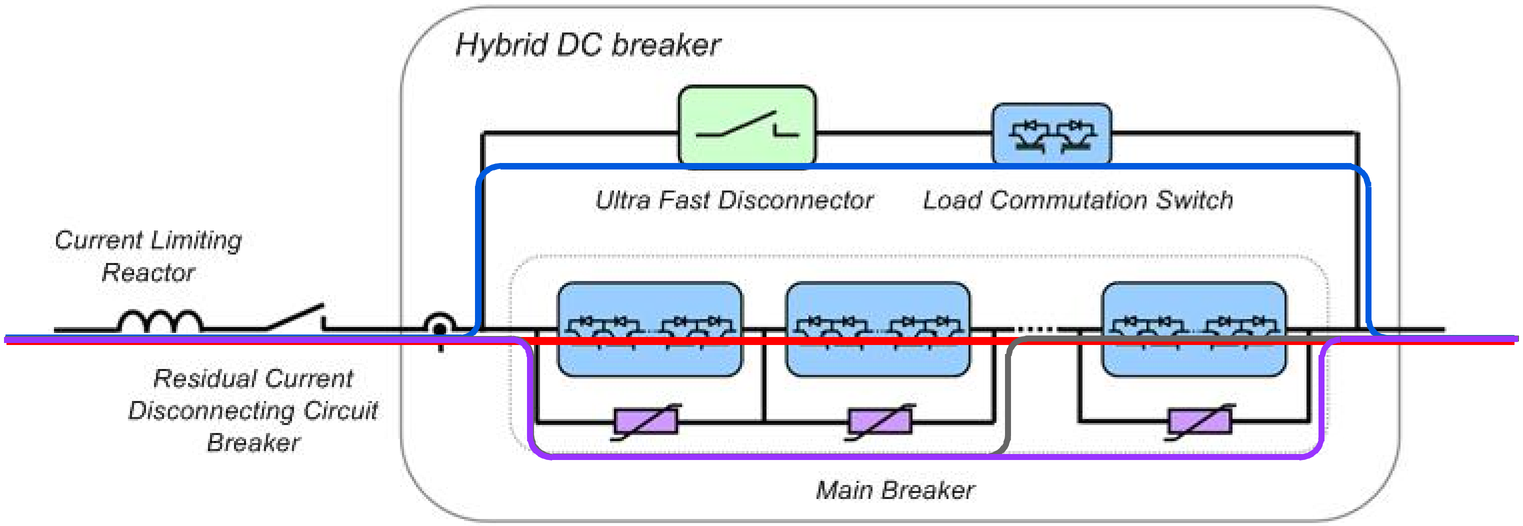
# Hybrid DC Breaker is well suited for HVDC grids




| | | |
|---|---|---|
| ▪ | Fast: | Breaking times of less than 2ms |
| ▪ | Powerful | Current breaking capability of 16kA |
| ▪ | Efficient | Transfer losses are less than 0.01% |
| ▪ | Modular | Easily adapted to actual voltage & current ratings |
| ▪ | Reliable | Protective current limitation, functional check while in service |
| ▪ | Proven | Power electronic design similar to converter technology |

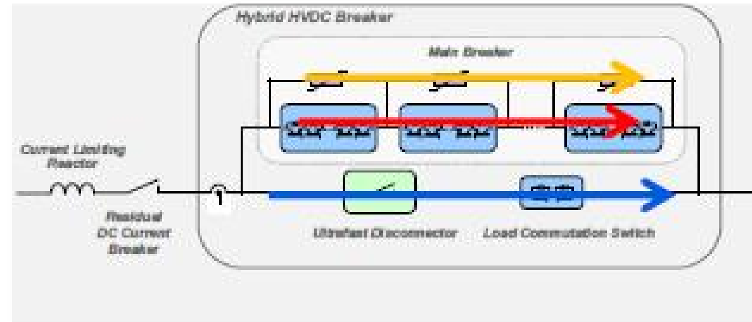
- DC Breakers are no longer a showstopper for large HVDC grids

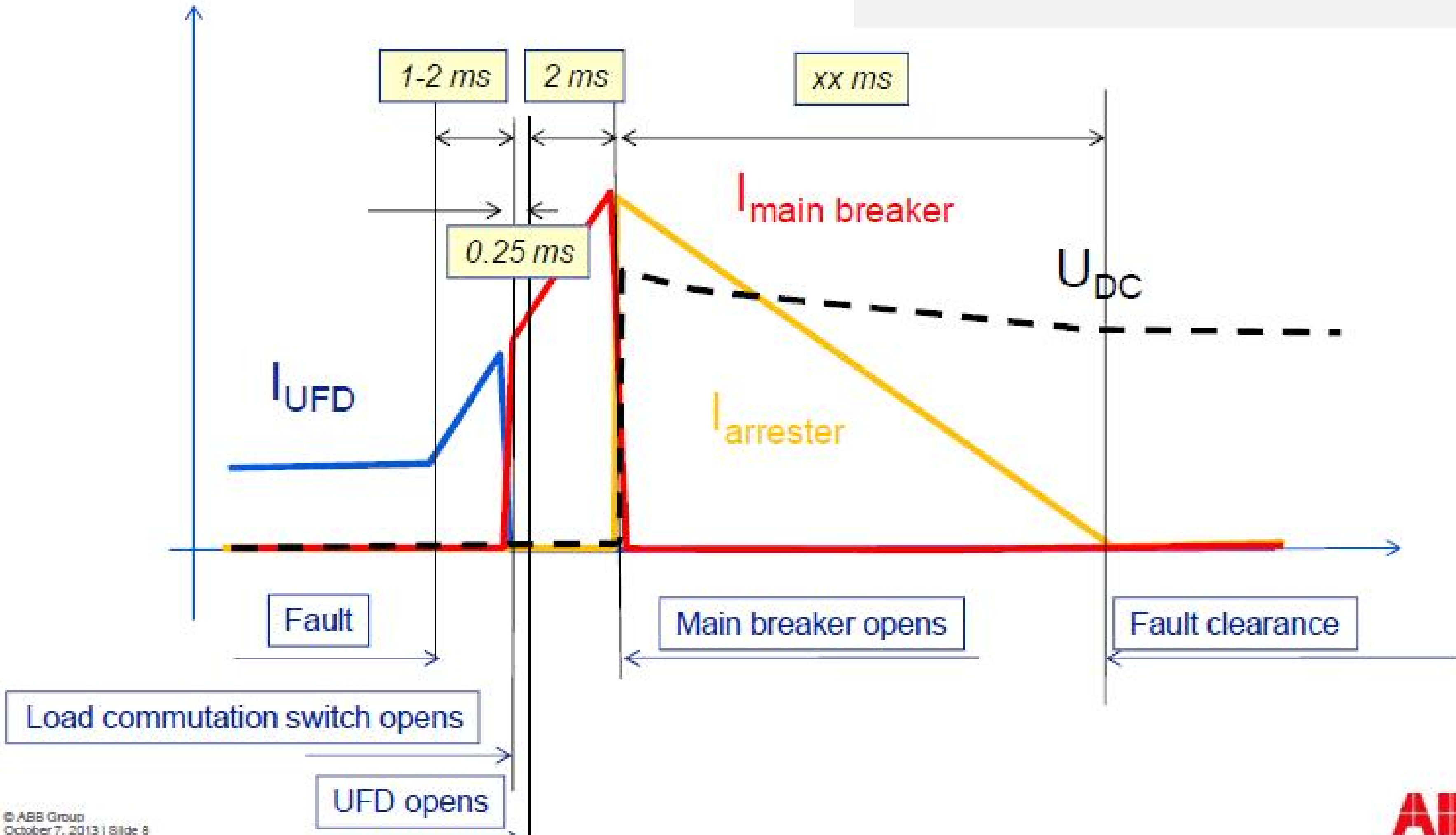
# Hybrid DC Breaker
# Fast breaking within time delay of selective protection



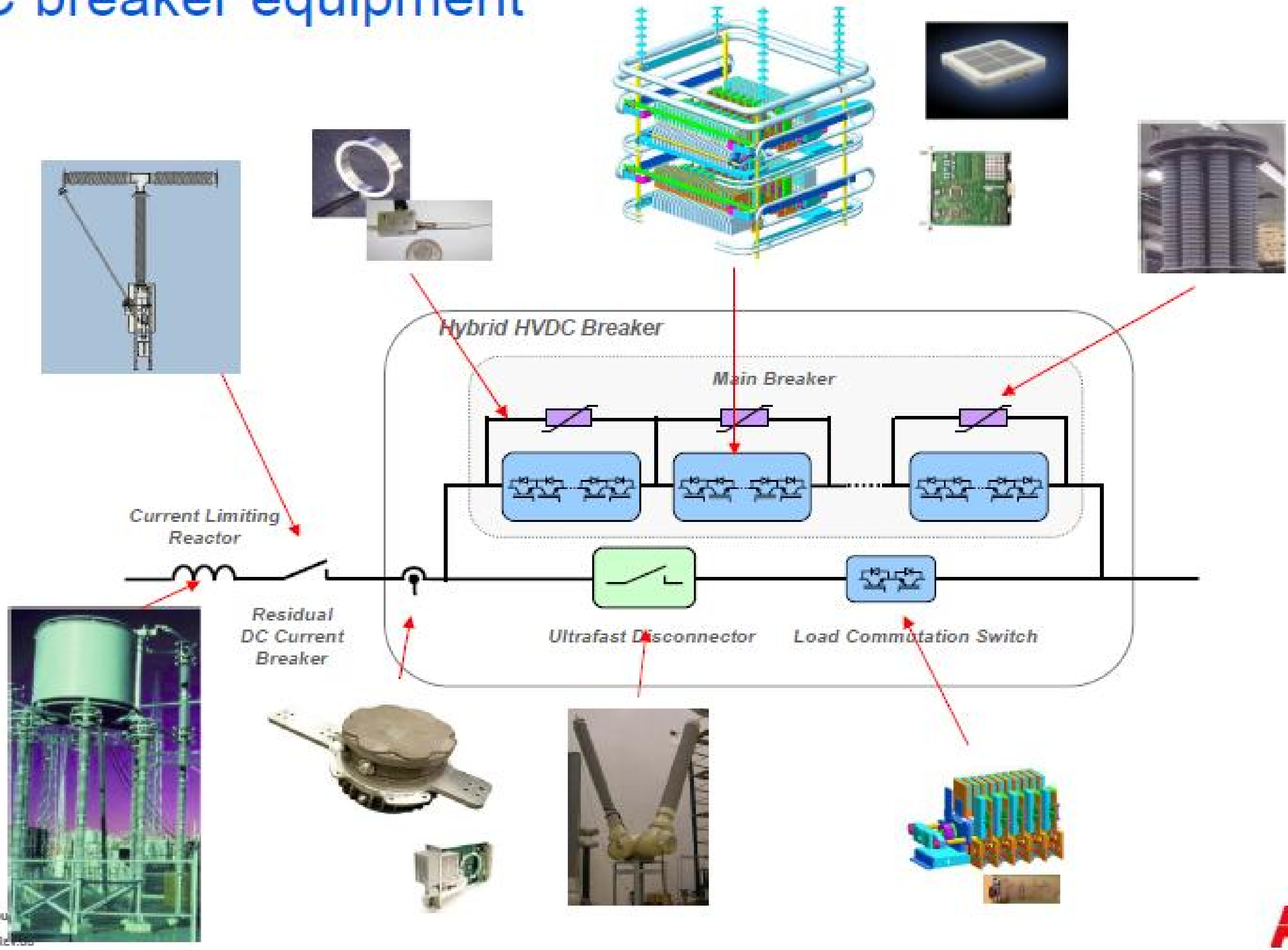

- Normal operation: Current flows in low-loss bypass
- Proactive control: Load commutation switch transfer current into Main Breaker switch, the Ultra Fast Disconnector opens with very low voltage stress
- Current limitation: Main Breaker switch commutates fault current into parts of the sectionalized arrester bank
- Fault clearance: Main Breaker switch commutates fault current into arrester bank

# Hybrid HVDC breaker
## Fault-clearing timeline



# Hybrid high voltage DC breaker
## DC breaker equipment



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