TSTE25 Power Electronics

Lecture 7

Tomas Jonsson
ISY/FS

LINKÖPING UNIVERSITY

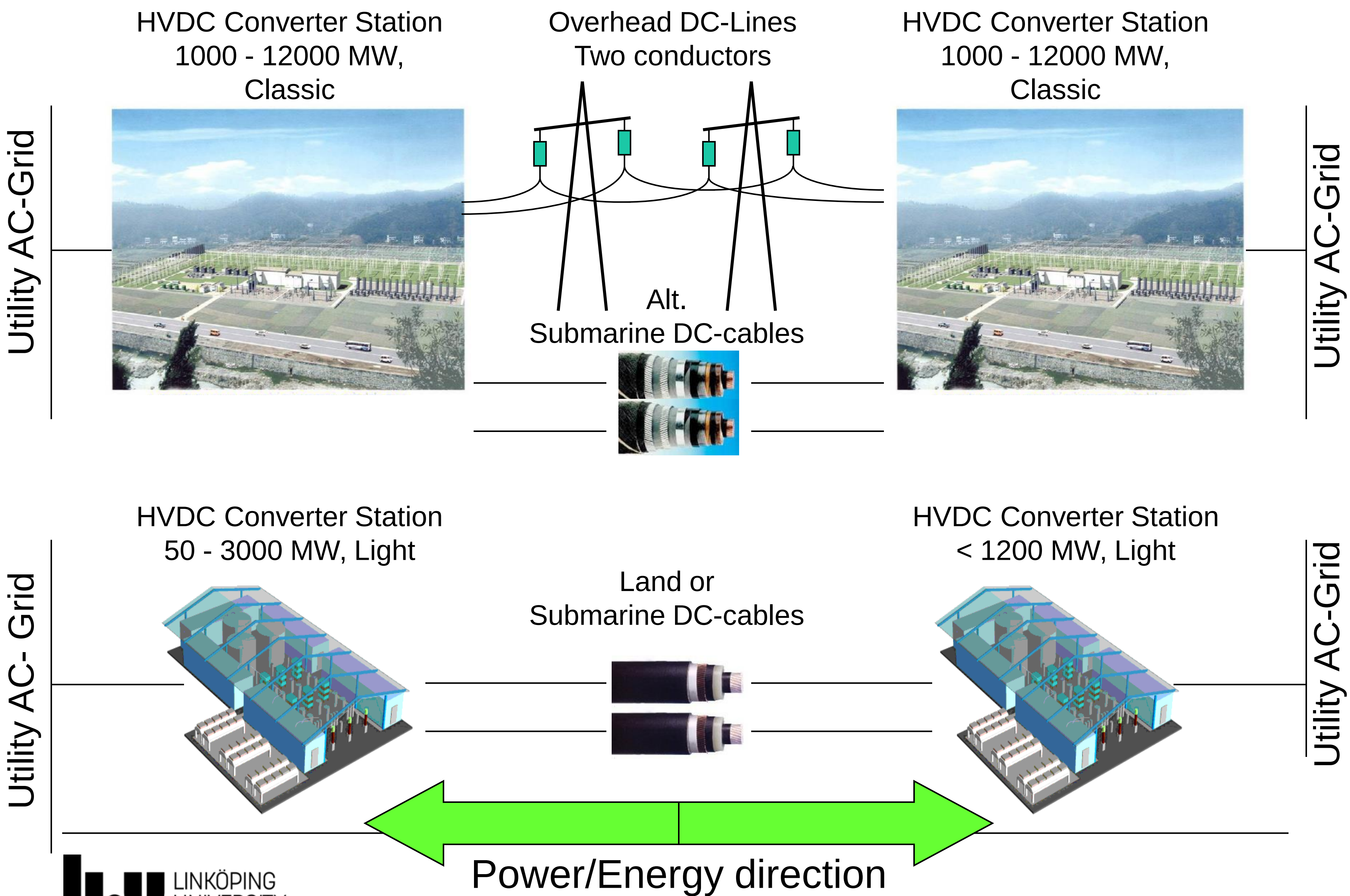
Outline

- HVDC Introduction
- Classic HVDC, Thyristor based
- VSC HVDC, IGBT based
- VSC in the power grid - Wind applications

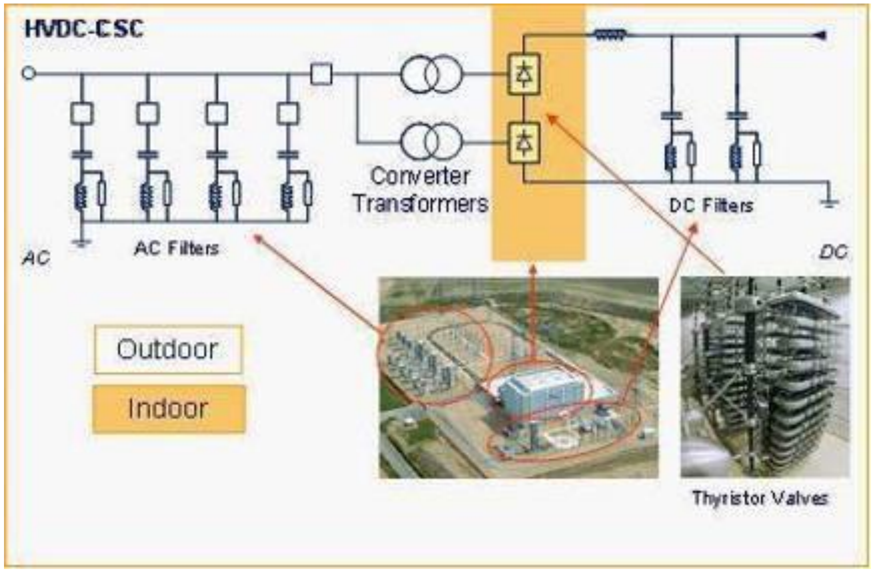
Lecture 7

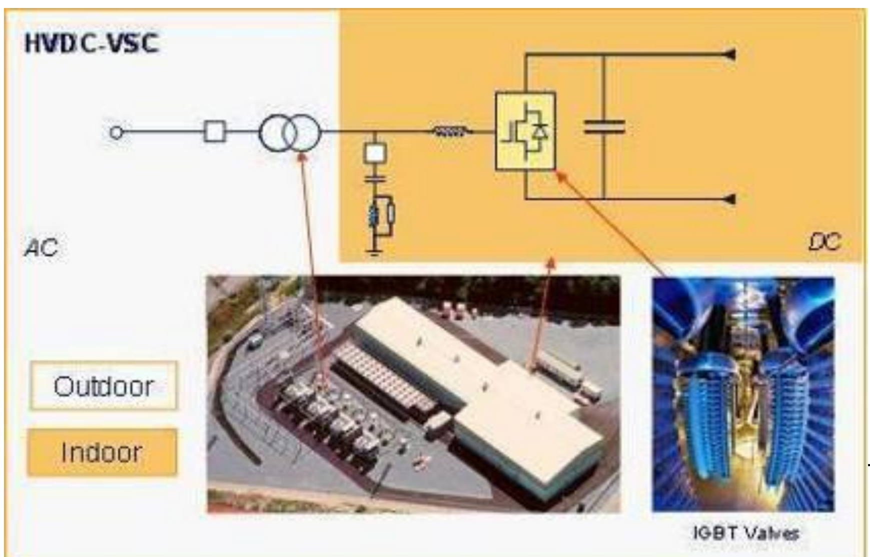
HVDC Introduction

What is an HVDC Transmission System?



LINKÖPING UNIVERSITY





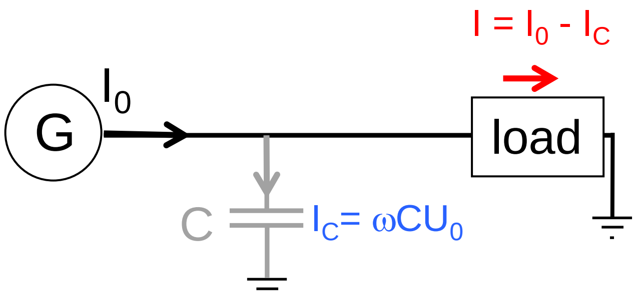
- HVDC Classic
  - Current source converters
  - Line-commutated thyristor valves
  - Requires 50% reactive compensation
  - Converter transformers
  - Minimum grid short circuit capacity > 2x converter rating

- HVDC Light
  - Voltage source converters
  - Self-commutated IGBT valves
  - Requires no reactive power compensation
  - “Standard” transformers
  - No minimum short circuit capacity, black start

Why HVDC is ideal for long distance transmission?

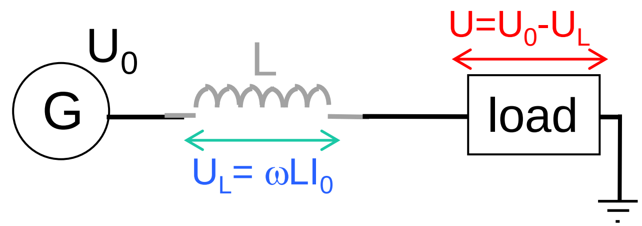
Capacitance and Inductance of power line

Cable



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

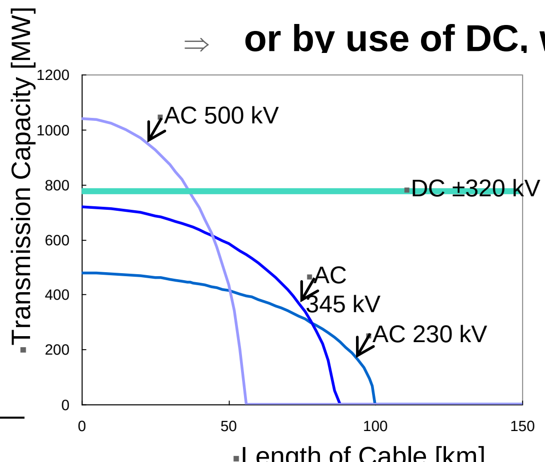
Overhead Line

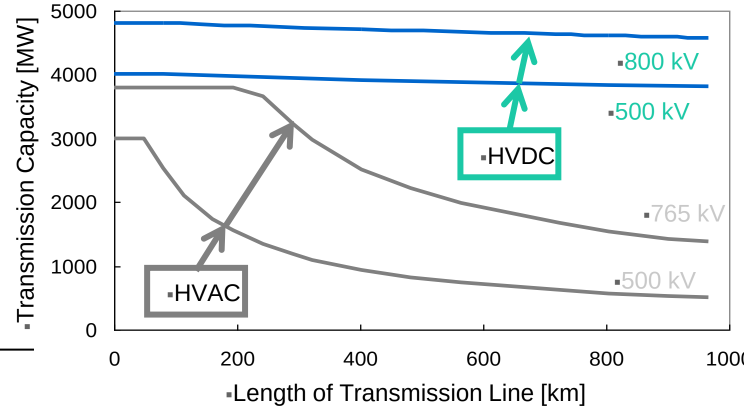


In overhead lines > 200 km, most of AC voltage is needed to overcome the “L” (inductance) of the line

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

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

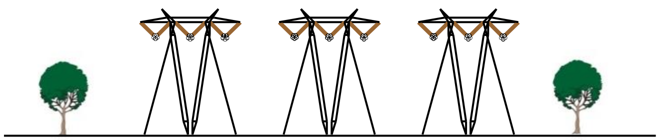




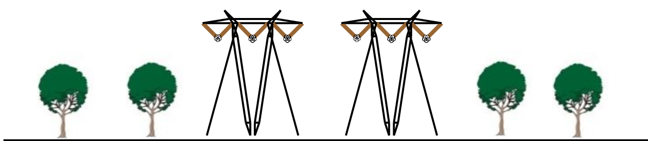
The transmission grid becomes increasingly important

Continued development of AC and DC technologies

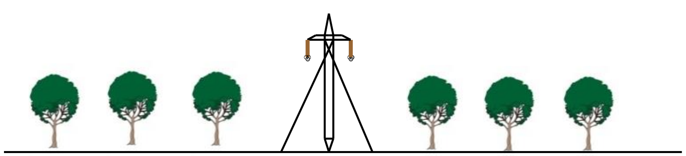
Different technologies :Same power transmitted



Traditional overhead line with AC

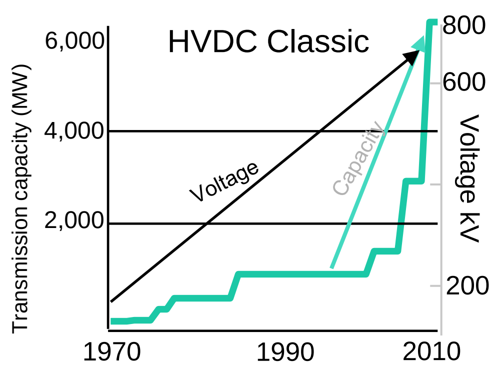


Overhead AC line with FACTS*

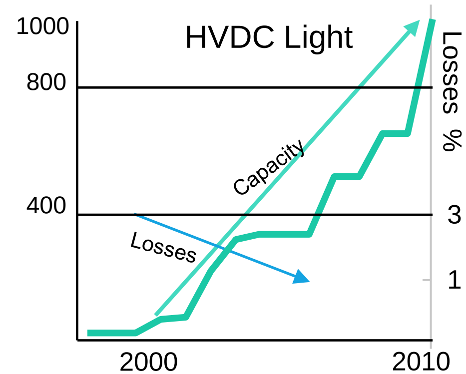


HVDC (high voltage direct current) Classic overhead line

Underground line with HVDC Light or AC cable



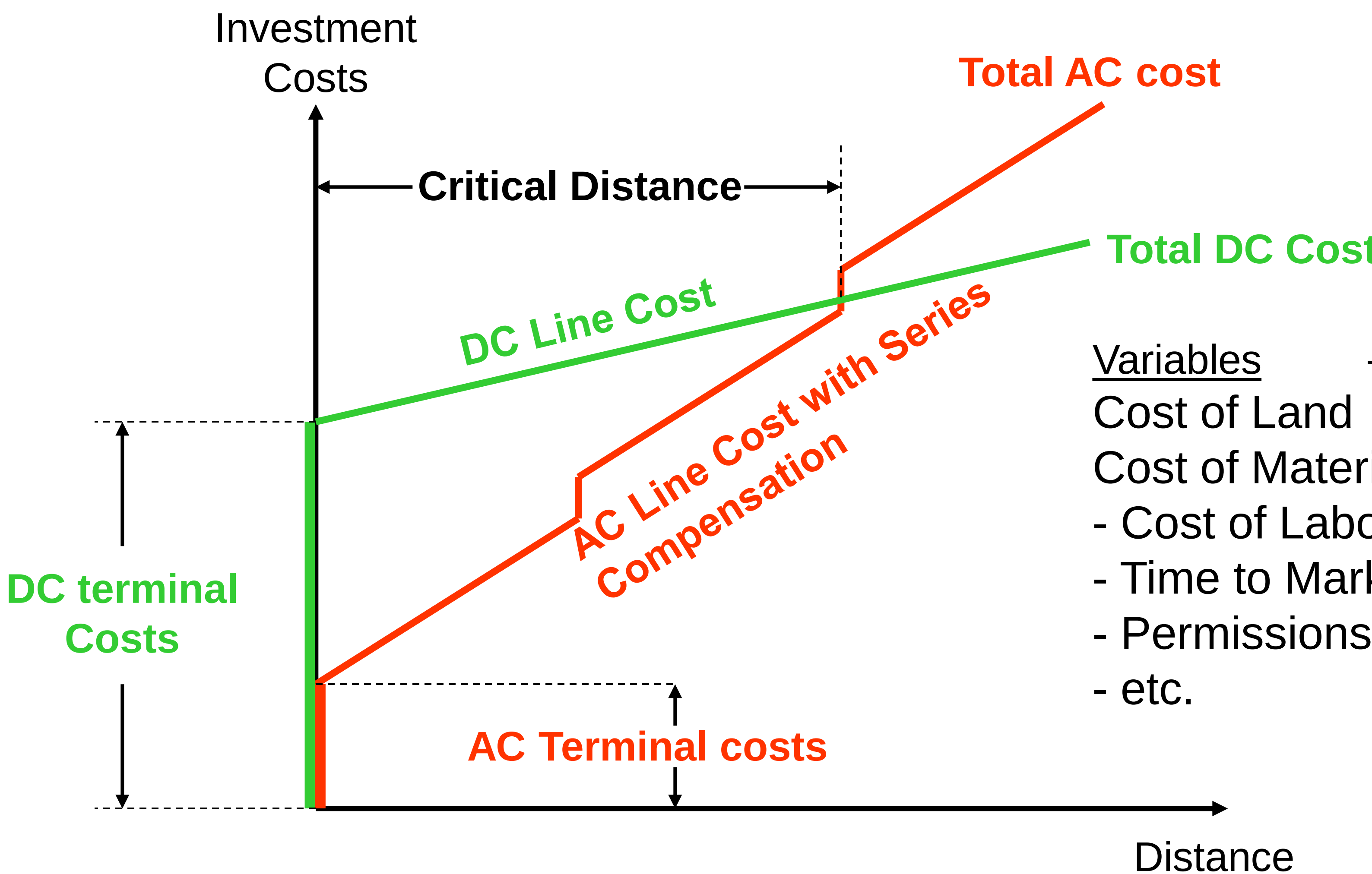
Capacity up 6x since 2000; Voltage up from +/- 100kV to +/- 800kV since 1970



- 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

Investment cost versus distance for HVAC and HVDC



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

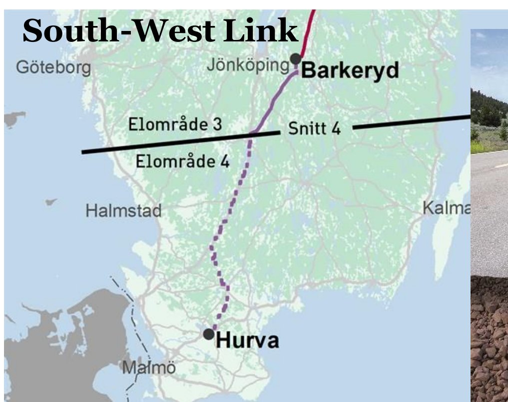
Market drivers for HVDC transmission

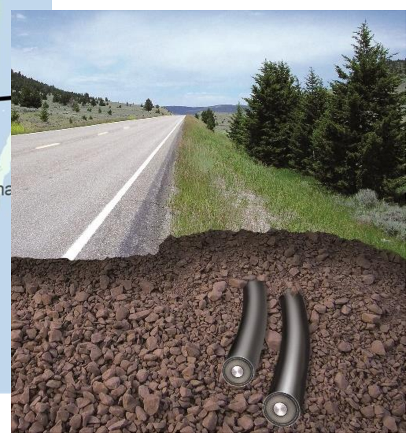
Environmentally friendly grid expansion

- **Integration of renewable energy**
  - Remote hydro
  - Offshore wind
  - Solar power
- **Grid reinforcement**
  - For increased trading
  - Generation sharing, international energy support
  - To support intermittent renewable energy

North Sea Link - North Sea Link

HVDC applications





HVDC Classic, thyristor based

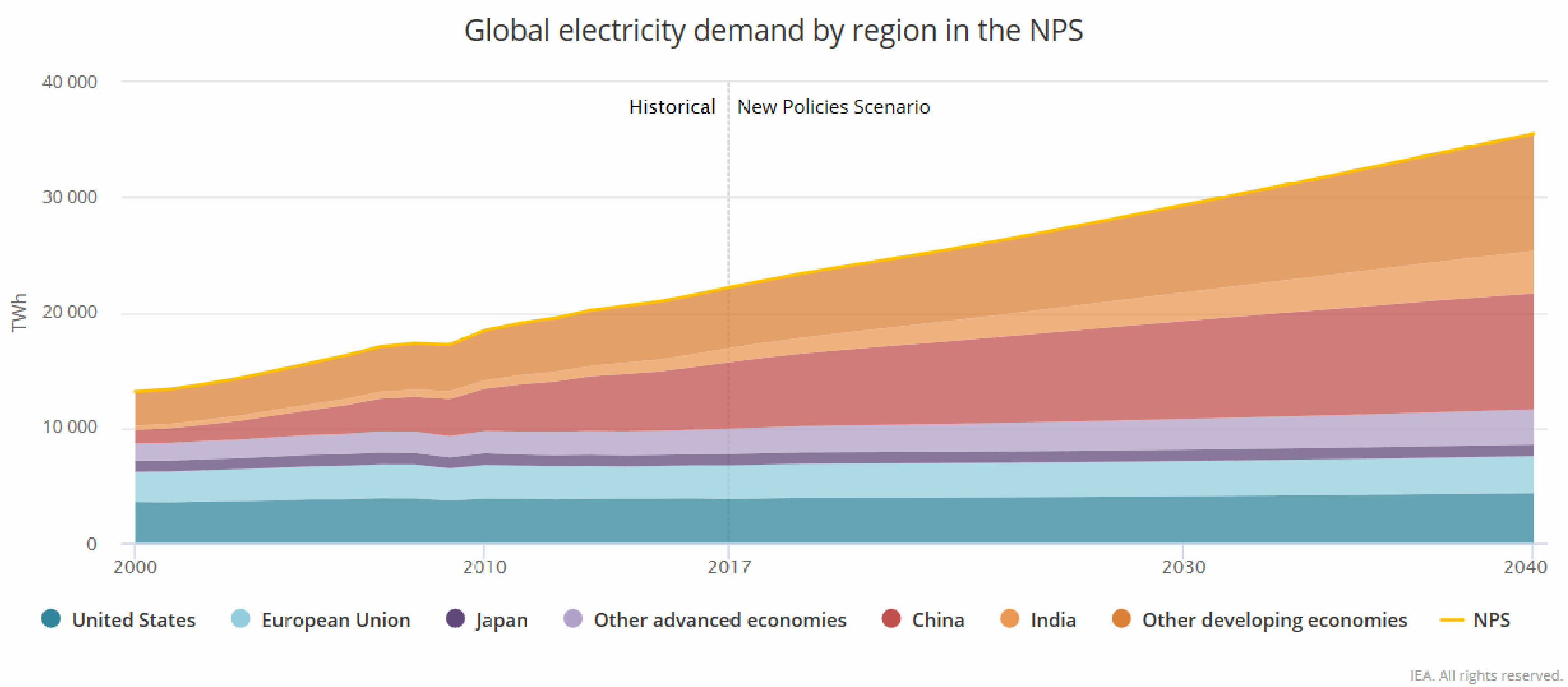
- Very long overhead line transmissions
- Very high power transmissions
- Very long sub sea transmissions

HVDC Light, IGBT based

- Offshore power supply
- Wind power integration
- Very long sub sea transmissions
- Underground transmission
- DC grids

Tackling challenges on path to low-carbon era

Forecast rise in electricity consumption by 2040

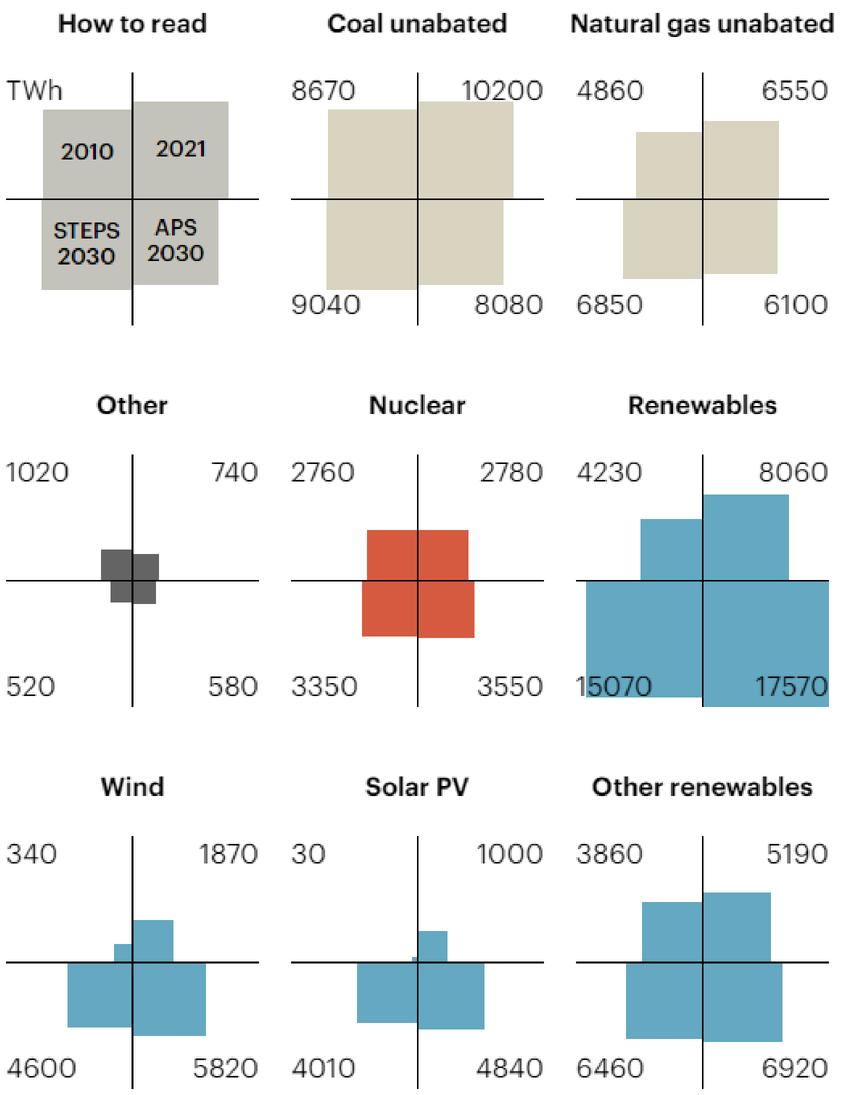


Meeting the rise in demand will mean adding a 1 GW power plant and all related infrastructure every week for the next 20 years

LINKÖPING UNIVERSITY

Source: IEA, World Energy Outlook 2018

Electricity mix by scenario



Stated Policies Scenario (STEPS)

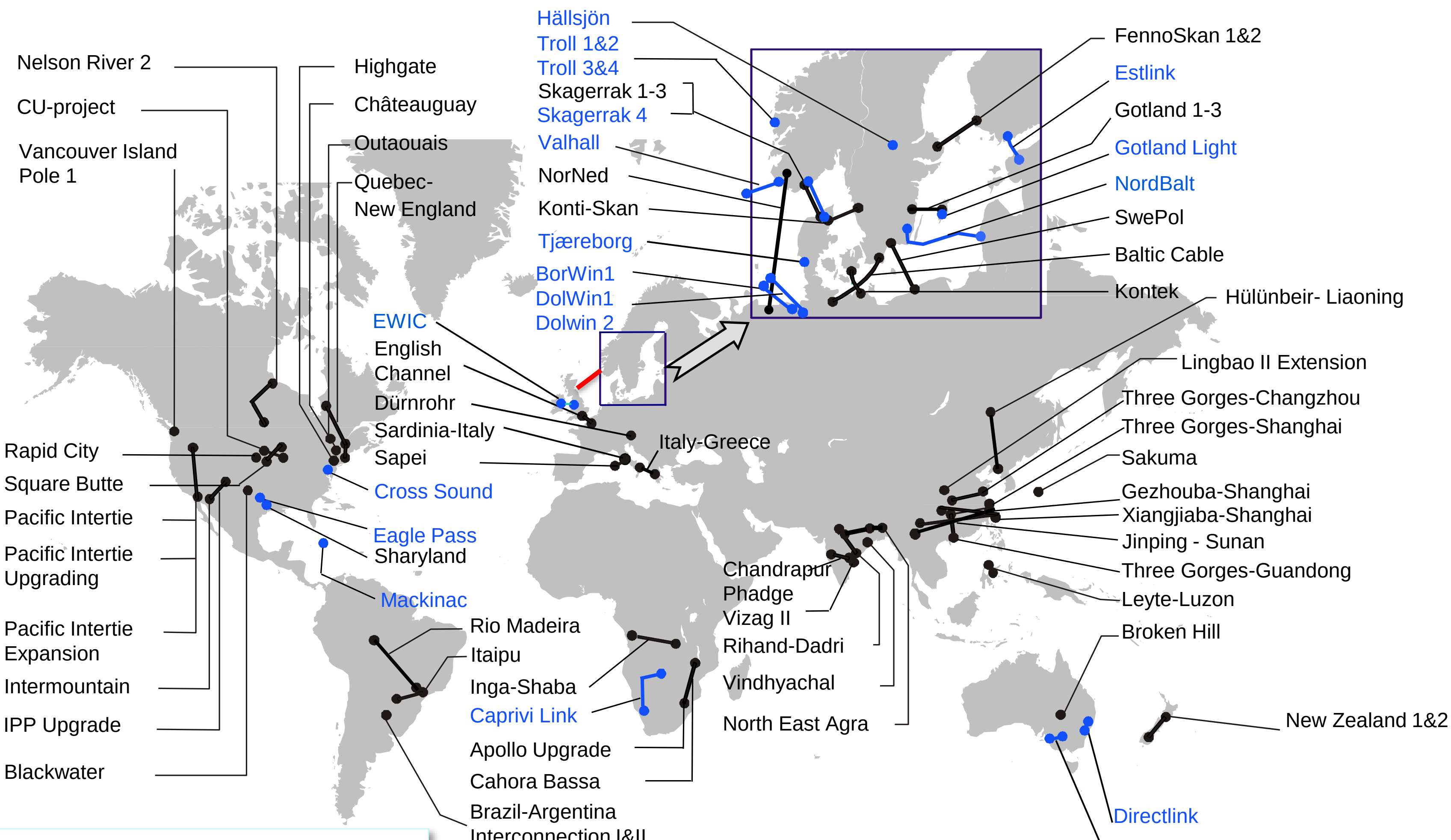
Announced Pledges Scenario (APS)

Source: IEA, World Energy Outlook 2022

1st HVDC power link
Gotland 20 MW subsea link 1954 by ASEA (ABB)

Worldwide HVDC projects

https://www.svk.se/om-kraftsystemet/kontrollrummet/

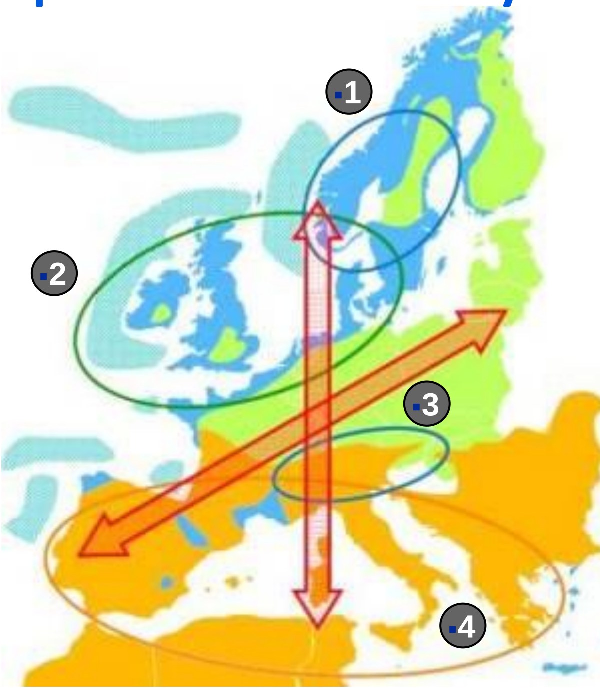


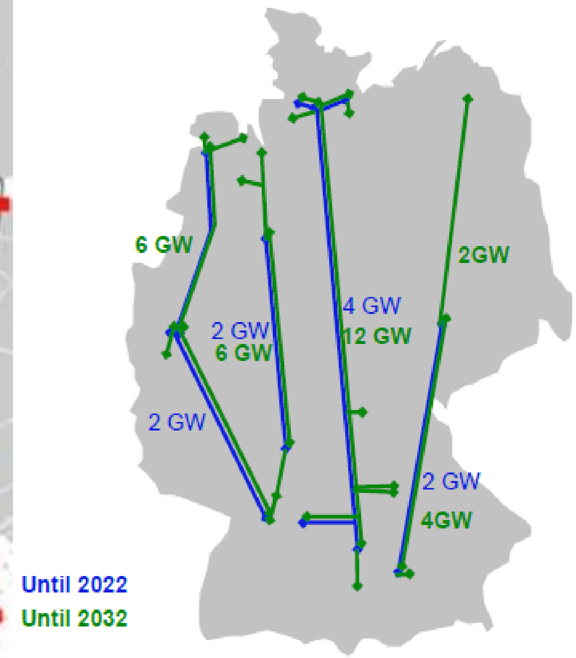
58 HVDC Classic Projects since 1958
14 HVDC upgrades since 1990
19 HVDC Light Projects since 1997

North Sea Link ENGLISH - YouTube

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)

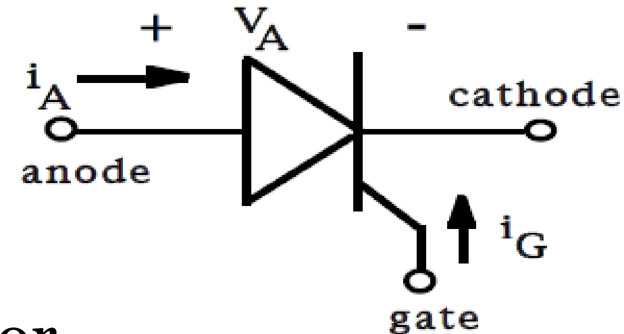
- Alternatives to nuclear-distributed generation
- Role of offshore wind / other renewables
- Political commitment
- Investment demand and conditions
- Need to strengthen existing grid

Lecture 7

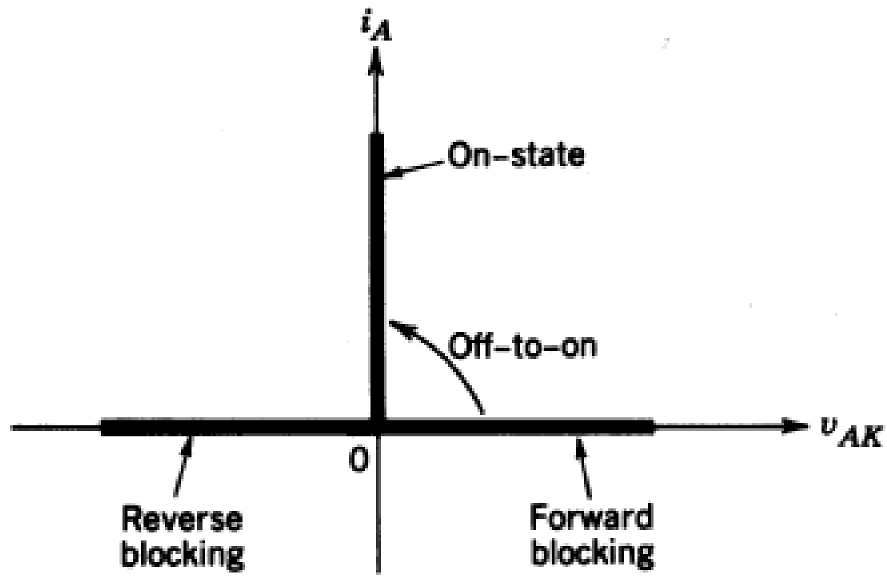
Thyristor based HVDC basic principles

Thyristors

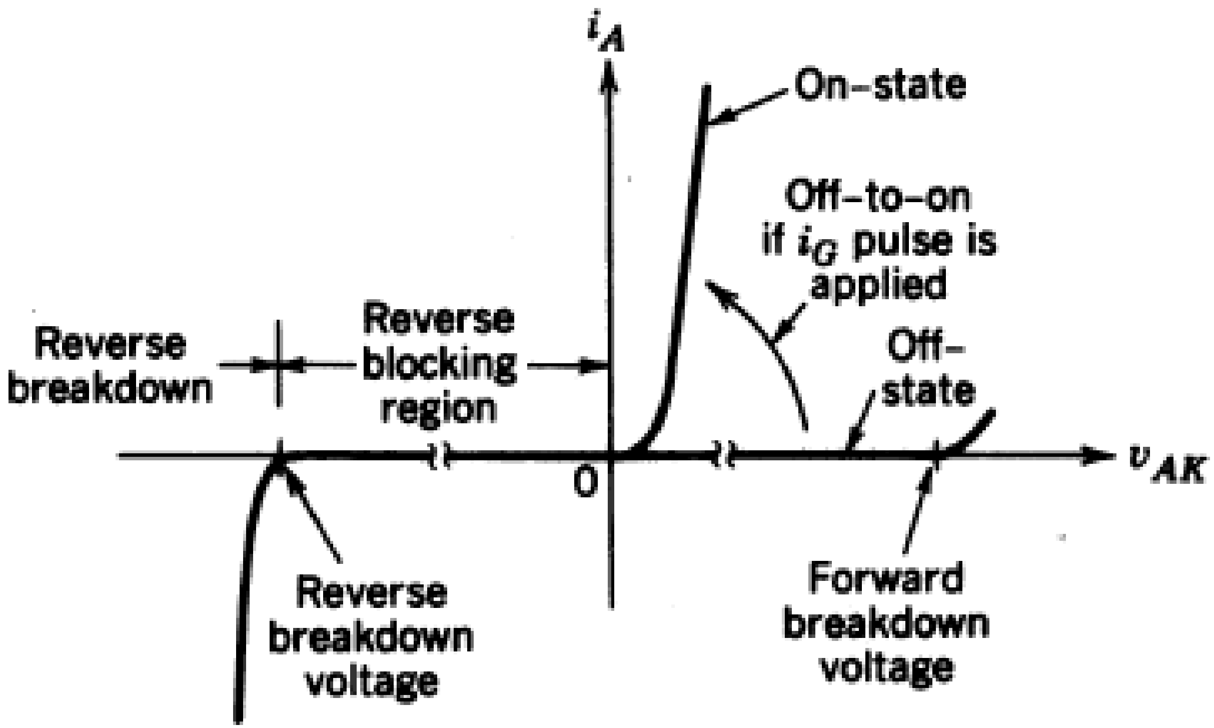
Thyristor circuit symbol.



- Diode with turn on control
- Pulse on gate when forward blocking turns on thyristor
- Current reversal followed by reverse blocking turns off thyristor
- 3 modes:
  - Forward blocking
  - On-state
  - Reverse blocking

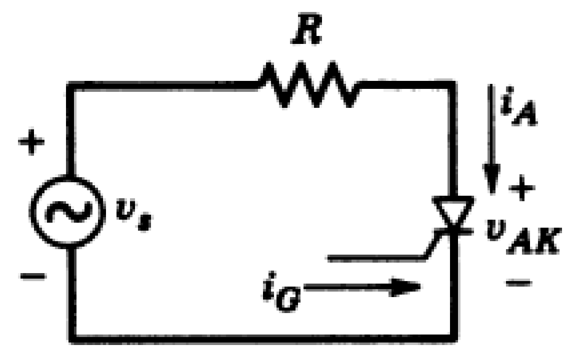


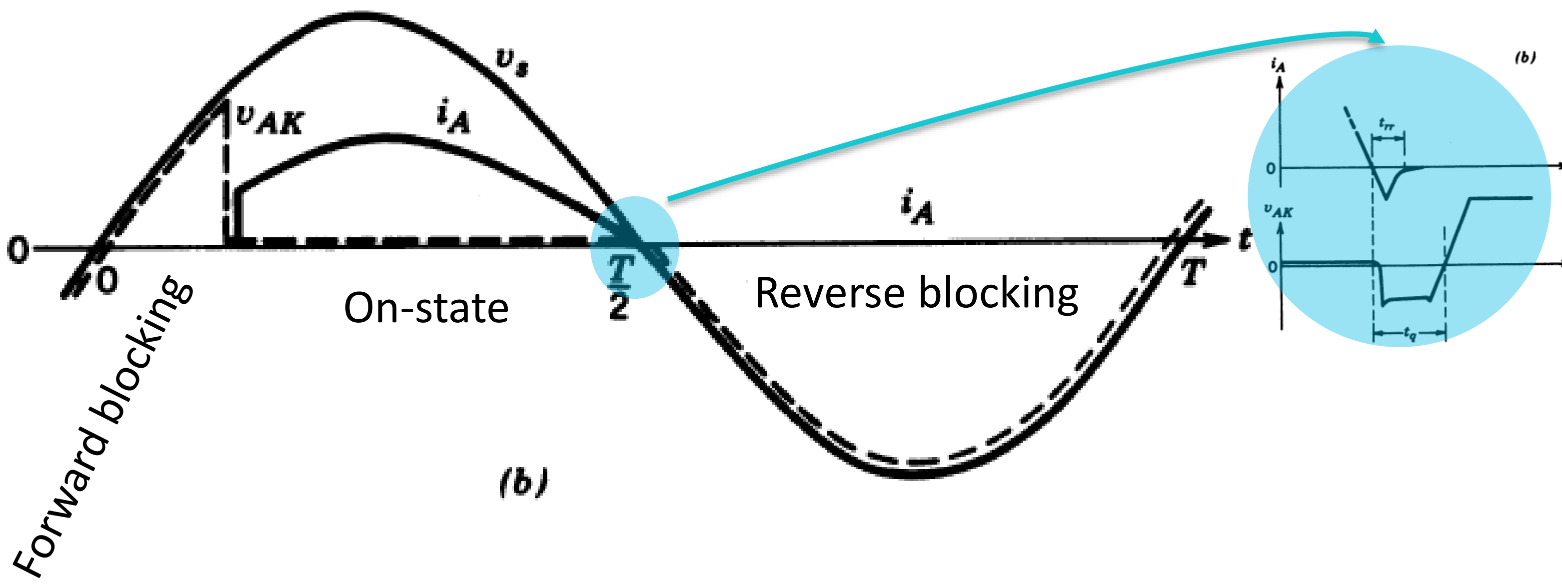
Actual thyristor characteristics



Thyristor, example circuit

- Thyristor can be triggered in interval
  $0 < t < T/2$

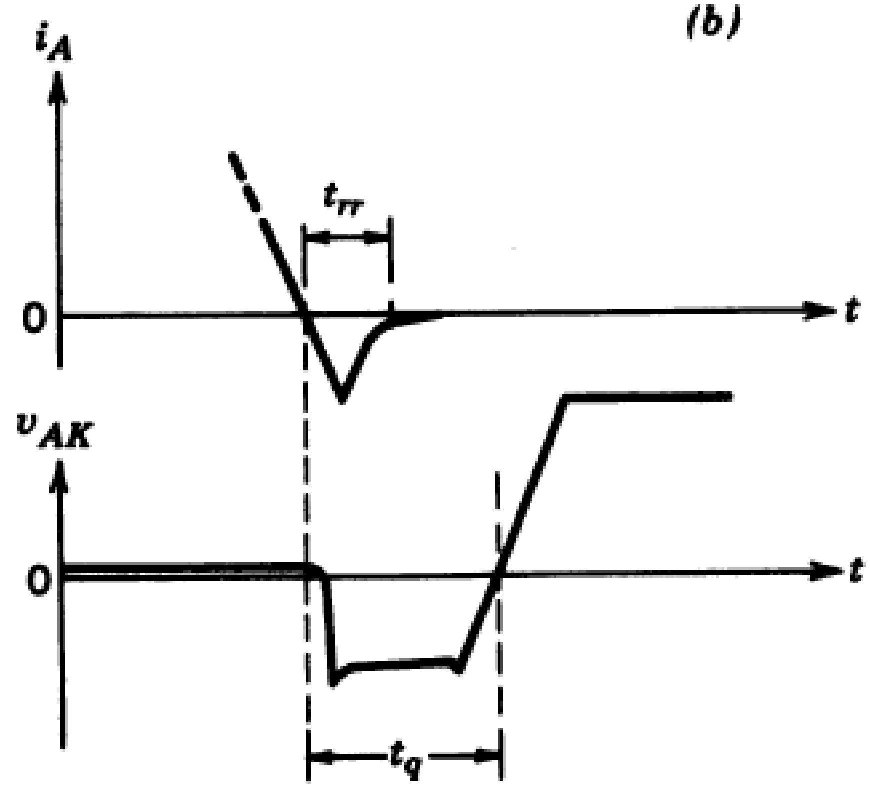




Thyristor turn-off process

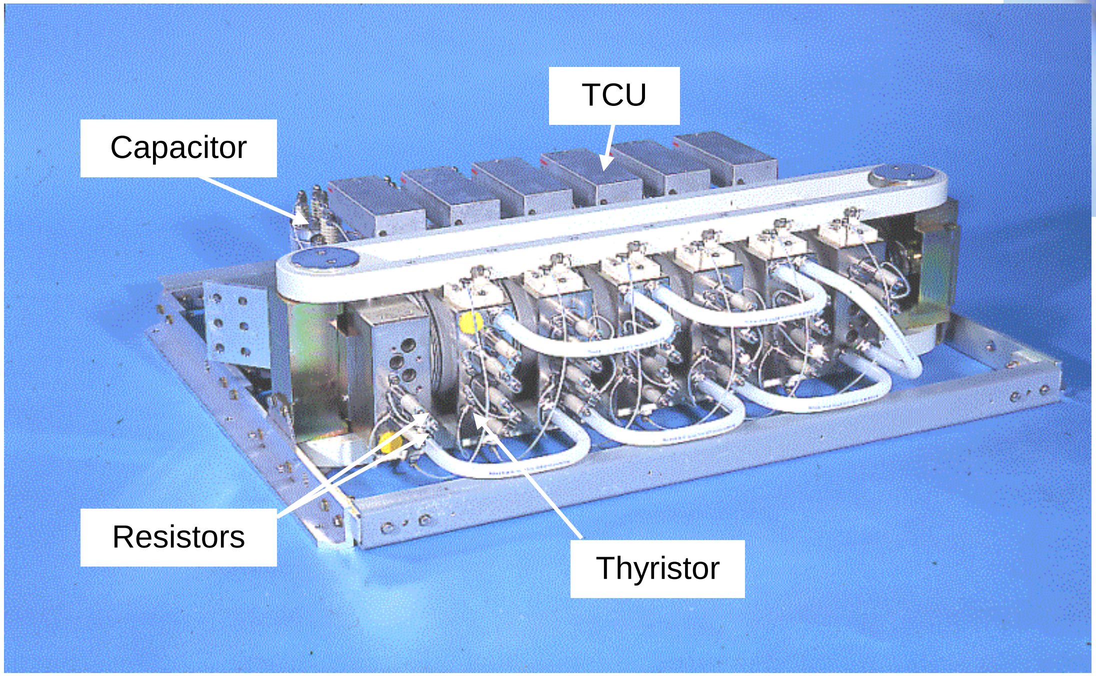
Succesful turn-off:

- Current reversal
  - reverse recovery as a diode
- Reverse blocking (negative v_{AK}) for $t \geq t_q$ Otherwise no turn-off

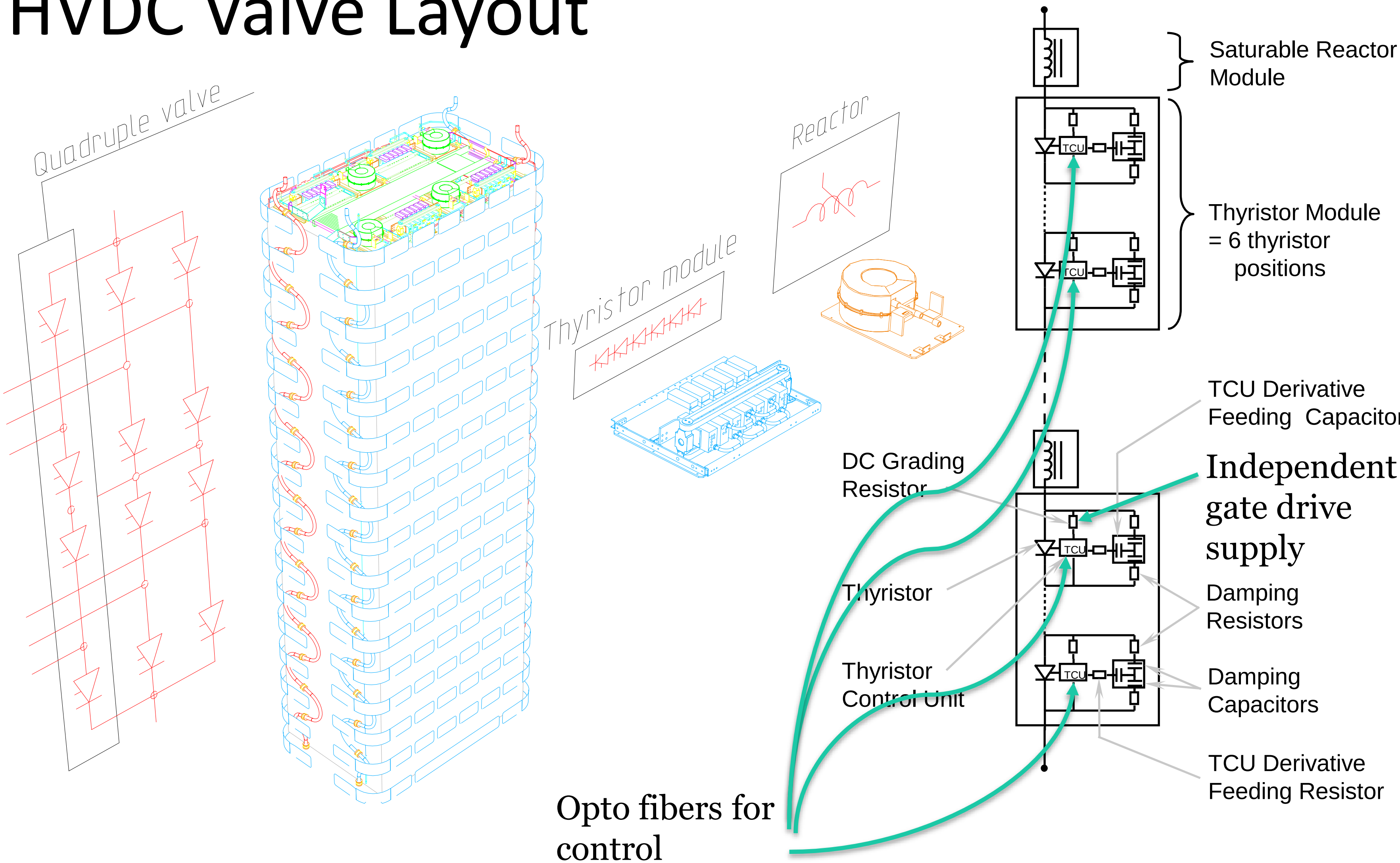


Thyristor presspack

- Active part on a single silicon wafer.

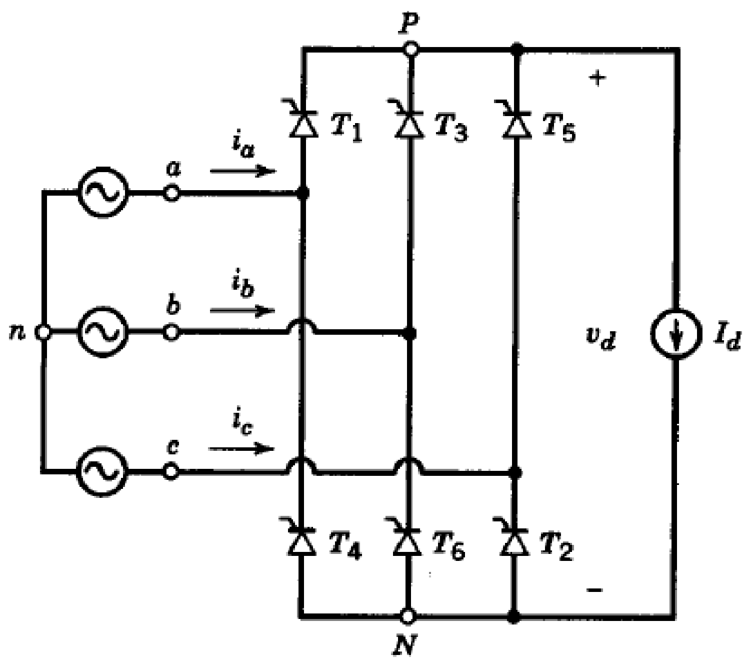


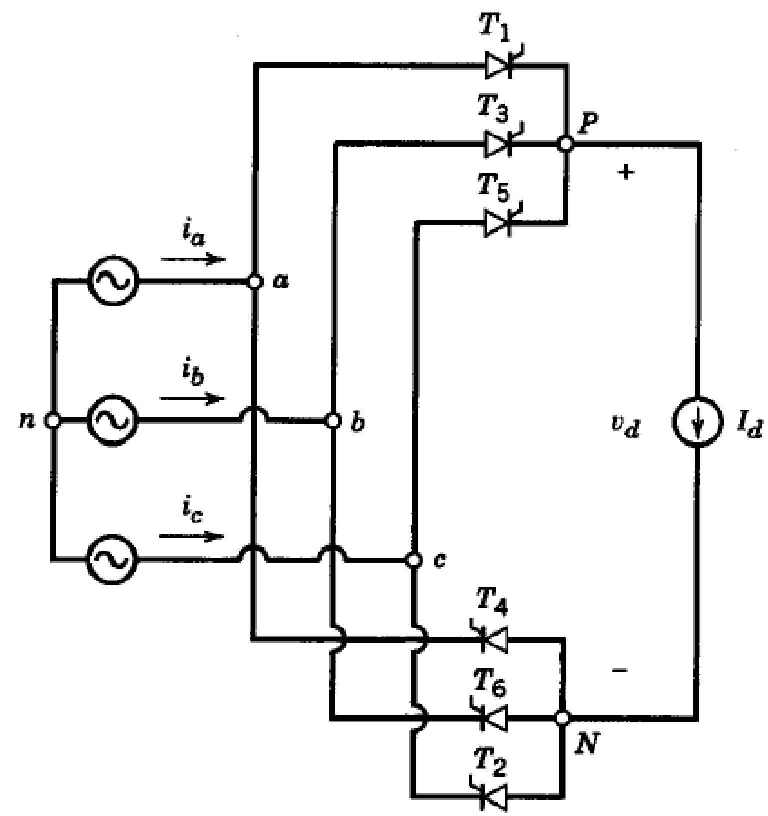
HVDC Valve Layout



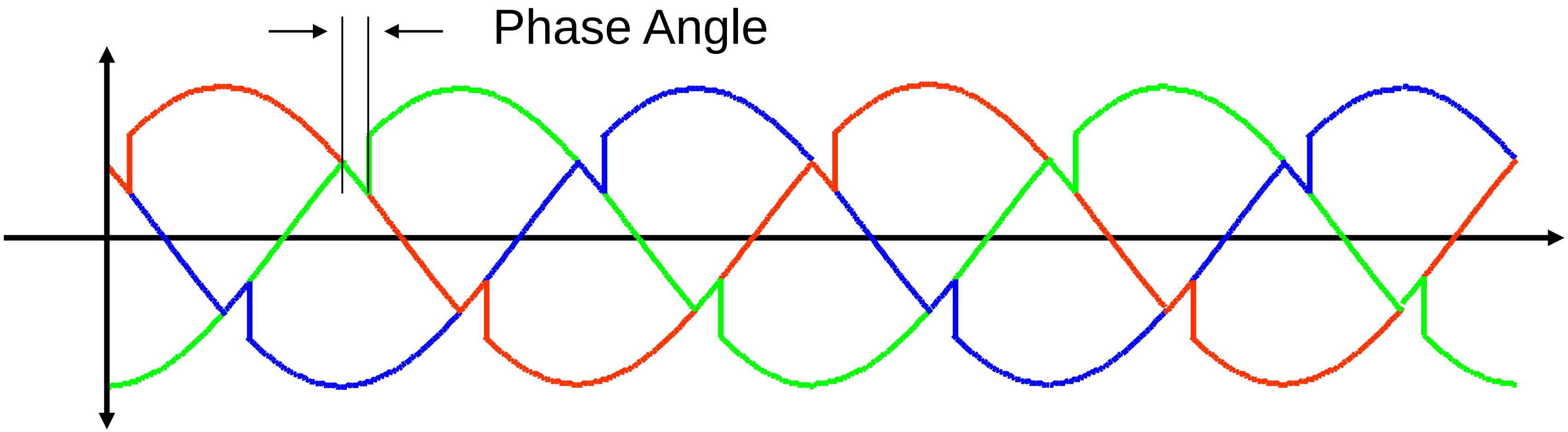
Three-phase thyristor converter

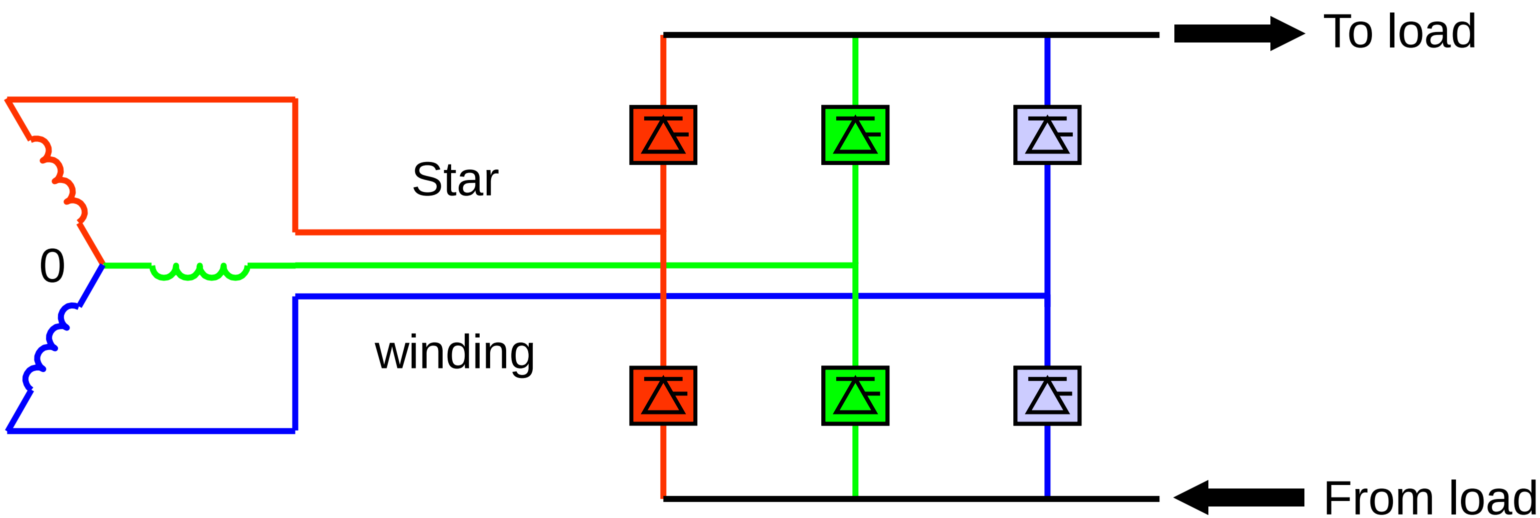
- One thyristor active in top group and one in bottom group





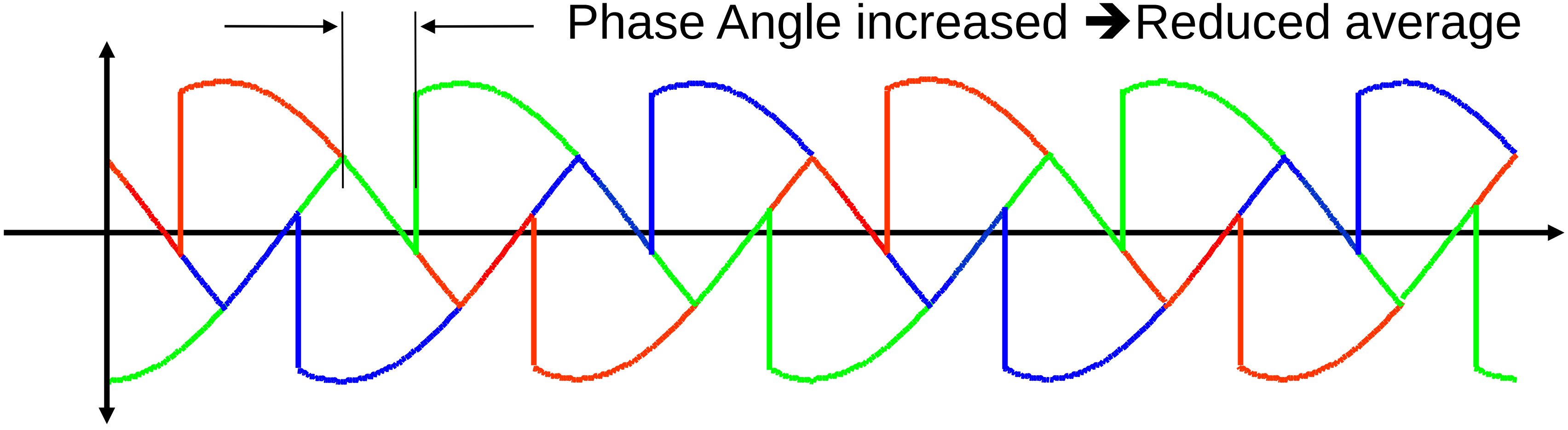
Thyristor rectifier operation

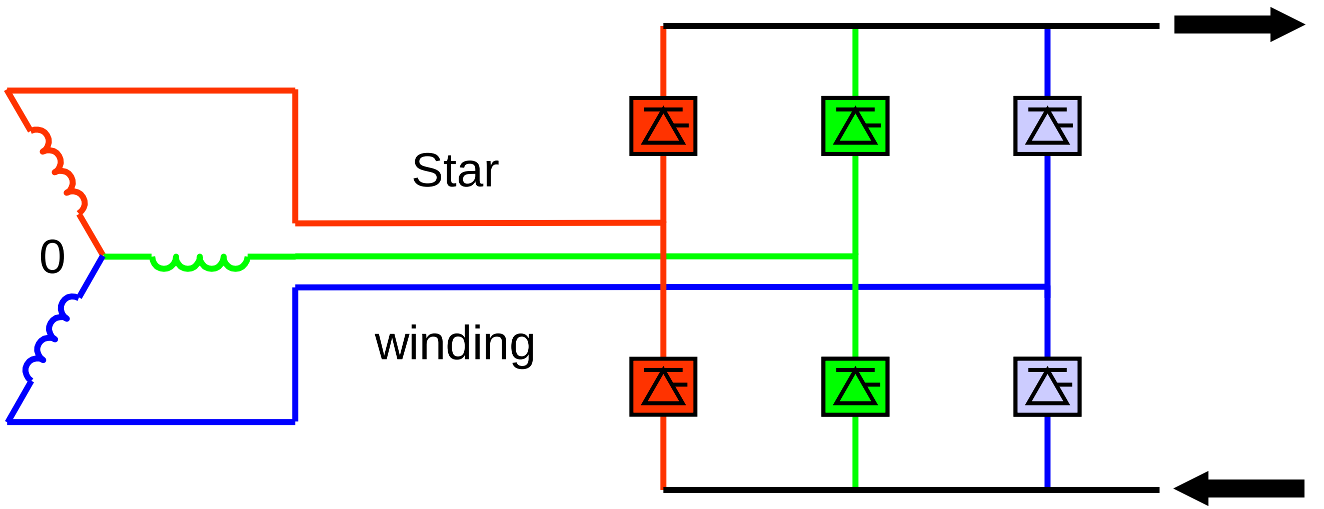




6-pulse Graetz rectifier bridge

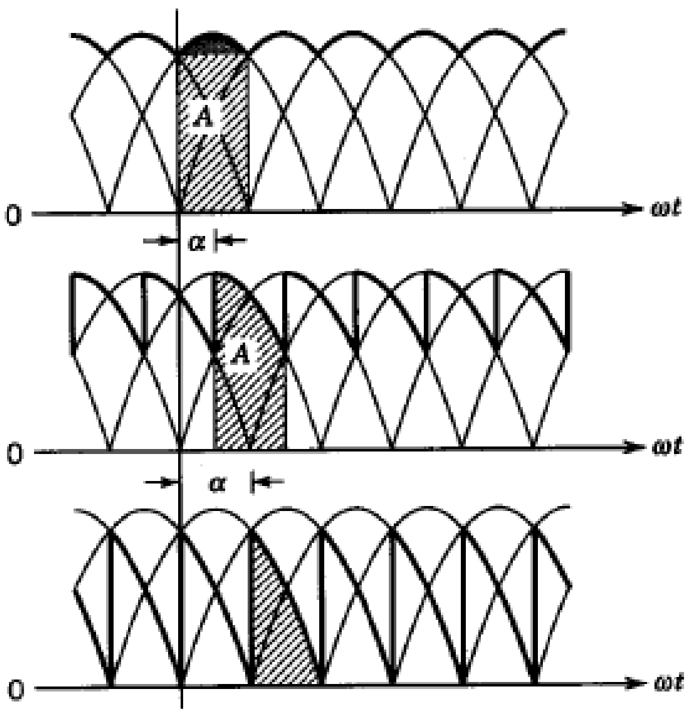
Thyristor rectifier operation





DC side voltage

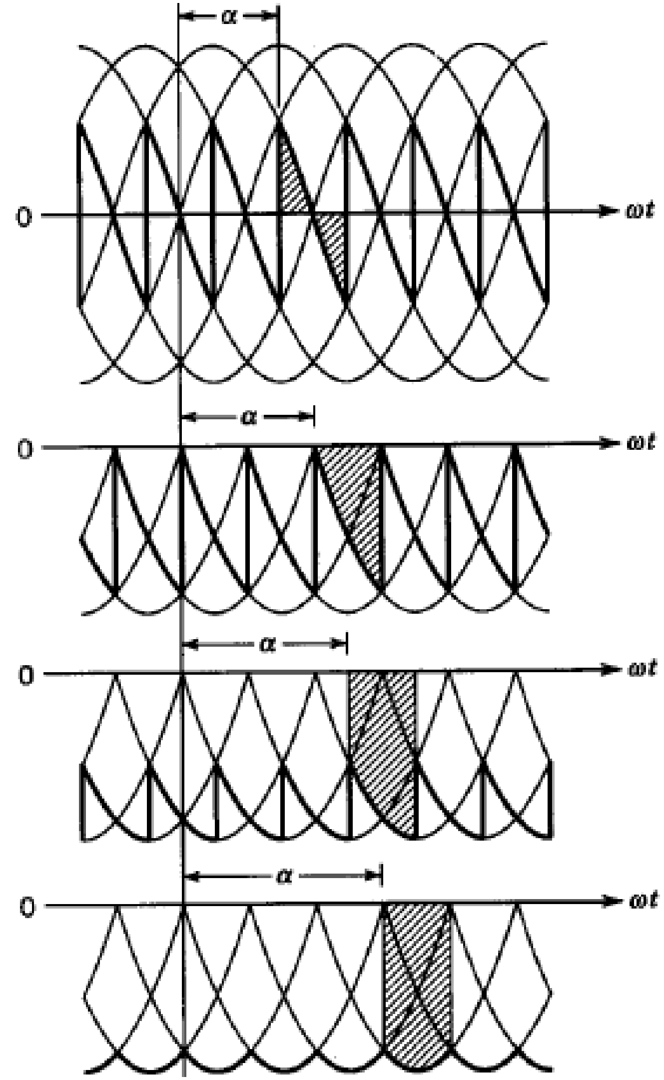
$$V_{do} = \frac{3}{\pi}\sqrt{2}V_{LL}cos(\alpha)$$
$$\approx 1.35V_{LL}cos(\alpha)$$



(a) α = 0

(b) α = 30°

(c) α = 60°



(d) α = 90°

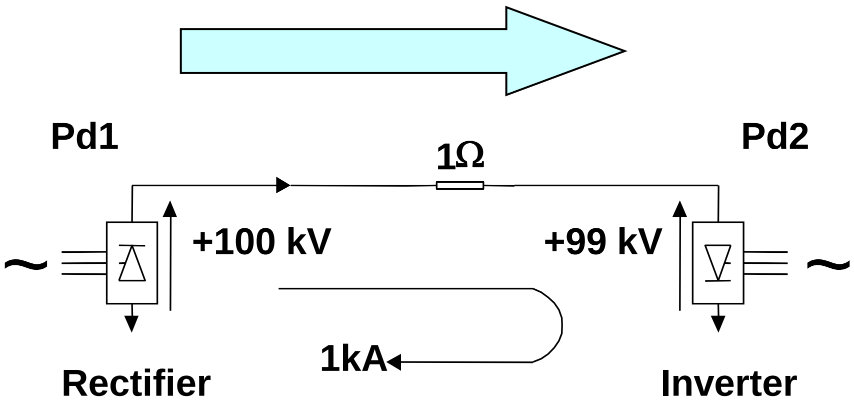
(e) α = 120°

(f) α = 150°

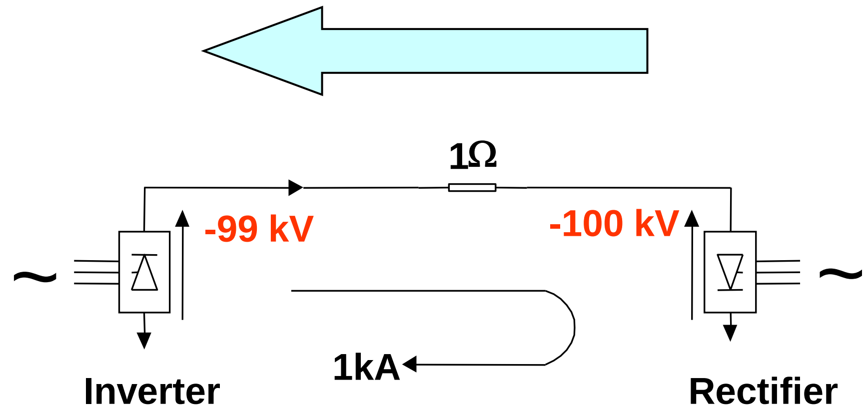
(g) α = 180°

HVDC - Controllability of power flow

Normal Power direction:



Power reversal:

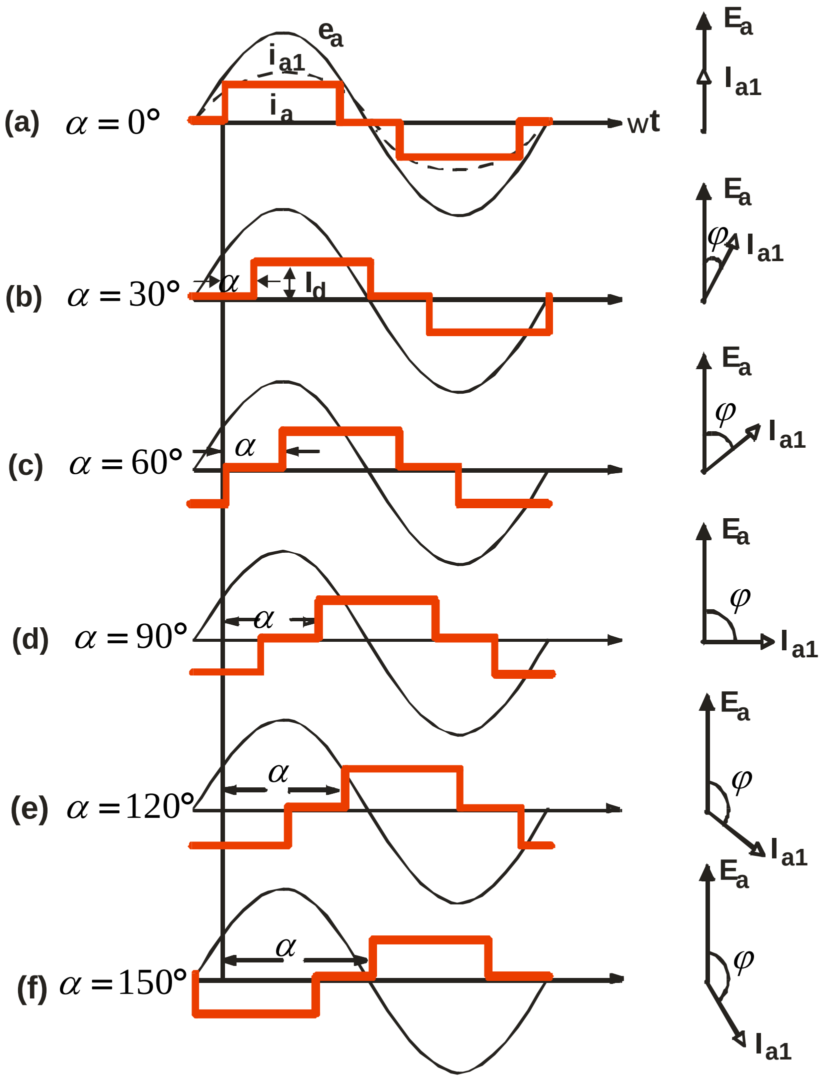


U_{d1}	U_{d2}	R_d	I_d	P_{d1}	P_{d2}
100	99	1	1	100	99
101	99	1	2	202	198
-99	-100	1	1	-99	-100

Fast and stable

power flow control

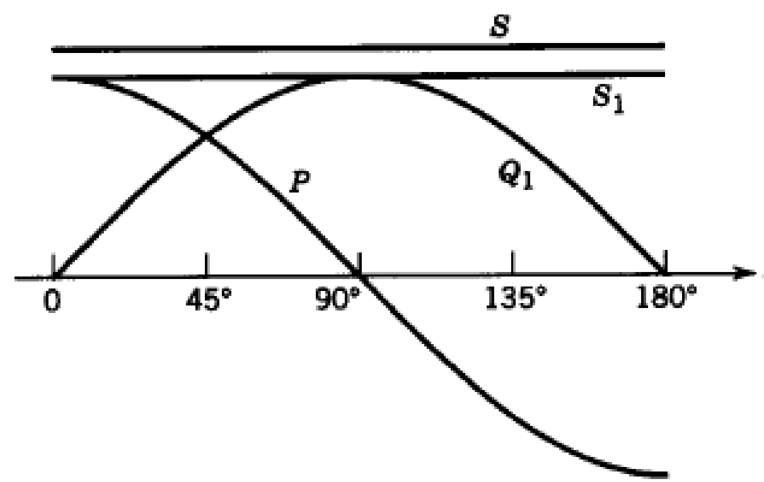
Relation between firing delay and phase displacement



$$DPF = \cos\Phi_1 = \cos\alpha$$

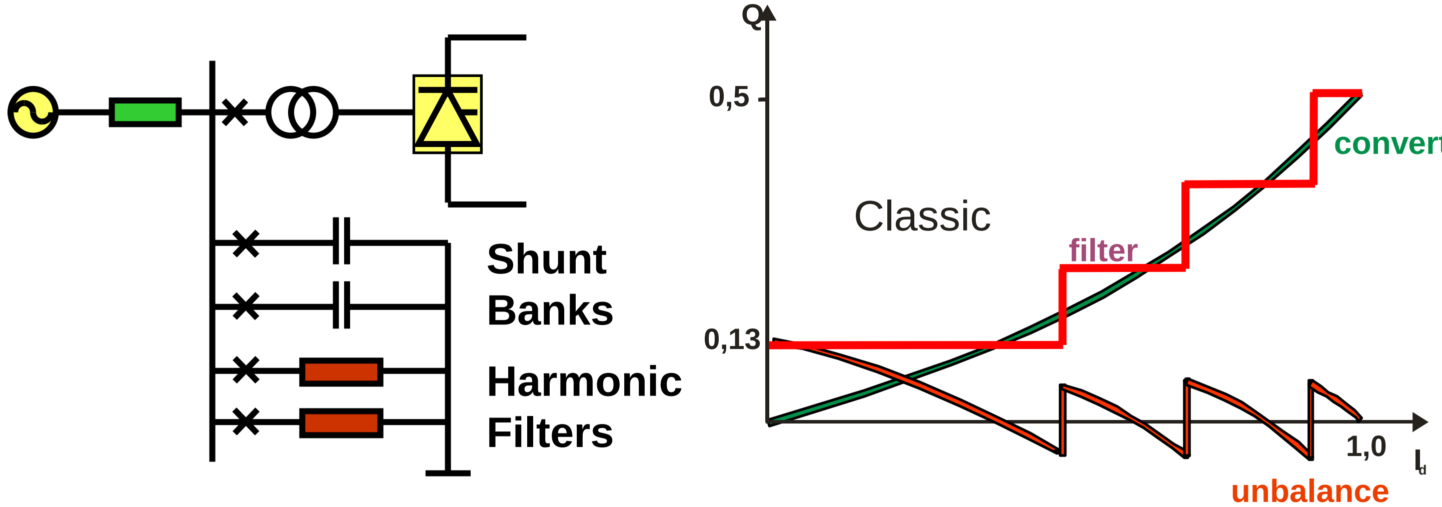
$$P = \sqrt{3}V_{LL}0.78I_d\cos\alpha$$

$$Q_1 = \sqrt{3}V_{LL}0.78I_d\sin\alpha$$

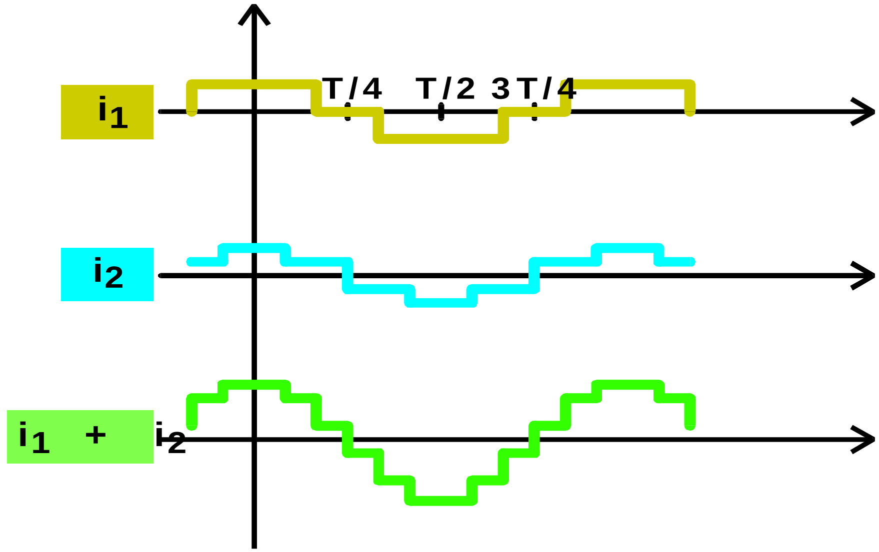


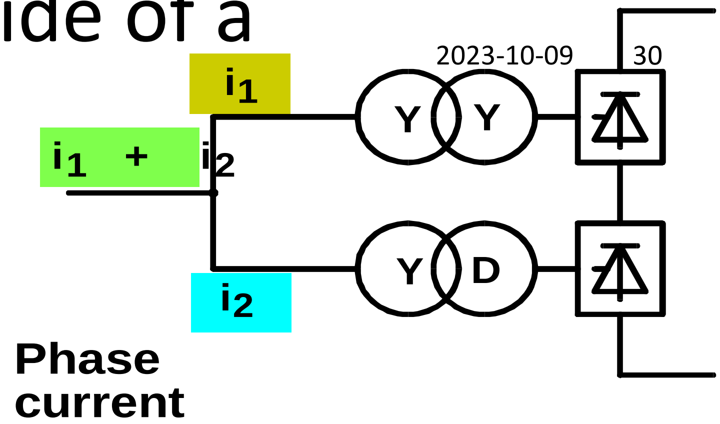
Classic HVDC, Active vs Reactive Power

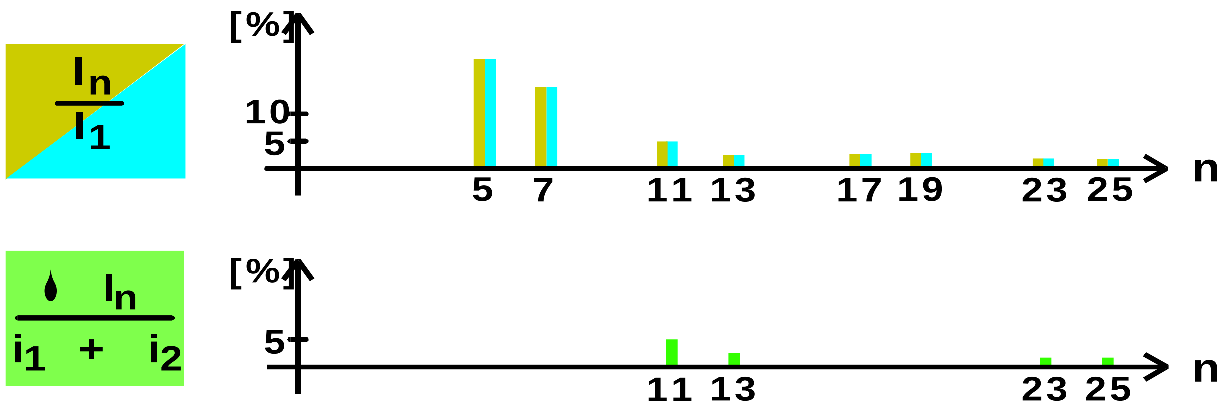
- **How the Reactive Power Balance varies with the Direct Current for a Classic Converter ....**



Harmonic currents on the AC side of a converter



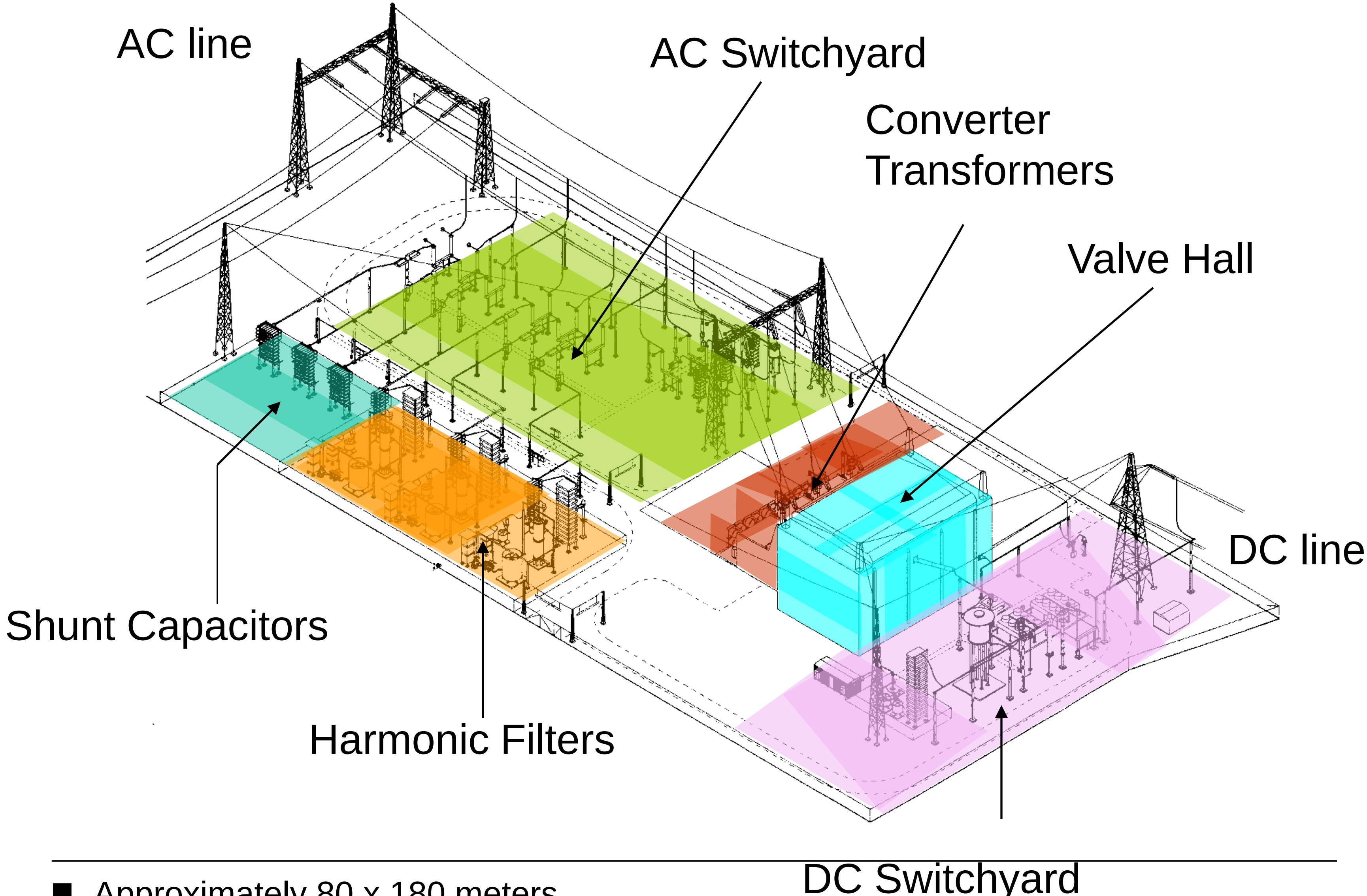




Baltic Cable 600 MW HVDC link

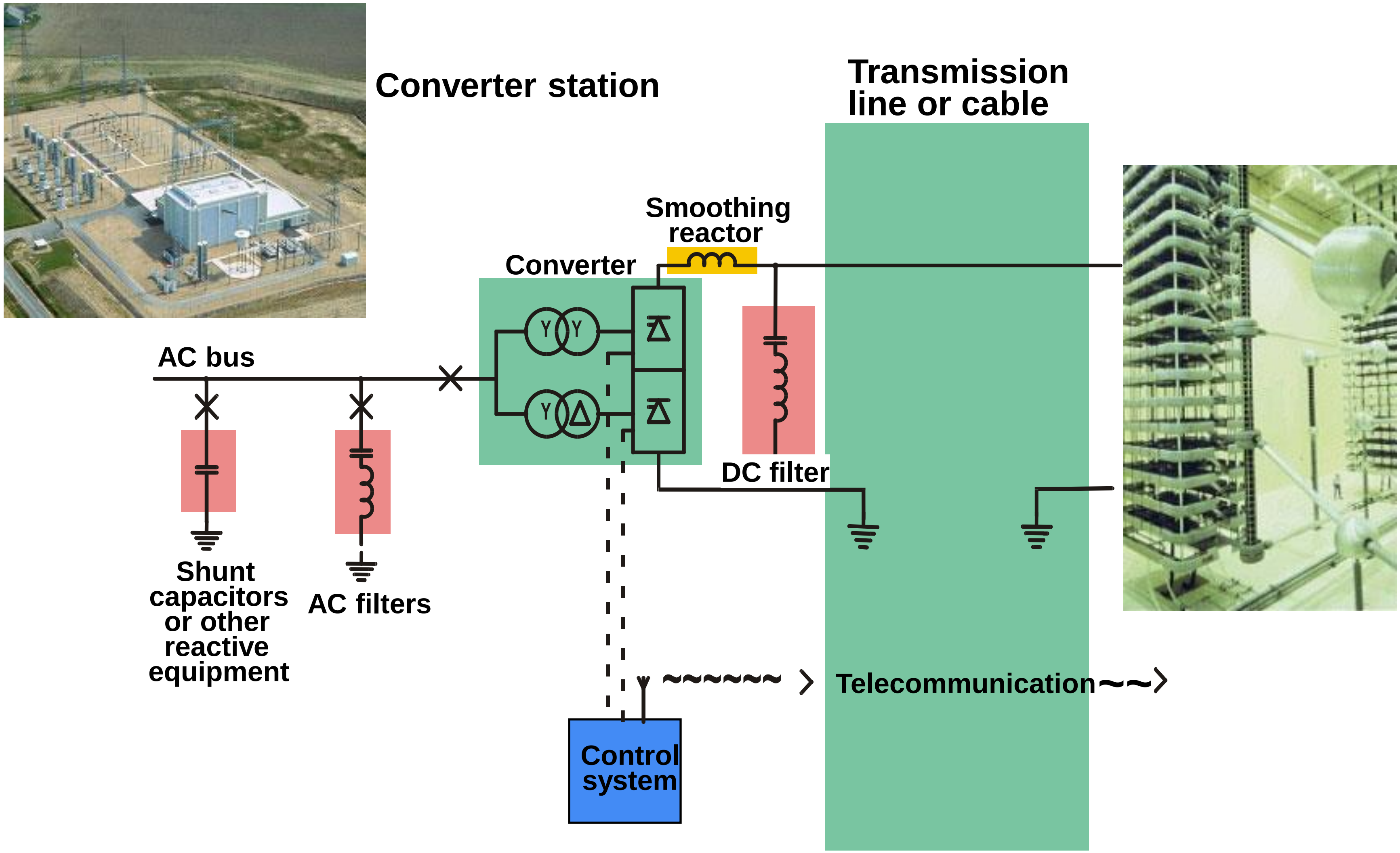
▪L36994

Monopolar Converter station, 600 MW



Approximately 80 x 180 meters

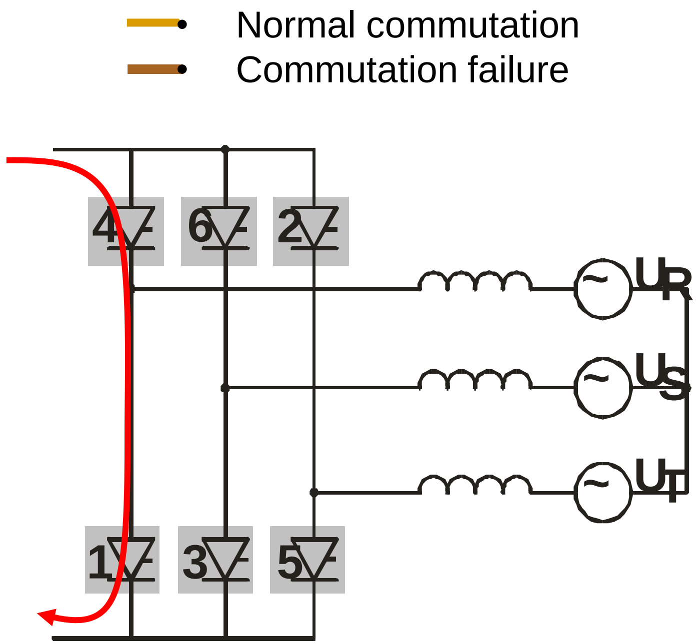
The HVDC Classic Monopolar Converter Station

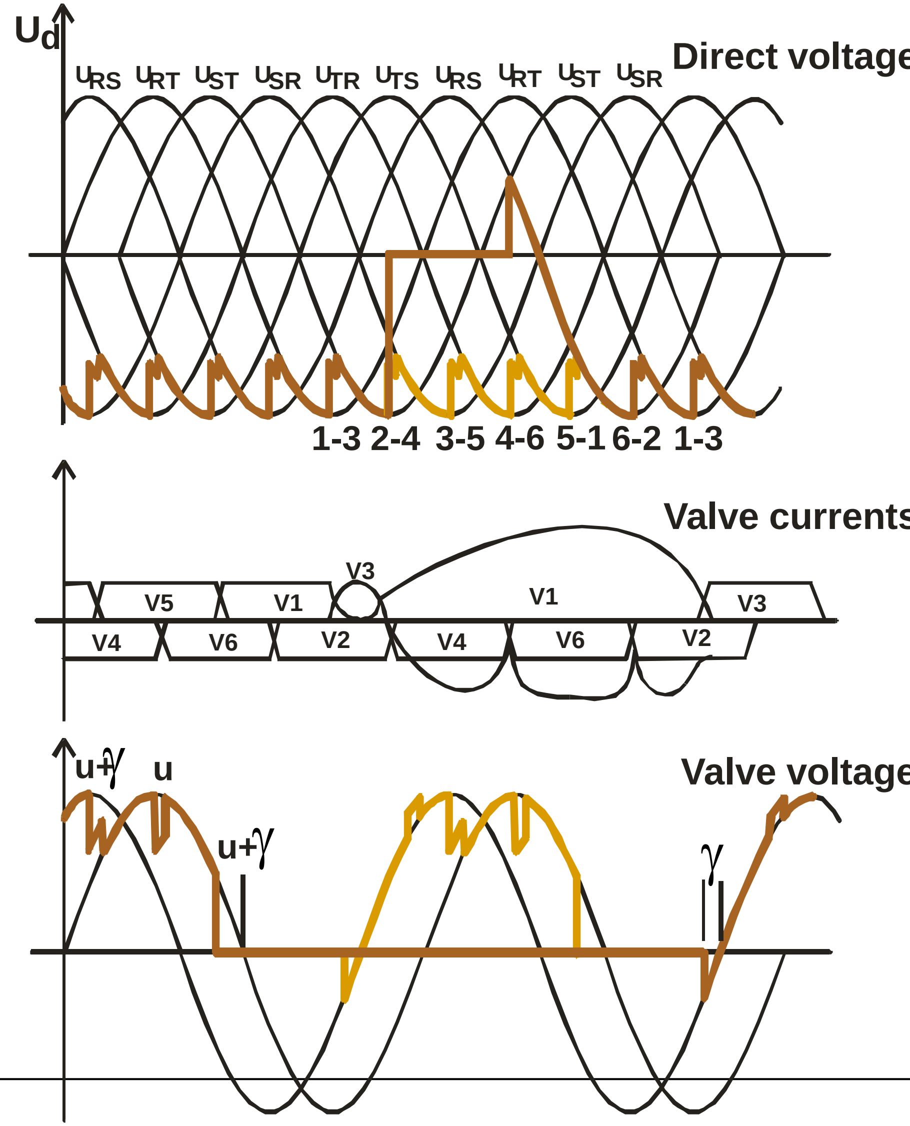


Longquan, China
HVDC Classic

LINKÖPING
UNIVERSITY

Waveshapes during a commutation failure





V1 & V4 conducting simultanously

⇓

DC side short circuit

Lecture 7

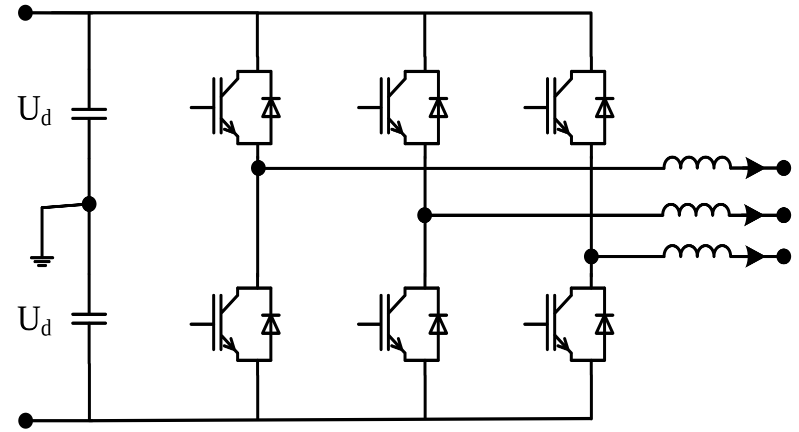
VSC HVDC, IGBT based basic principles

VSC HVDC basic principles

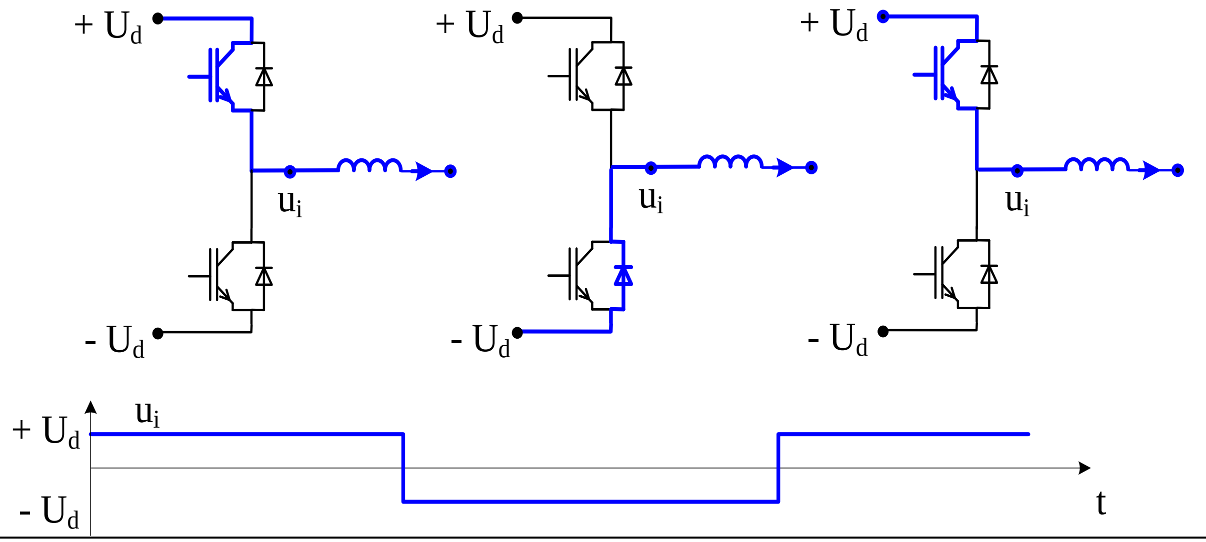
2. VSC converter topologies

Two-level voltage source converter.

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



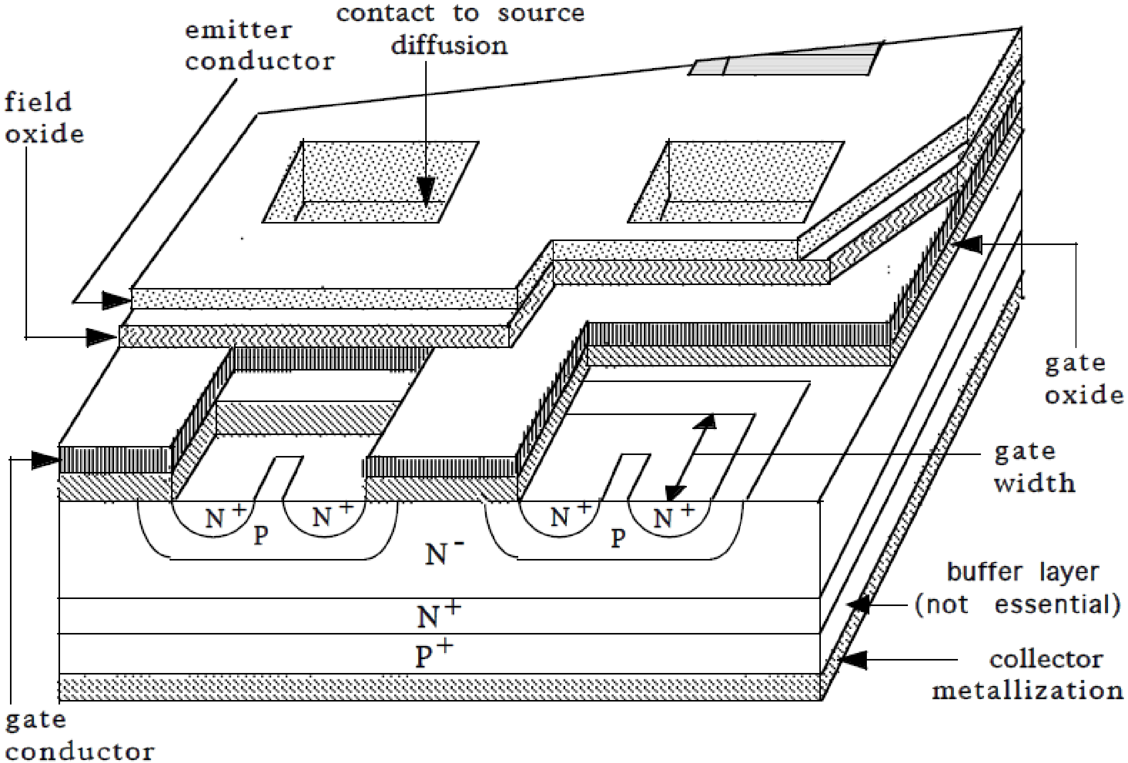
Basic operation of a phase leg:

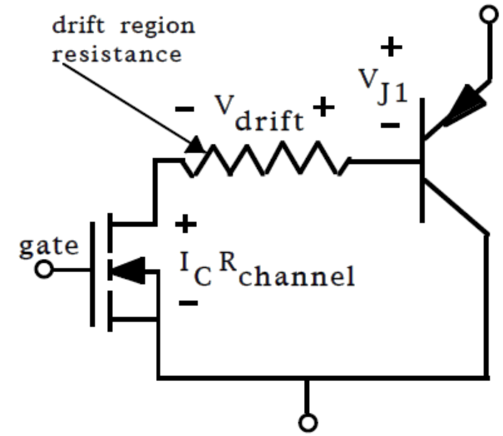


LINKÖPING UNIVERSITY

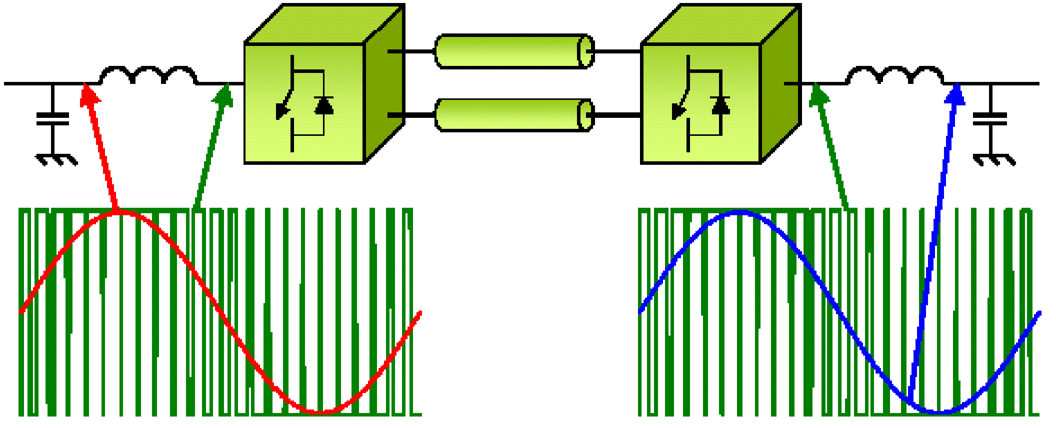
Insulated gate bipolar transistor (IGBT)

- High voltage and current capability
- Chip view, and approximate equivalent circuit



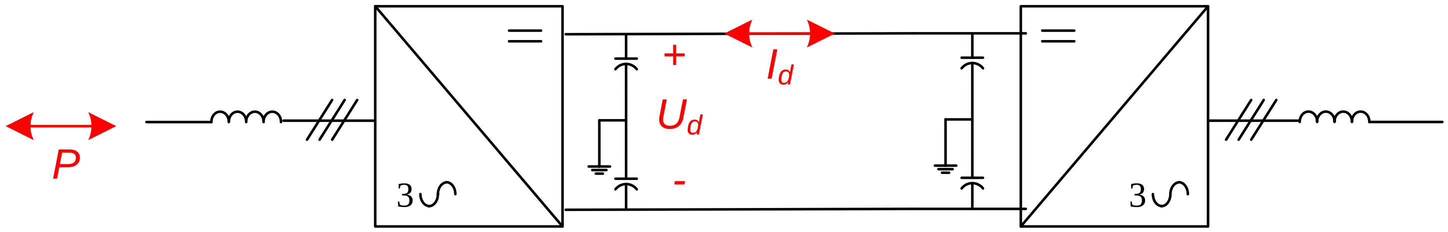


Pulse width modulation of AC voltages

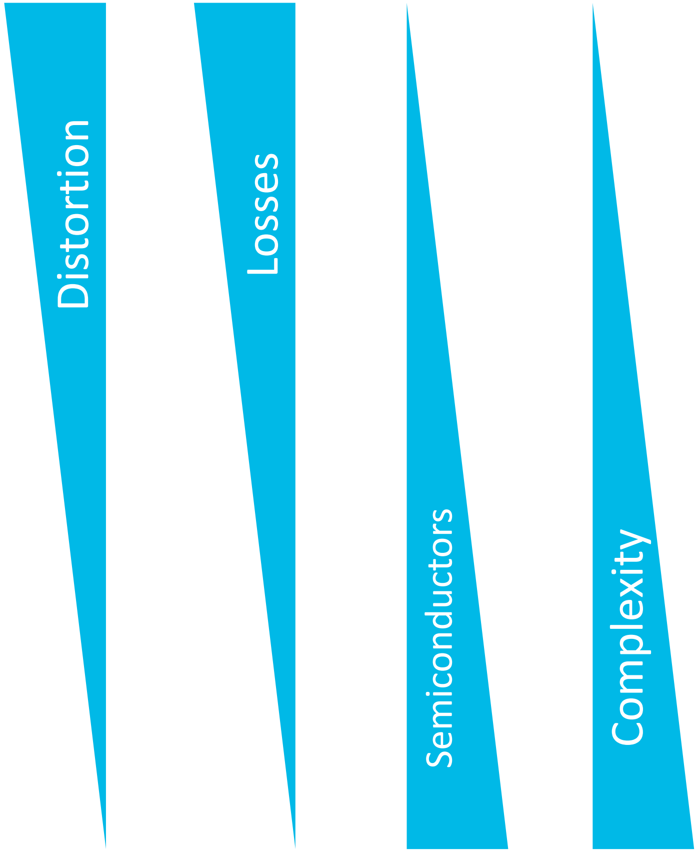


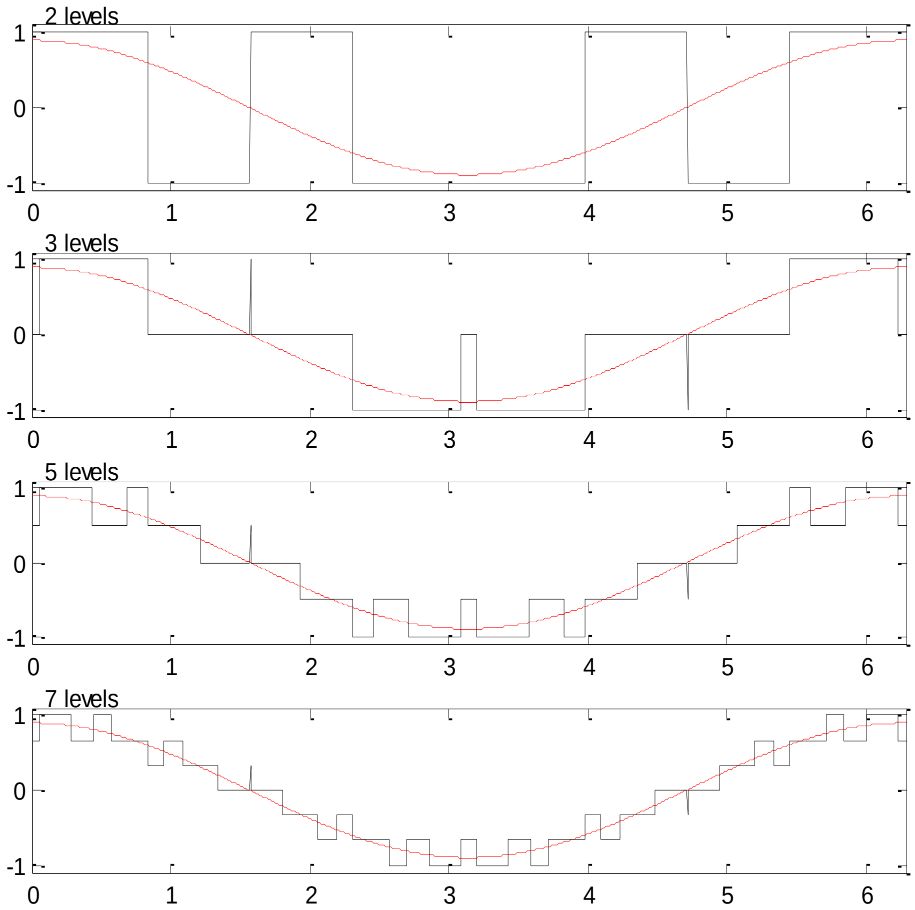
Small filters, both on AC and DC side

Power direction reversal through DC current reversal



Multilevel topologies

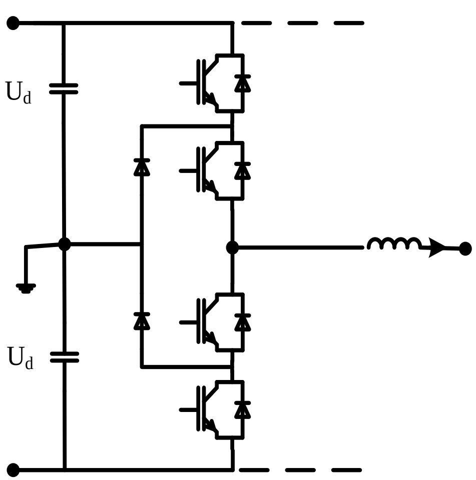




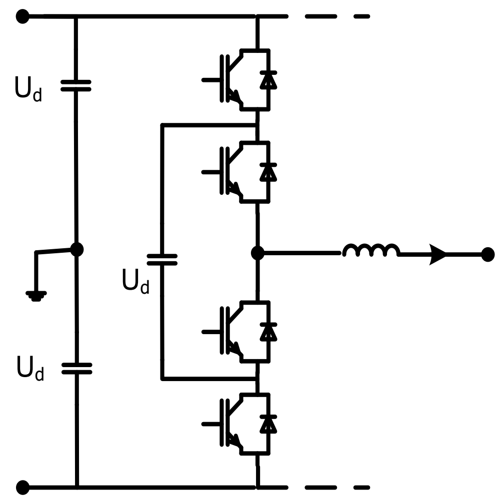
LINKÖPING UNIVERSITY

Multilevel converter topologies

Neutral point clamped (NPC) topologies



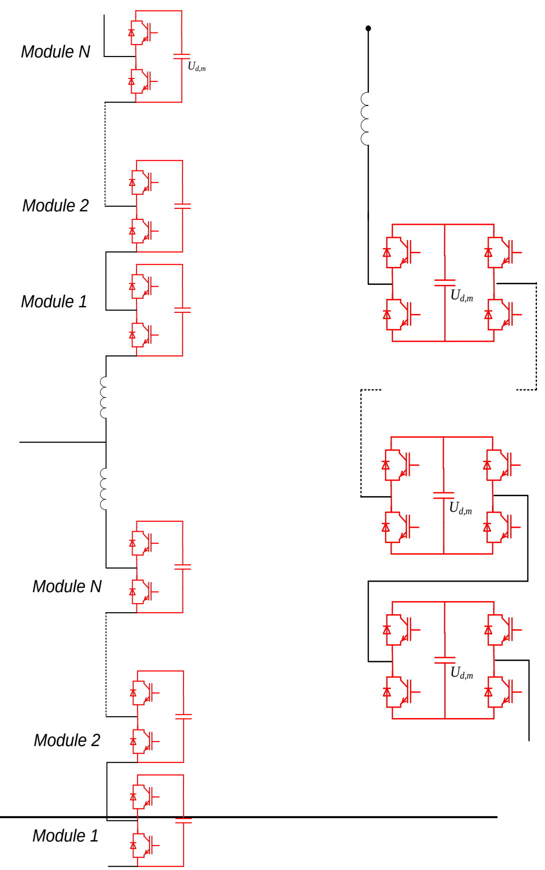
Flying capacitor topologies



Cascaded topologies

Modular Multilevel Converters (MMC)

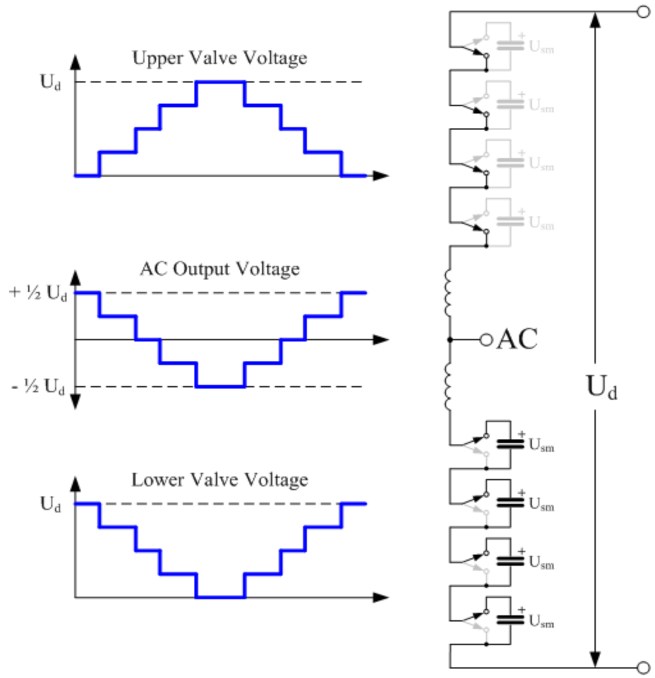
Half-bridge and full-bridge variants

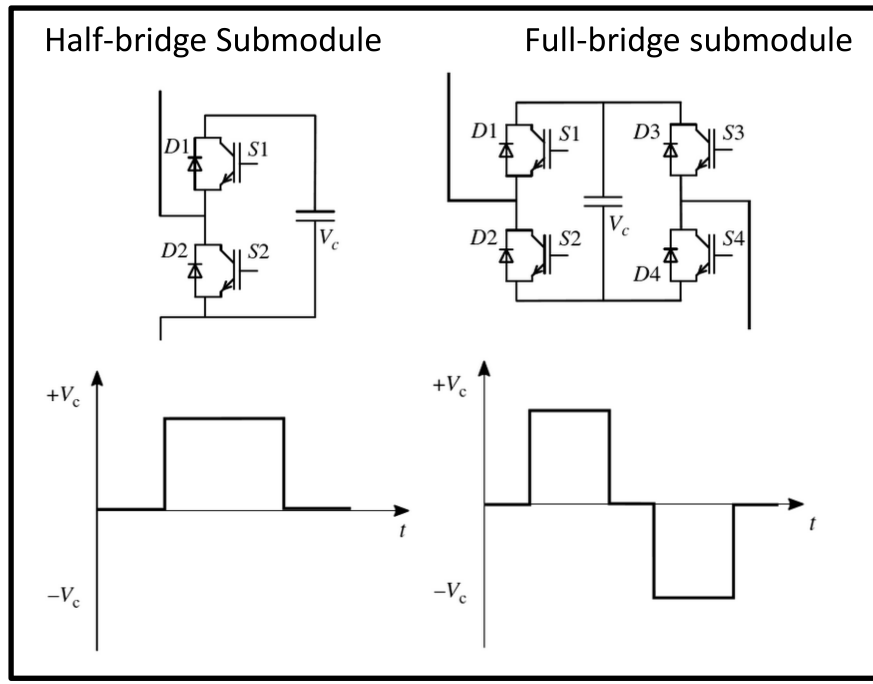


One phase leg, or equivalent, shown in each case

Modular Multilevel Converters (MMC)

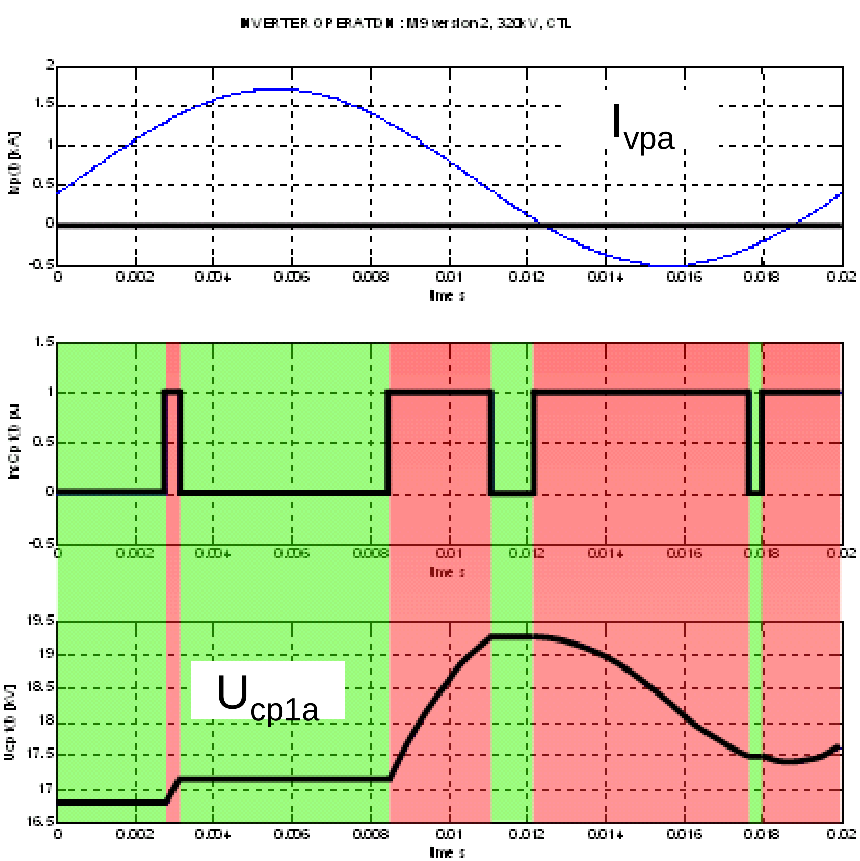
- Operating principle

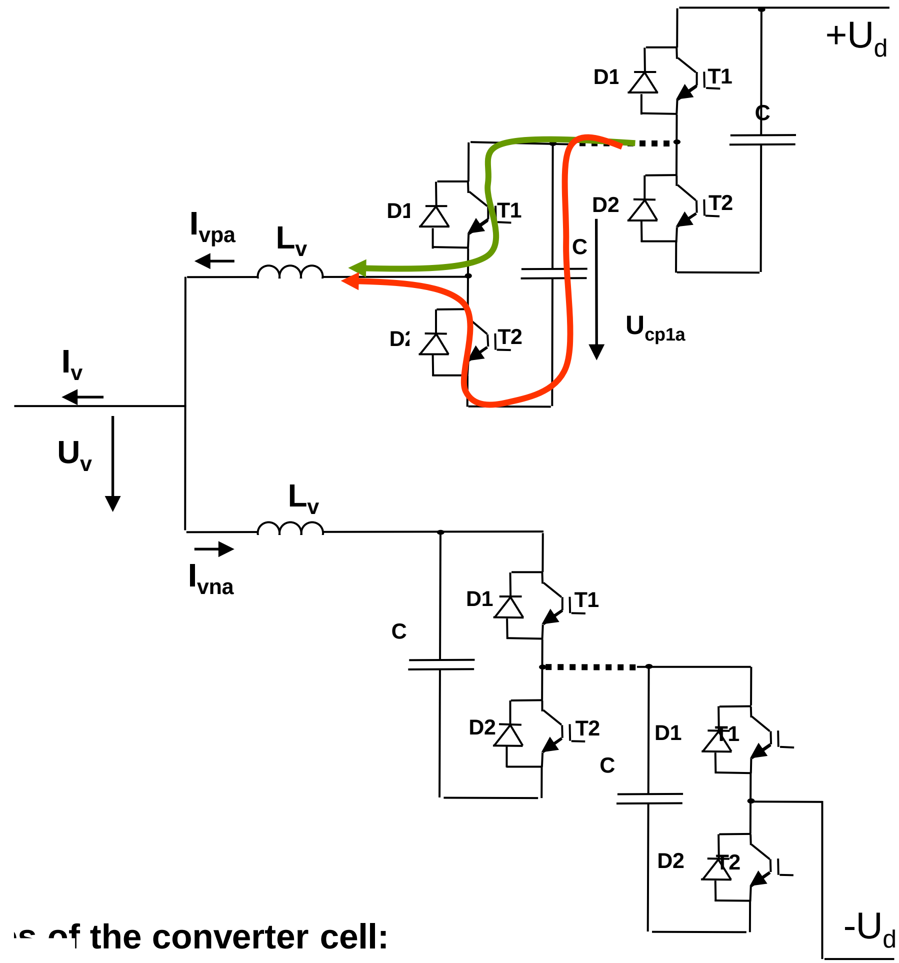




MMC basic principles

MMC-converter, switching principle

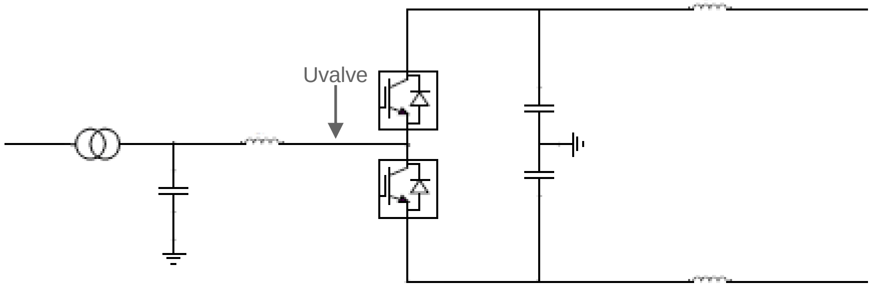


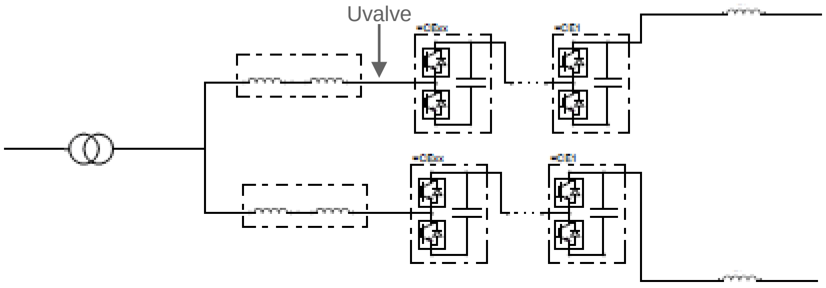


…s of the converter cell:

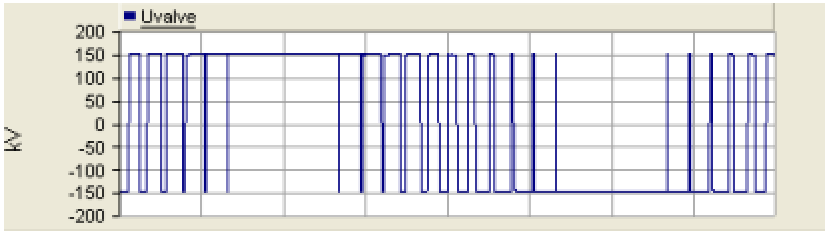
- Bypass mode. Cell capacitor is bypassed. (Green curve)
- Inserted mode. Cell capacitor is inserted and giving contribution to converter output voltage
- Blocked mode. All IGBTs non-conducting

Voltage comparison: 2-level vs. MMC

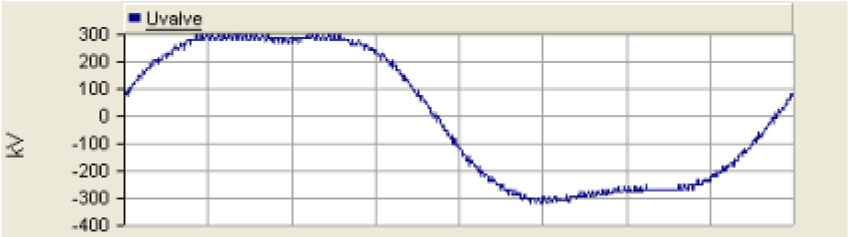




2-level ±150 kV_{dc}

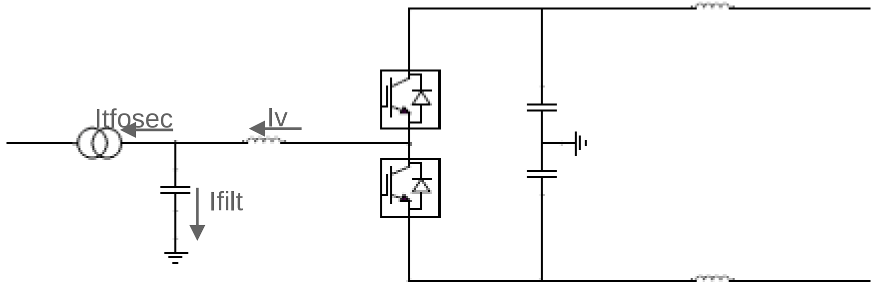


MMC ±320 kV_{dc}

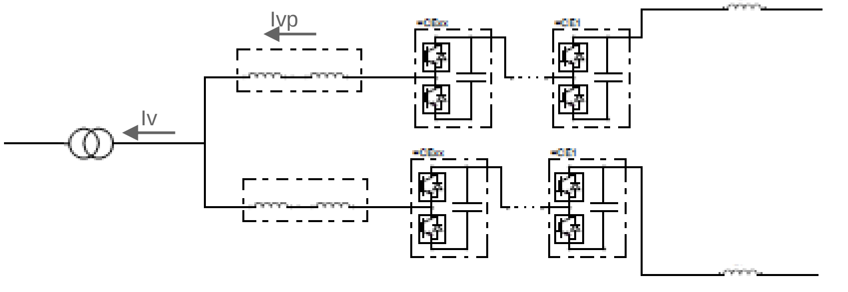


LINKÖPING UNIVERSITY

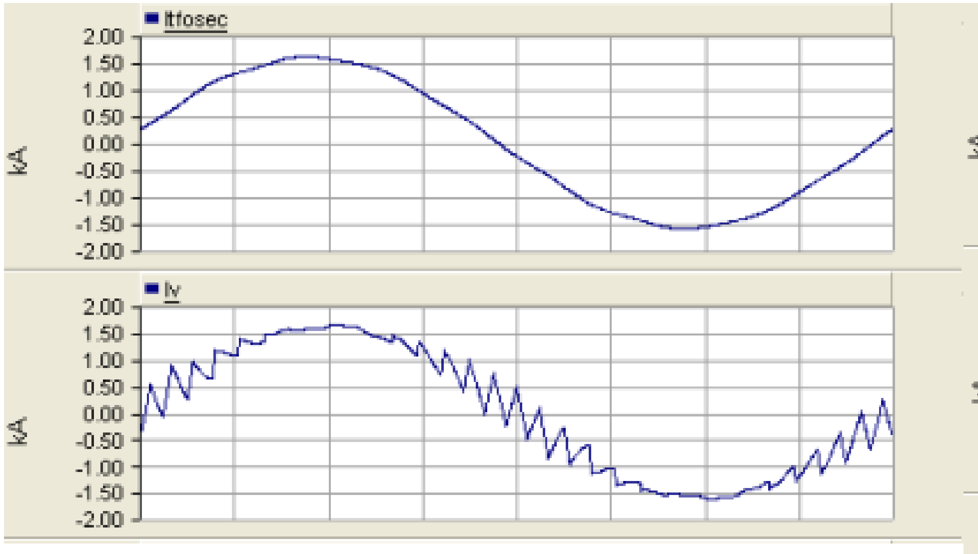
Current comparison: 2-level vs. MMC

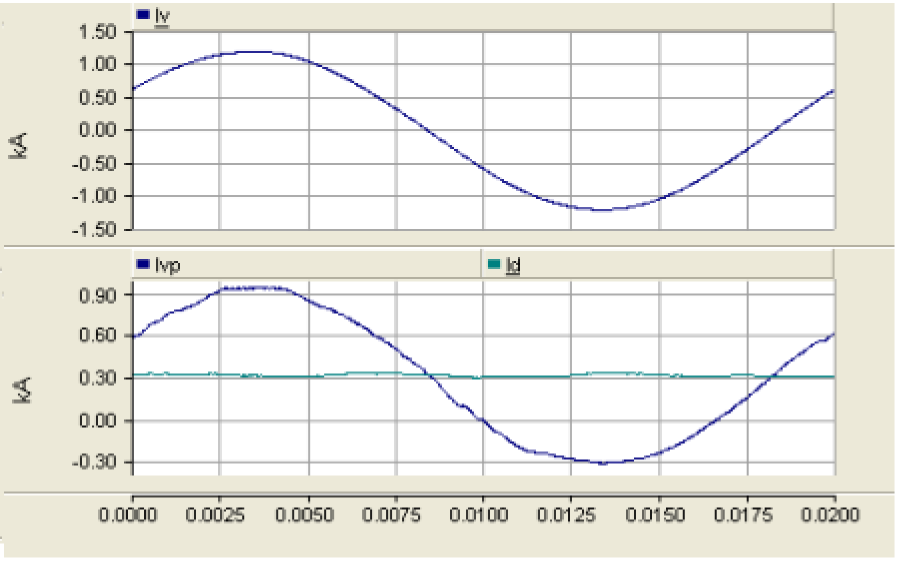


2-level



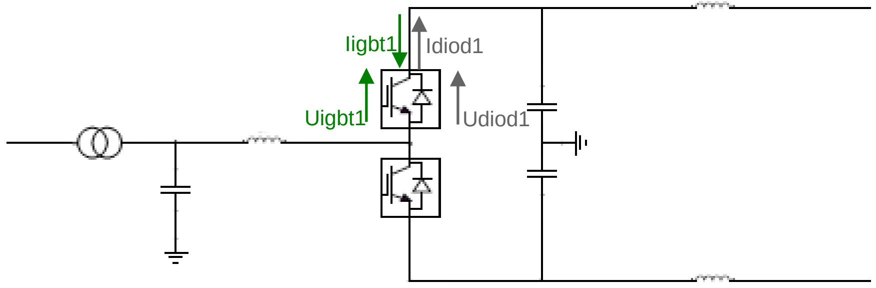
MMC

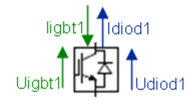


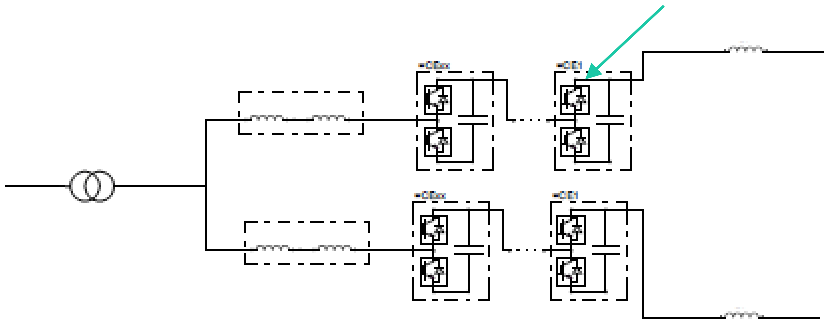


No filters required

Switching comparison: 2-level vs. MMC

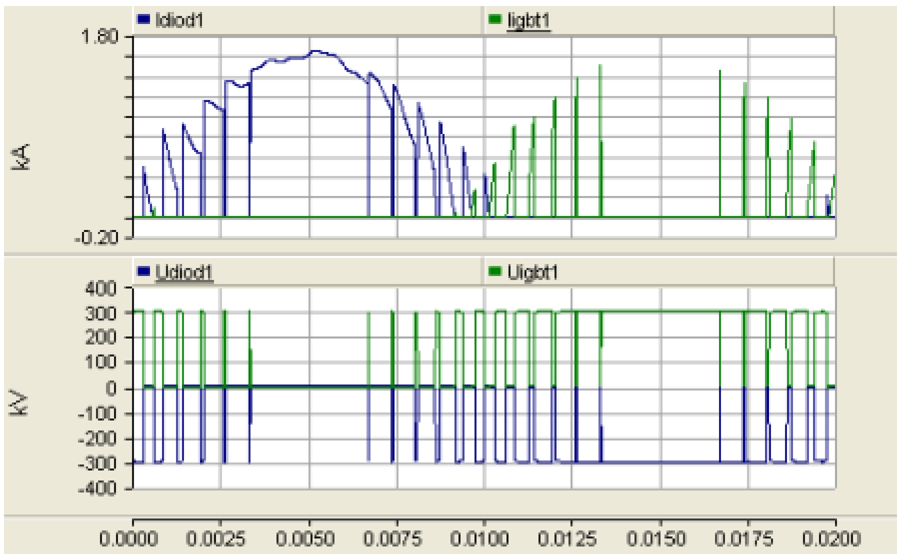




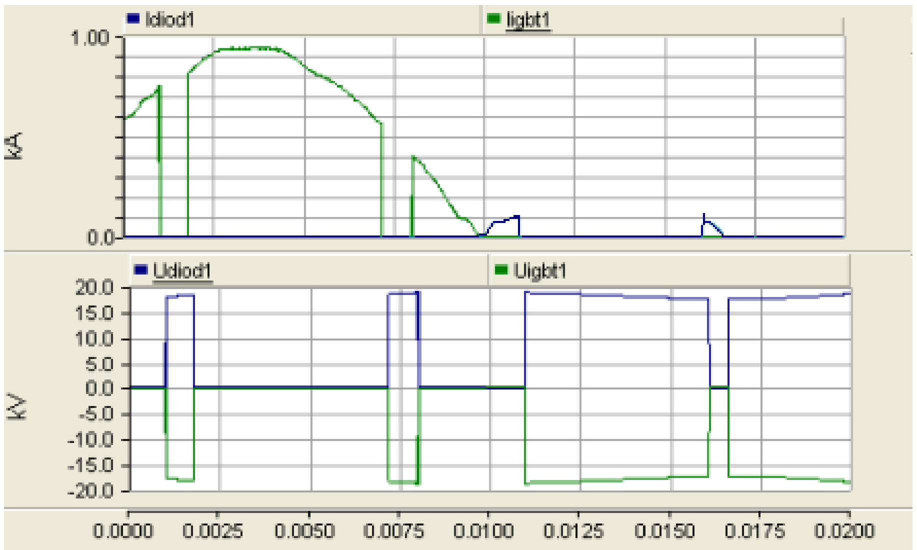


MMC: lower sub-module switching frequency - Reduced losses

2-level

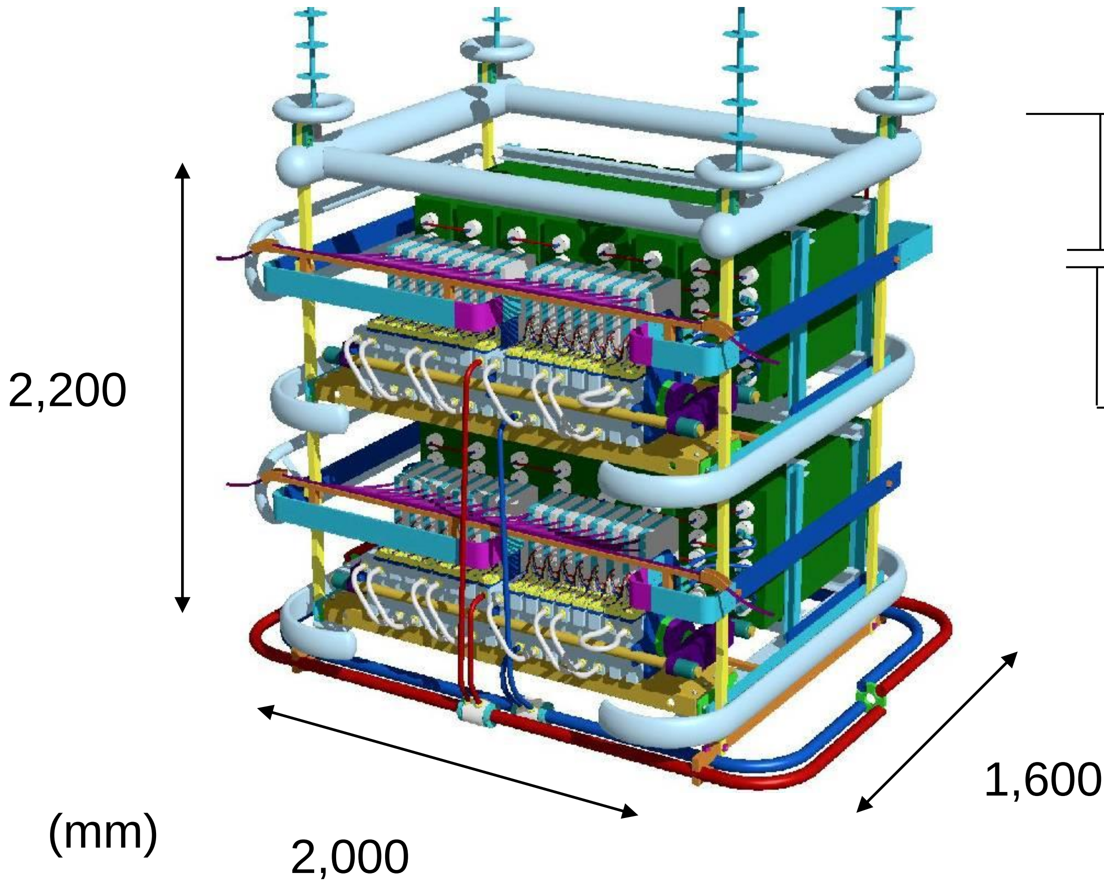


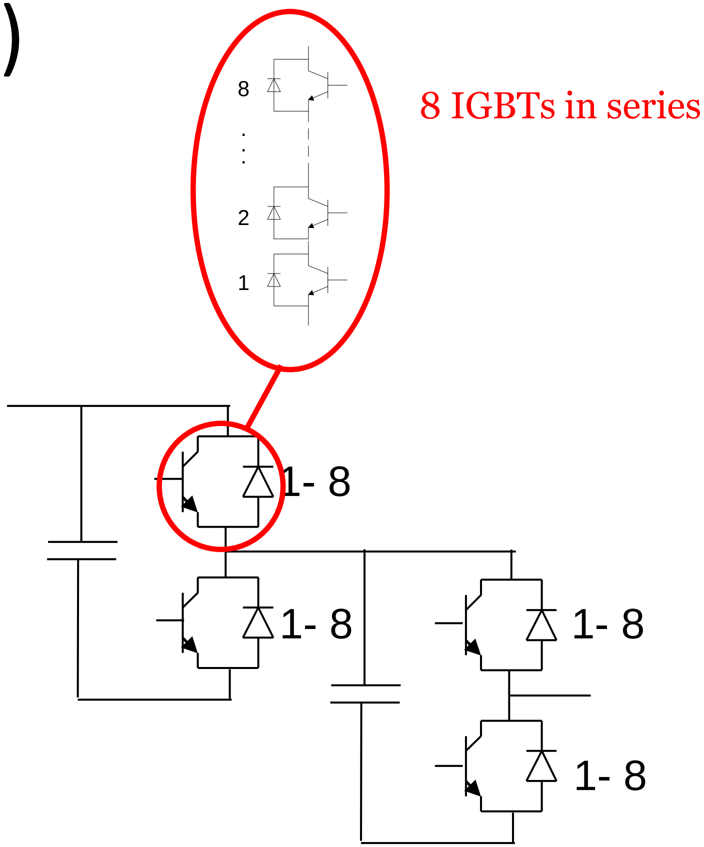
MMC



HVDC Light Generation 4 (ABB)

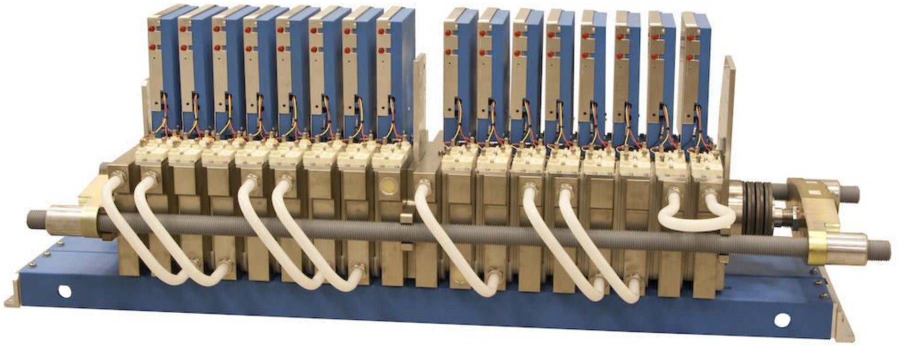
Double cell

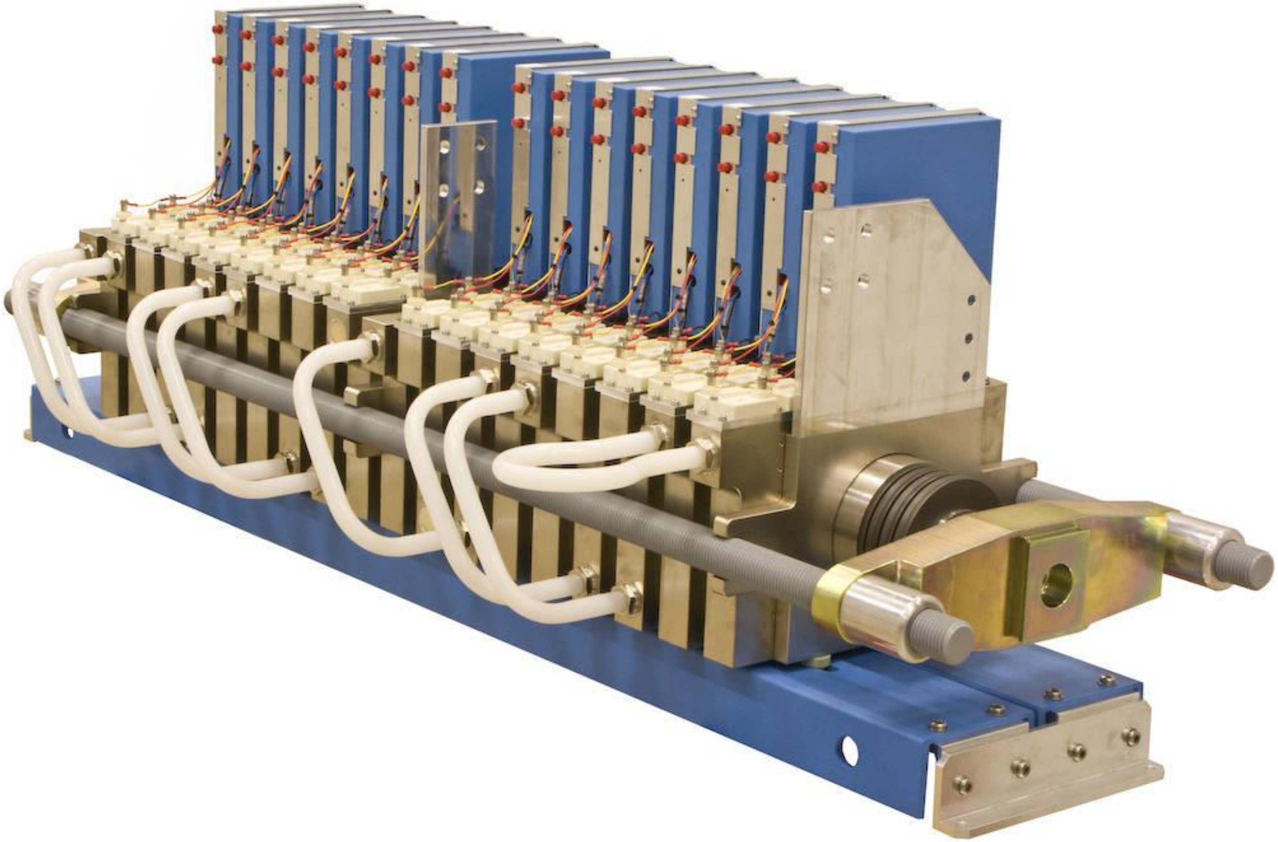




Mass 3,000 kg

IGBT Module





LINKOPING
UNIVERSITY

IGBT inner structure

LINKÖPING UNIVERSITY

Lecture 7

VSC in the power grid
Wind applications

Offshore Wind Power Connectors

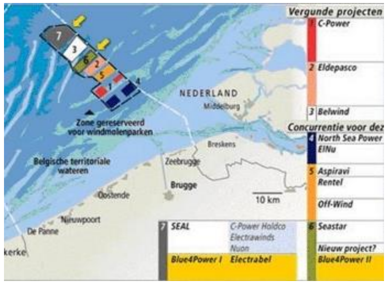
Planned installations – Europe

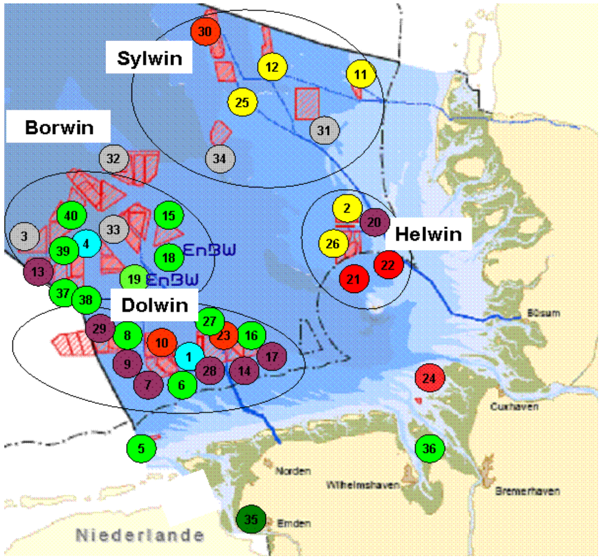
Wind farms increase in size.

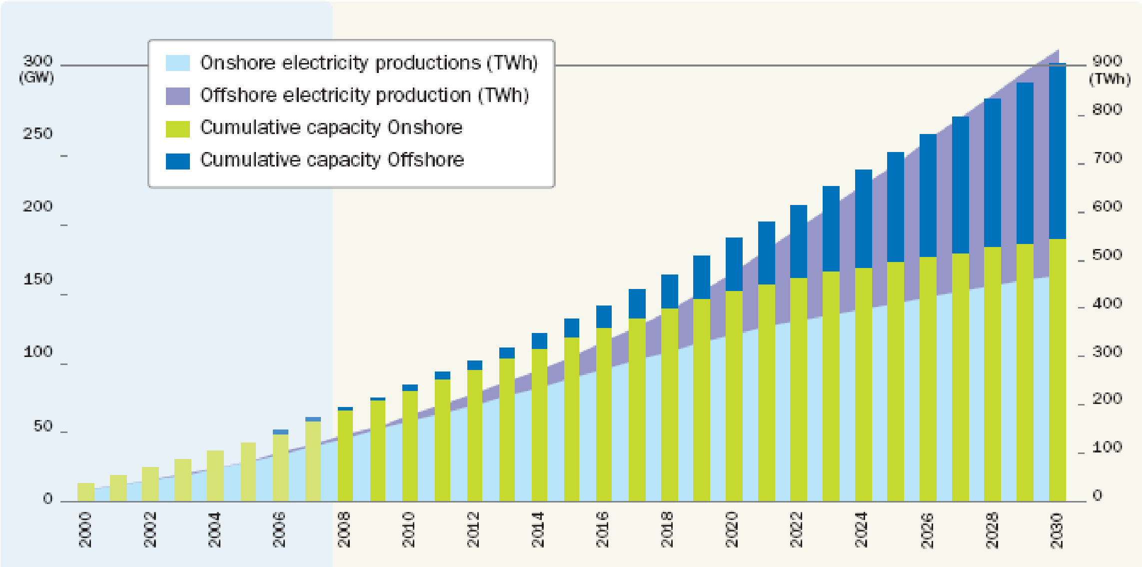
Most of them above 300 MW.

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)



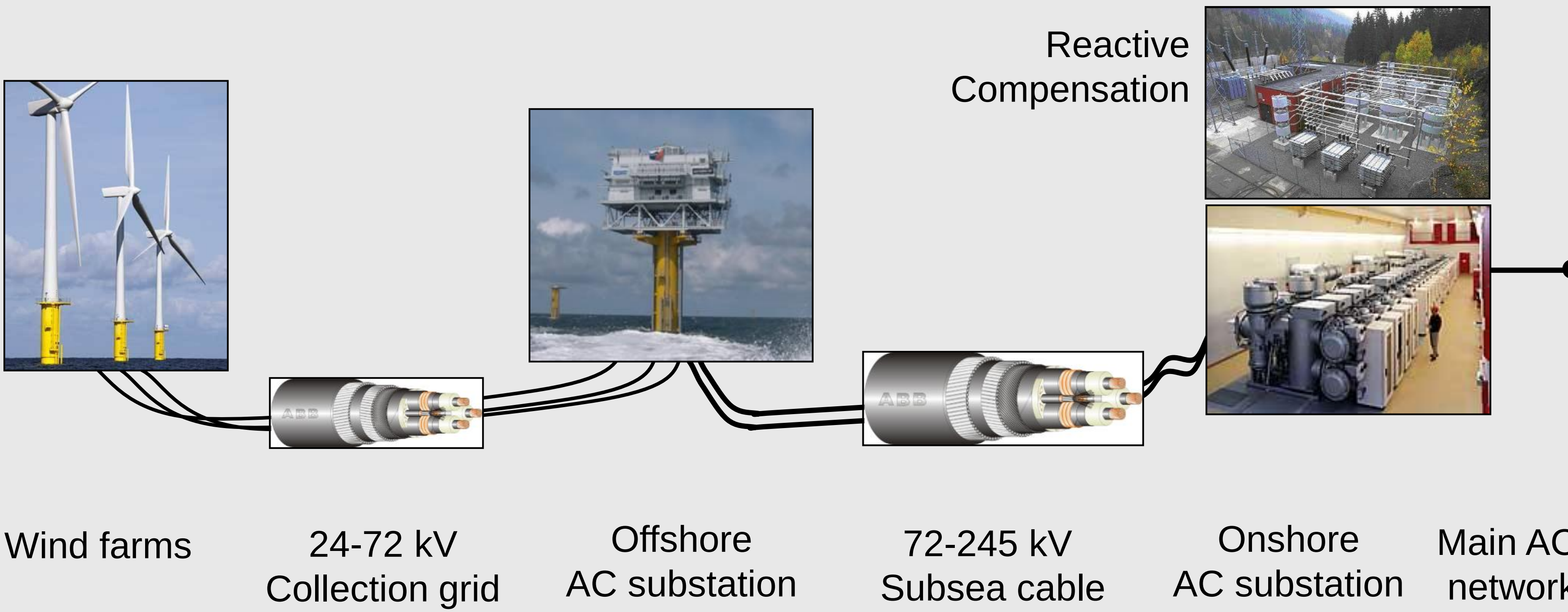




LINKÖPING UNIVERSITY

Overview

Offshore AC wind power connectors



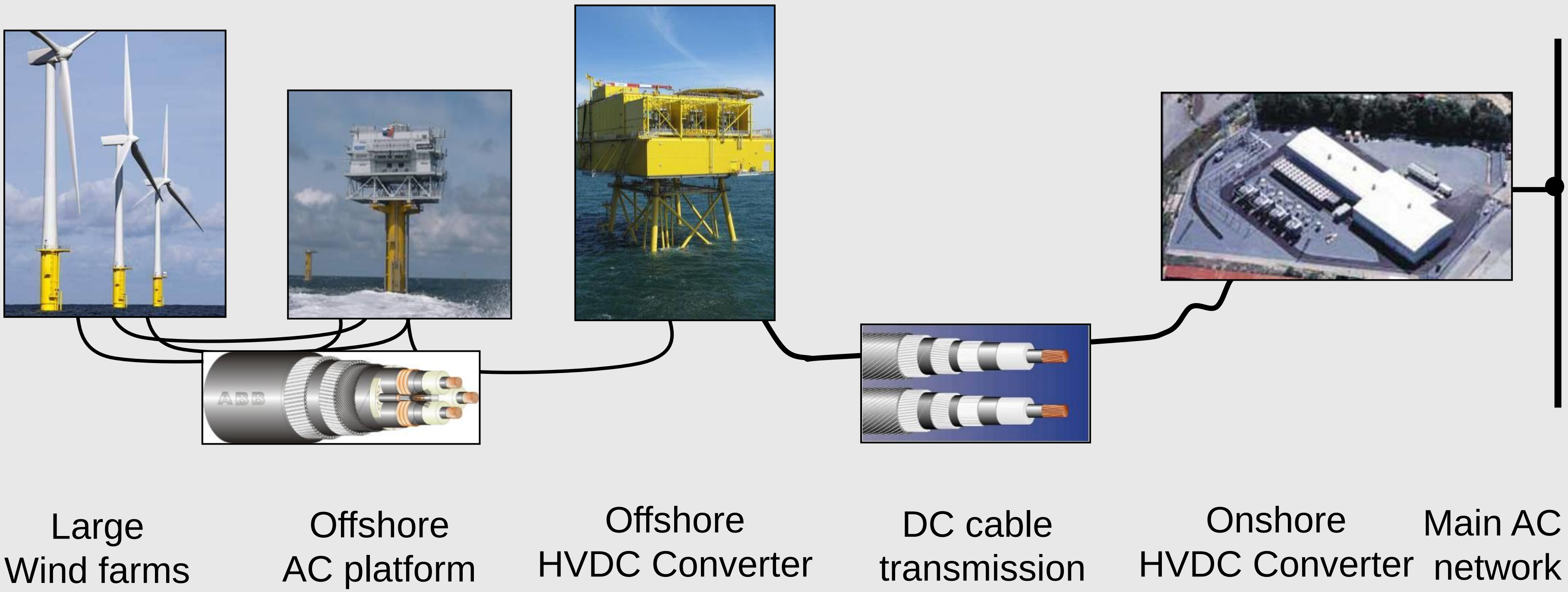
50 – 300 MW: 72-150 kV
200 – 500 MW: 150-245 kV

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	

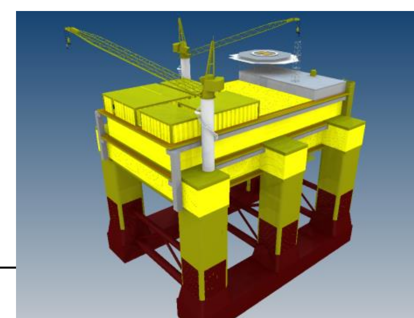
VSC technology for compact solutions. ABB with 10 years experience (13 references)

Borwin 1, Dolwin 1 & 2, TenneT 2GW Offshore

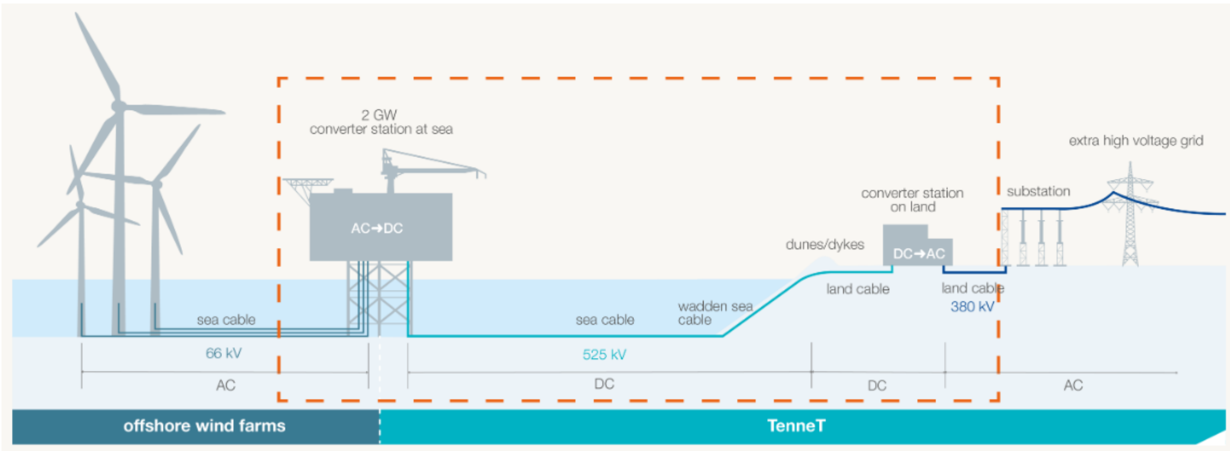
Main data	Borwin 1	Dolwin 1	Dolwin 2	2 GW
In operation:	2010	2013	2015	2029-
Power rating:	400 MW	800 MW	900 MW	2000 MW
AC Voltage Platform: Onshore	170 kV 380 kV	155 kV 380 kV	155 kV 380 kV	66 kV 380 kV
DC Voltage:	±150 kV	±320 kV	±320 kV	±525 kV
DC underground cable: DC submarine cable:	2 x 75 km 2 x 125 km	2 x 75 km 2 x 90 km	2 x 45 km 2 x 90 km	

DOLWIN1: efficiently integrating power from offshore wind

DOLWIN alpha platform loadout



TenneT 2GW program



The following projects are part of the 2GW Program:

Germany

Project	Year of commissioning
BalWin3	2029
BalWin4	2029
LanWin1	2030
LanWin2	2030
LanWin4	2031
LanWin5	2031

The Netherlands

Project	Year of commissioning
IJmuiden Ver Beta	2029
IJmuiden Ver Alpha	2029
IJmuiden Ver Gamma	2029
Nederwiek 1	2030
Nederwiek 2	2030
Nederwiek 3	2031
Doordewind 1	2031
Doordewind 2	2031

LINKÖPING UNIVERSITY

[The 2GW Program | TenneT]

www.liu.se

LINKÖPING UNIVERSITY