Tutorial I: HVDC Transmission

HVDC Fundamentals and State-of-the-Art: A Vendor Perspective

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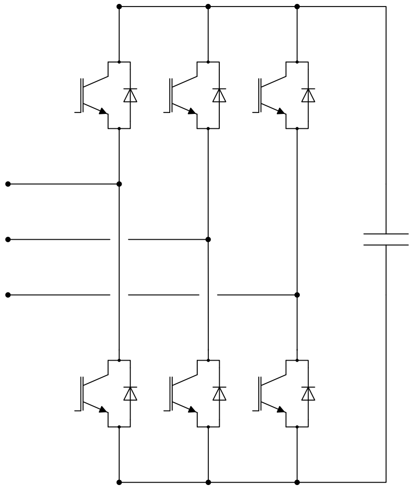
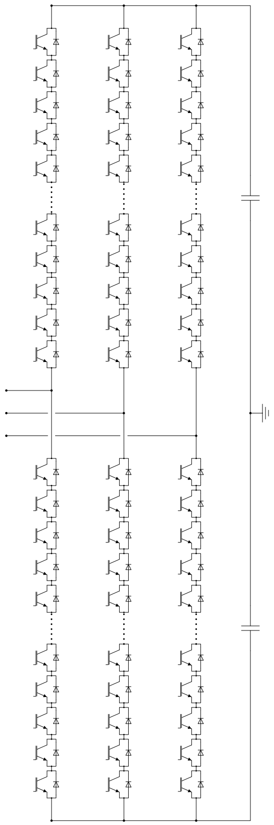
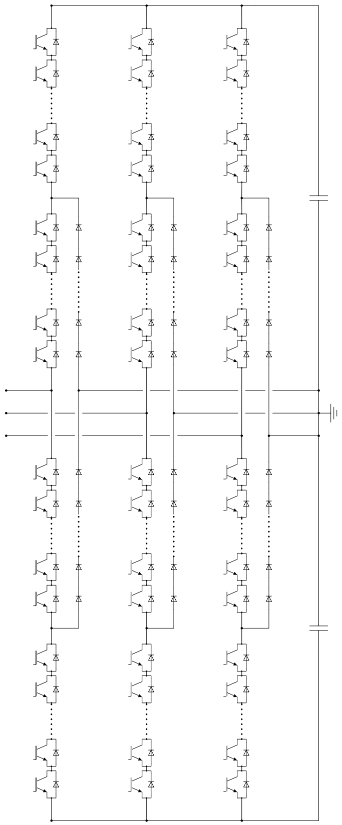
VSC-HVDC technology
2-Level and 3-Level

https://www.mobility.siemens.com/us/en/portfolio/rail/rolling-stock/locomotives.html





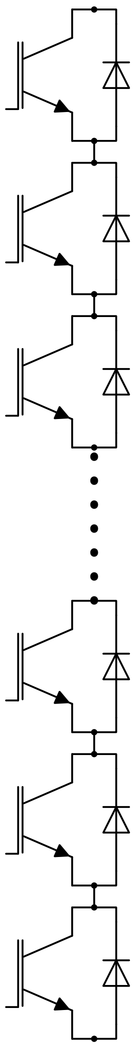
2-Level Converter



3-Level Converter

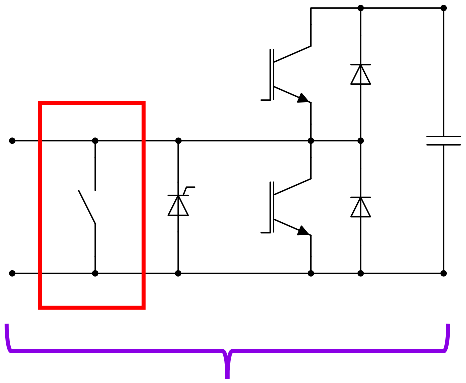
VSC-HVDC technology
2-Level and 3-Level

- Central energy storage (capacitor)
- Series connection of IGBTs
- High switching frequency (> 2kHz)
- High switching impulses
- HF filter requirement
- High losses (due to high switching frequency)
- **Controllable IGBT failure**:
  - ➢ In case of a fault IGBT will form a short circuit
  - ➢ IGBT is capable to operate in short circuit till the next maintenance cycle
  - ➢ Application of special IGBTs

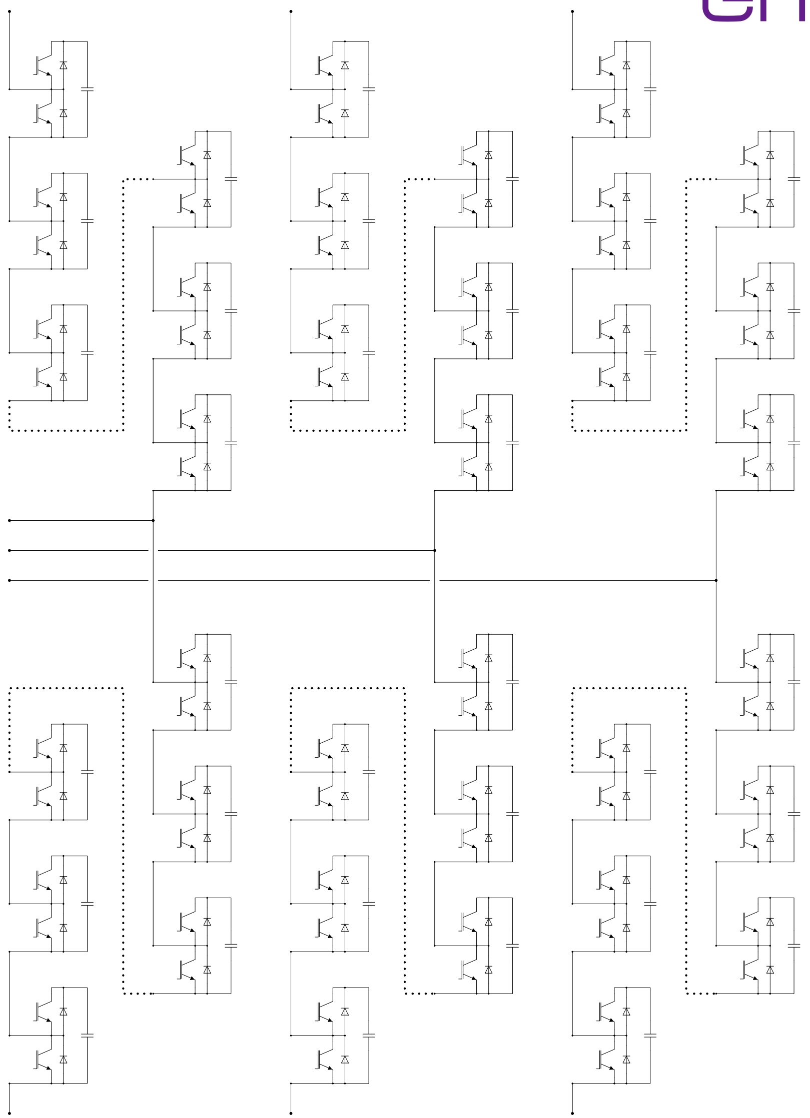


Modular Multilevel Converter (MMC)

- Distributed energy storage in Submodules (SM)
- Low switching frequency
- Application of standard industrial IGBTs
- In case of a fault the faulty IGBT can be bypassed by a mechanical switch



Submodule



MMC

- All HVDC suppliers are using now the same VSC-Technology: **Modular Multilevel Converter (MMC)**
- Technology firstly introduced by Siemens in 2010 with Transbay Cable Project in SF bay
- Using the same VSC-Technology helps to develop the technology and learn from operational experiences
- MMC Technology is also used in modern STATCOM systems

VSC HVDC comparisson

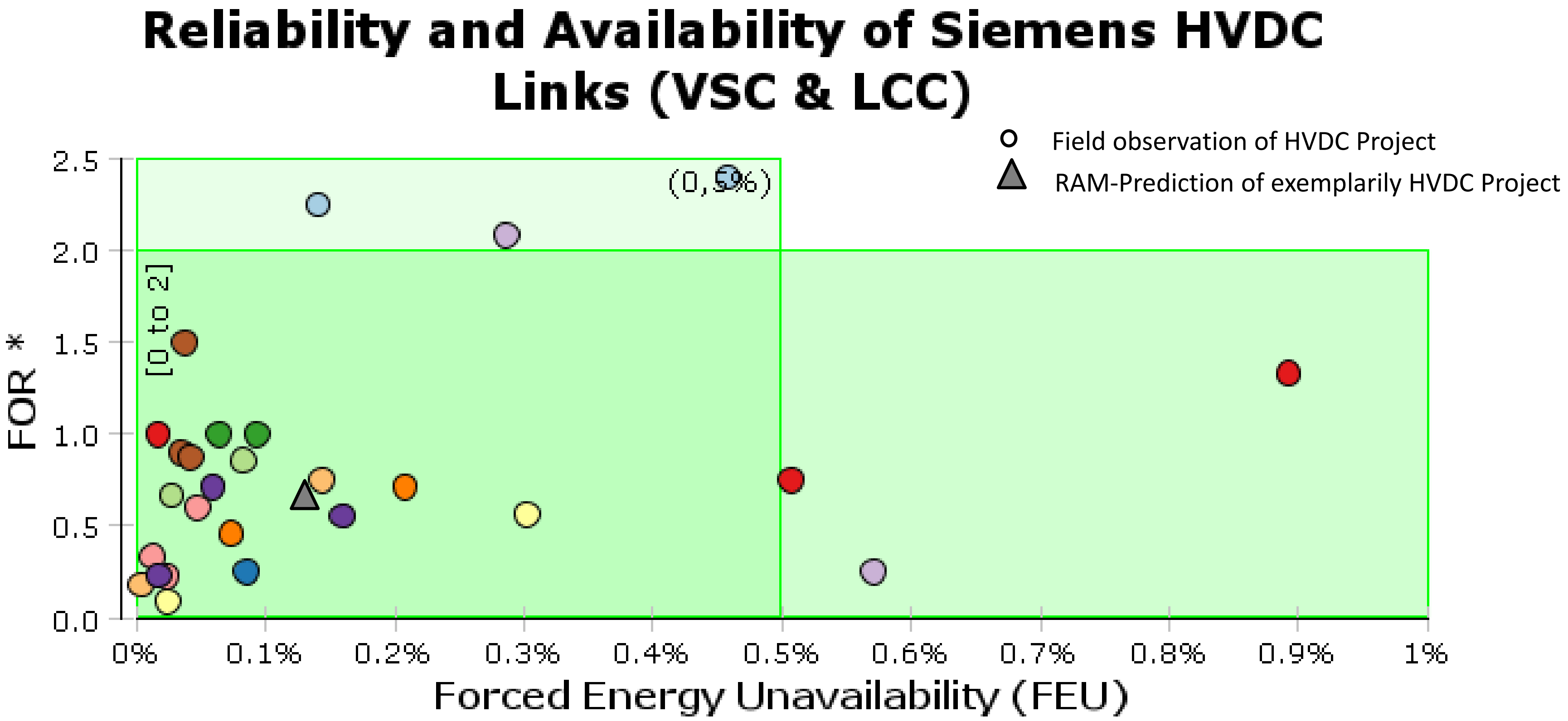
2-Level and 3-Level	MMC
Special IGBTs with **short-on-fail capability**	**Standard** industrial IGBTs
High switching frequency	Low switching frequency
High losses	Small losses (down to 0.7%)
HF filter requirement	HF filter can be avoided
	Modular design allows easy scaling for DC voltages
	Reduced harmonics
	High reliability
	High power ratings > 3GW

MMC Set-Up

https://www.hitachienergy.com/ca/fr/news/press-releases/2021/12/hitachi-energy-wins-major-contract-for-the-first-of-its-kind-sub-sea-power-transmission-network-in-the-mena-region-advancing-a-sustainable-energy-future-for-abu-dhabi

https://www.ge.com/news/taxonomy/term/6426

Reliability



- The VSC and LCC FOR and FEU are very similar
- The majority of the outages happen at the beginning of the project lifetime
- Outages are mostly caused by auxiliary and C&P systems
- Operation data of many VSC systems is publicly available

FEU: Forced Energy Unavailability
FOR: Forced Outage Rate

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LCC vs VSC

LCC	VSC
Line **C**ommutated **C**onverter	**V**oltage **S**ourced **C**onverter **F**orced **C**ommutated **C**onverter (FCC)
Thyristors with turn on capability	**IGBTs** with turn-on and turn-off capability and **energy storage** capability
Reactive power compensation requirement	Reactive power injection and absorption capability Reduced AC yard requirements
Minimum AC grid strength requirement	Islanded network operation capability
High power capability	PressPack IGBTs have similar current ratings as Thyristors
Station losses of up to 0.7%	Station losses of up to 0.7%
Power flow direction control by DC voltage polarity change	Power flow direction control by DC current direction change
Inherent DC fault clearance capability	DC fault clearance with Full Bridge (FB), DC breakers or AC breakers (increased fault clearing times)

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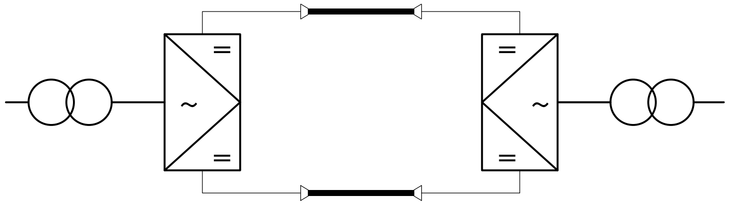
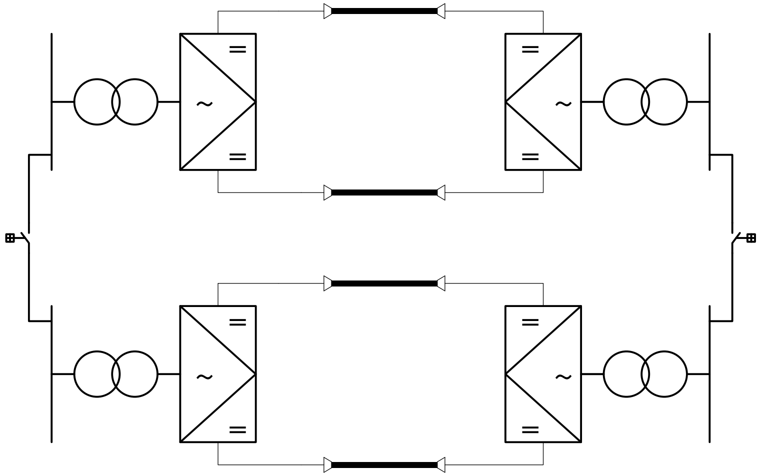
DC circuit topologies
Symmetrical Monopole (SMP)





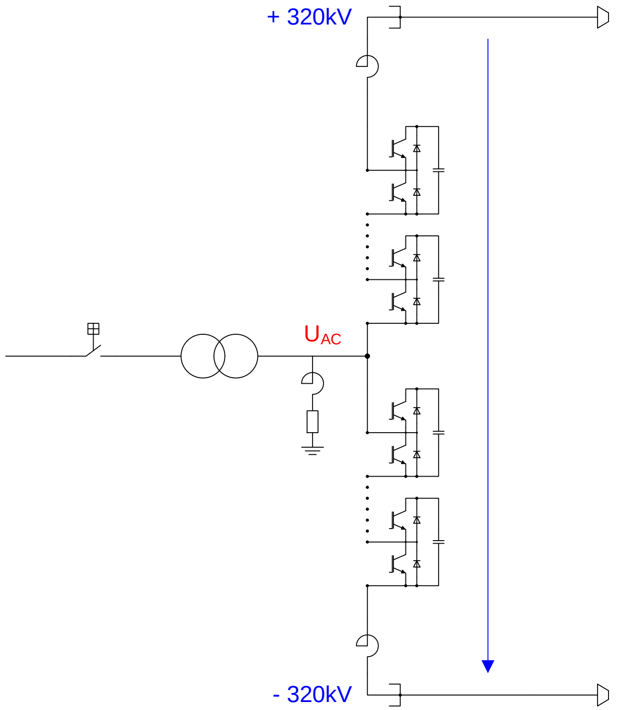
Symmetrical Monopole

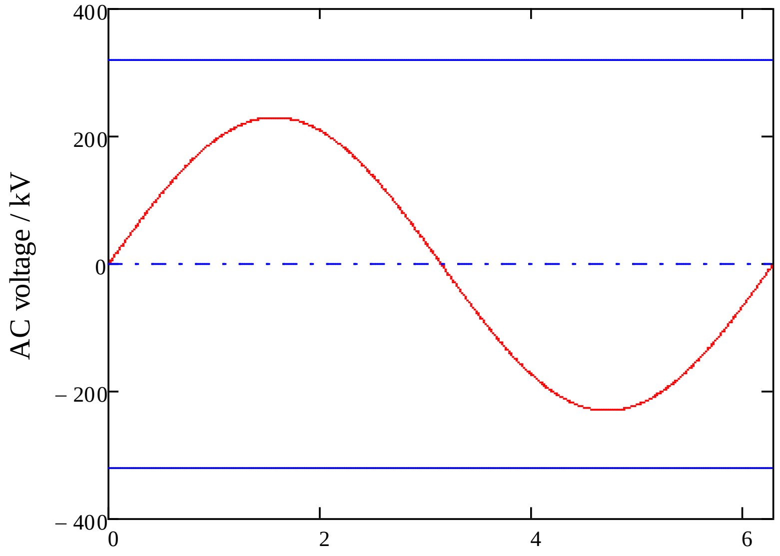
- TBC
- ALEGrO
- NEMO
- ElecLink
- ...

Dual Symmetrical Monopole

- INELFE
- PK2000

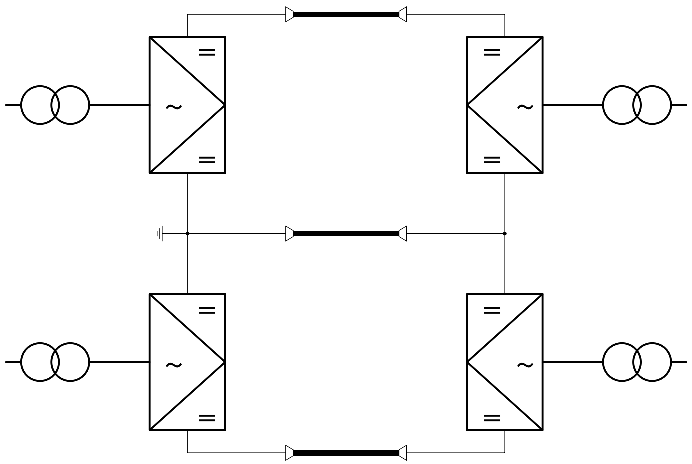
SMP Voltage stress





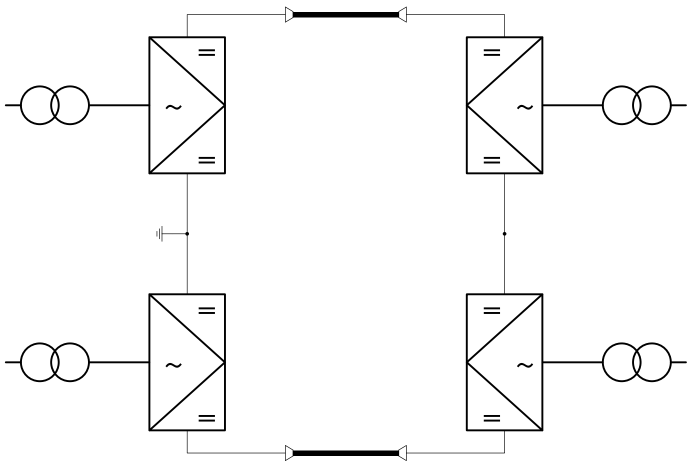
- No DC voltage stress on the converter side of the transformer → Standard AC equipment can be used

DC circuit topologies
Bipole (BIP)



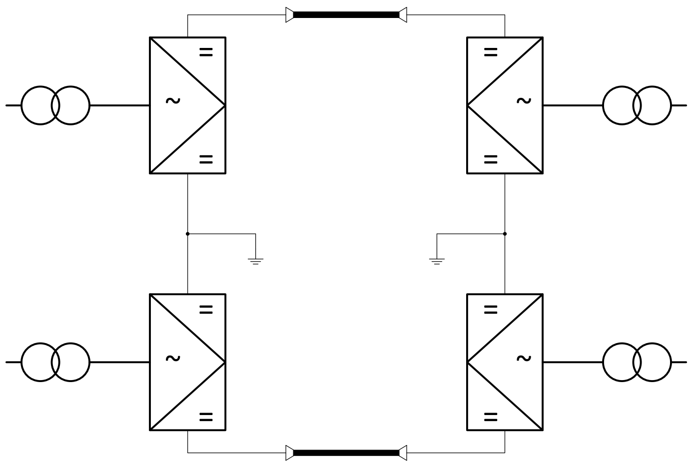
Bipole with
Dedicated Metallic Return (DMR)

- Ultranet
- Grain Belt Express



Rigid Bipole

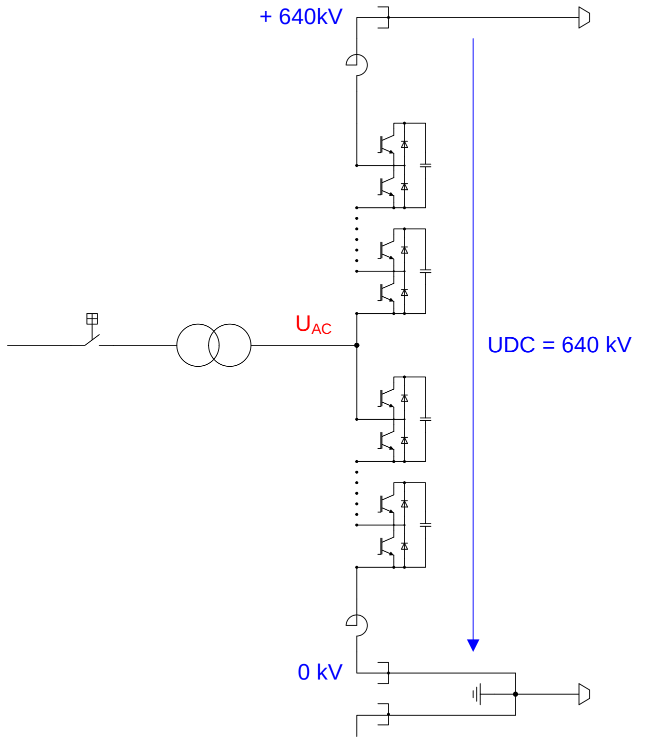
- Viking Link
- SuedLink
- SuedOstLink
- NeuConnect

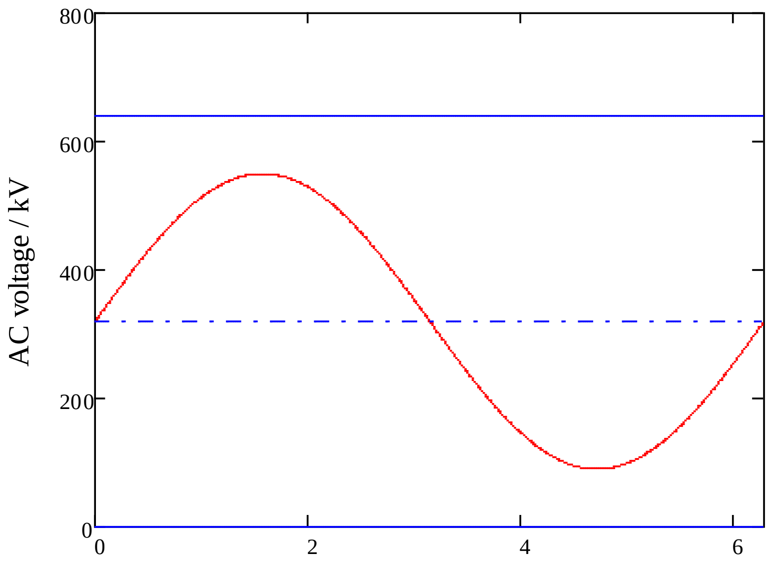


Bipole with
Earth Electrode

- Attica – Crete
- Tyrrhenian Link

BIP Voltage stress



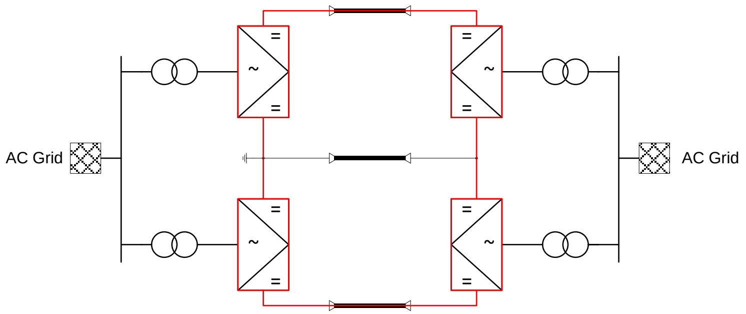


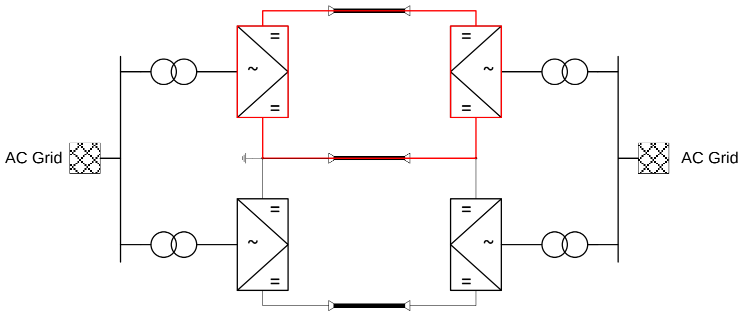
- DC voltage stress on the converter side of the transformer → "HVDC Equipment" must be used

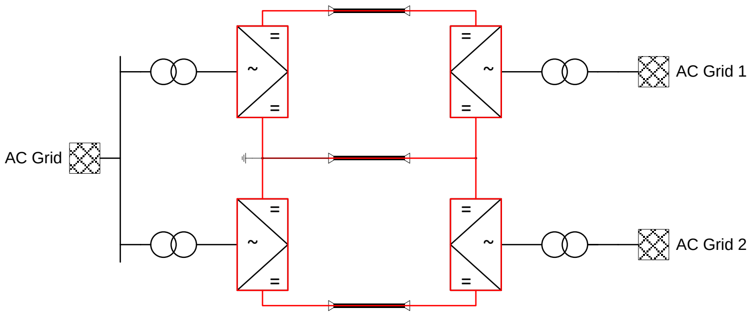
DC circuit topologies

	Symmetric Monopole	Rigid Bipole	Bipole with Metallic Return Bipole with Earth Electrode
DC conductors	2	2	3 2 + Earth Electrode
Power transmission in case of converter fault	0 %	50 %	50 %
Power transmission in case of DC conductor fault	0 %	0 %	50 %
Economical DC voltage	≤ 400 kV	> 500 kV	> 500 kV
Costs	$	$$	$$$
Max. Power	1400 MW (320 kV) 1500 MW (400 kV)	2000 MW	3000 MW

BIP Operation Modes





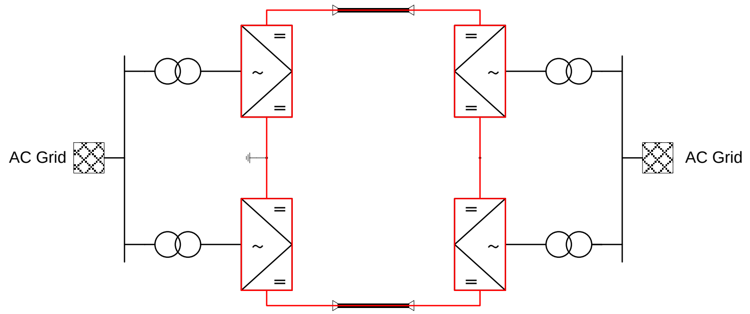


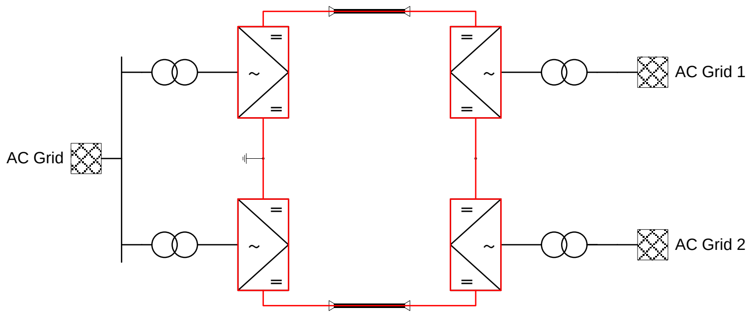
- Bipolar operation – Balanced mode
- Poles are running with at the same power
- No current is running through the DMR
- Losses optimized operation

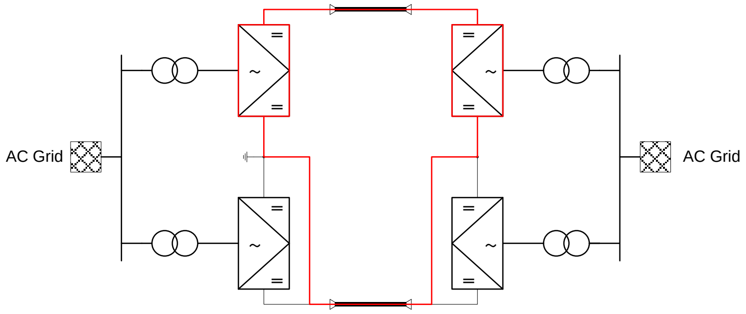
- Monopolar operation
- Emergency mode operation
- Instant operating mode change
- If system is not operating at full power in balanced mode, the power can be ramped up to the max transmission power

- Bipolar operation – Unbalanced mode
- Split-Busbar
- Current running through the DMR in case of different power flow in the AC Grid
- Reduced reduncancy

Rigid Bipole Operation Modes







- Common-busbar operation
- Standard operation mode

- Split busbar operation
- Poles must have the same power during all operating modes (also during dynamic operation)

- Monopolar operation
- Reconfiguration takes > 1s

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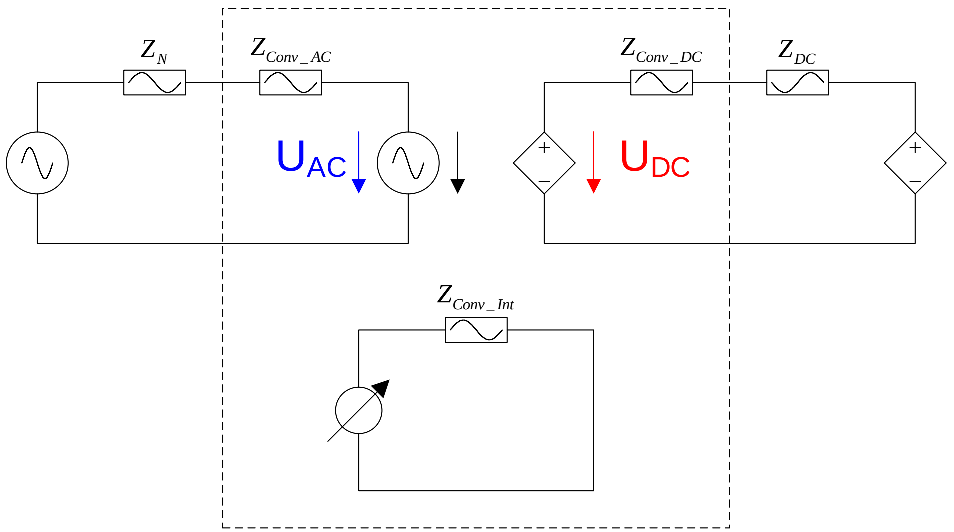
Basic Principles of MMC converters



Half Bridge (HB)	Full Bridge (FB)
$U_{AC} < U_{DC}$	$U_{AC} <> U_{DC}$
$U_{AC} > U_{DC}$ is overmodulation. In this state the converter can not be controlled causing undefined power flow and equipment overload	Operation with $U_{DC} = 0$ is possible while mainting the full reactive power control on the AC side

System capability is defined by the converter current: DC Current + AC current

Principle of the control

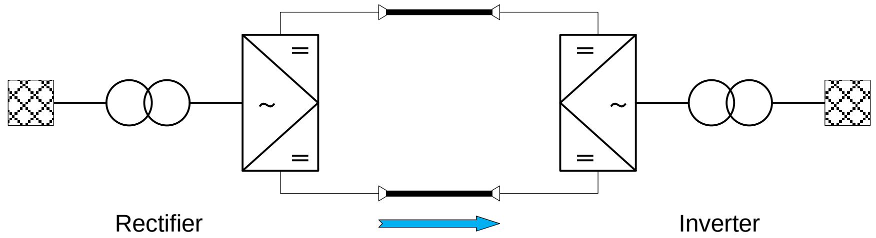
- AC control is defined by the AC grid codes
  - Grid Following: AC behaves as a current source
  - Grid Forming: AC behaves as a voltage source

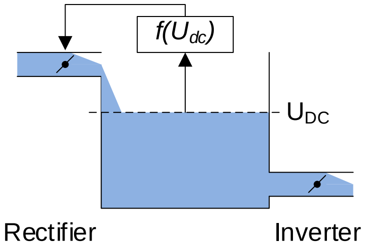
- DC control defined by individual suppliers depending on the system configuration (cable vs. OHL)
  - Interoperability activities on the DC side are ongoing to allow multiterminal operation with different suppliers

- Internal control is mostly used for **energy balancing**

- **The size of the converter is defined by dynamic performance requirements**

Steady State Operation
Control principle

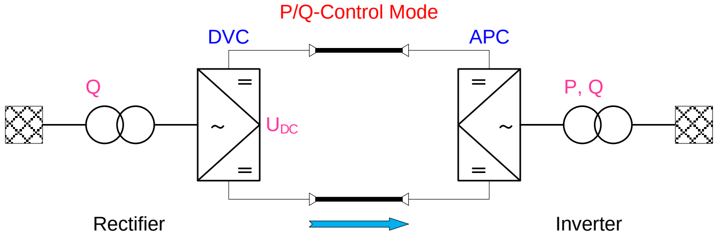




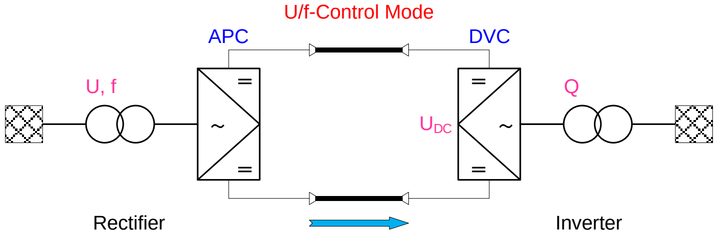
- One station controls DC voltage → Operation in Direct Voltage Control Mode (DVC)
- One station controls active power → Operation in Active Power Control Mode (APC)

- APC has two different operating modes (Parameters defined for "Internal Converter Controls")
  1. P/Q – Control mode→ Definition of Active Power / Reactive Power
  2. U/f – Control mode → Definition frequency and voltage

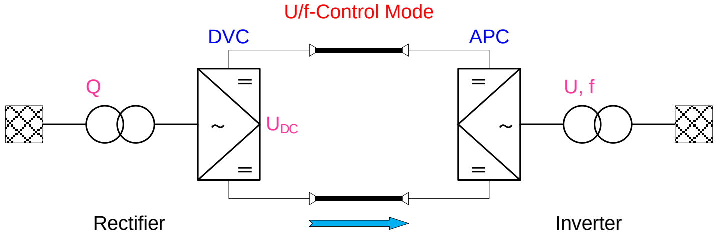
Steady State Operation
Control principle



- Standard Operation
- Station which sees the highest DC voltage controls the DC voltage
- Active power can be defined at any station



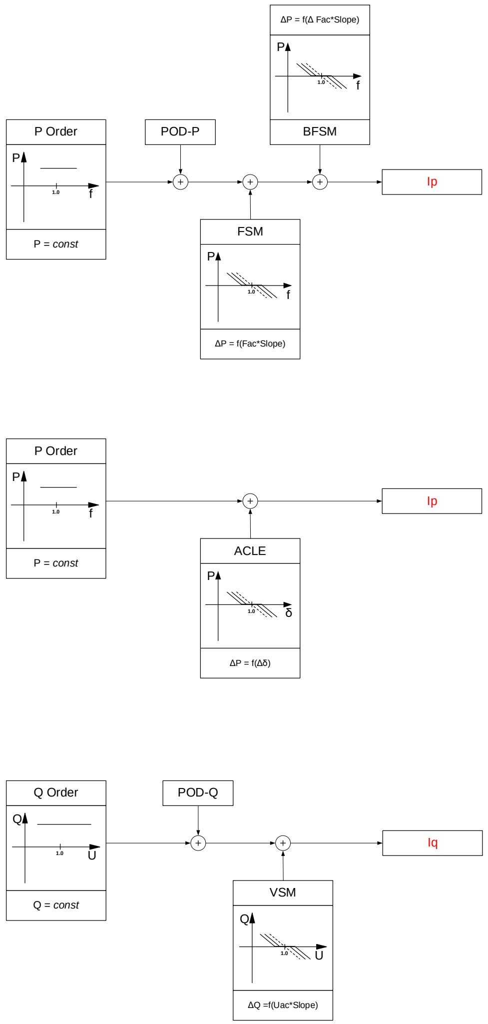
- Wind Farm connection
- Rectifier receives power coming from WTG
- Inverter needs to consider the DC line voltage drop



- Black Start Operation
- Rectifier receives power coming from WTG
- Inverter needs to consider the DC line voltage drop

Control Values

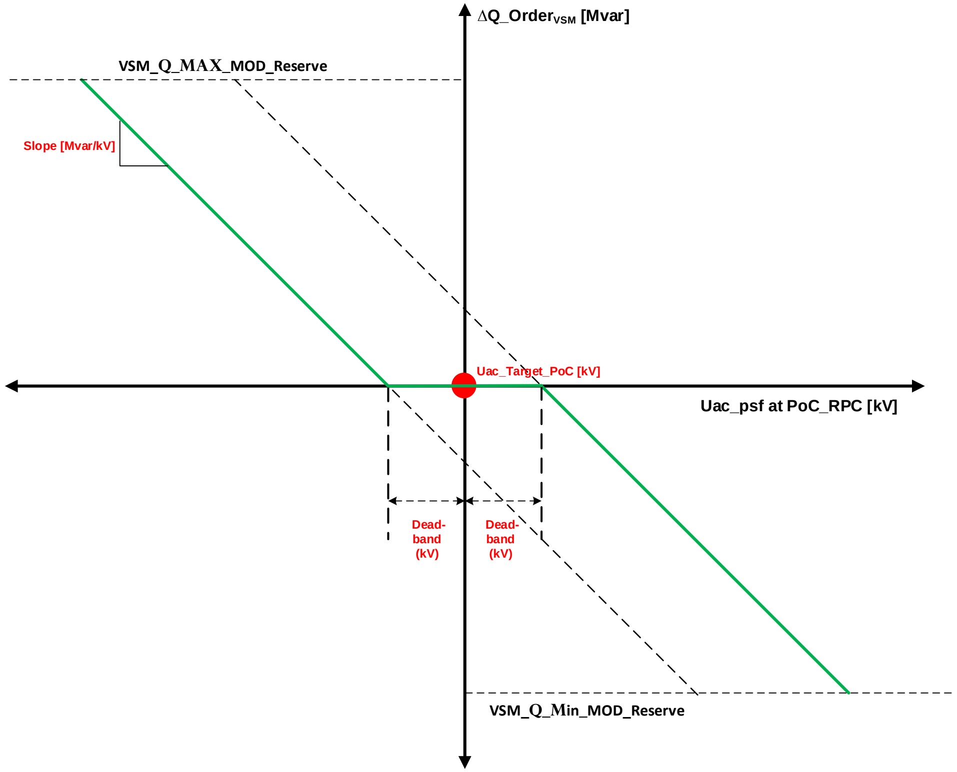
Active & reactive power definition
PQ Mode



- Modulation principle in the control mode
- Definition of a constant value, modulation of further power values depending on parameters such as frequency and voltage
- Most common modulation functions:
  - ➢ VSM: Voltage sensitive mode
  - ➢ ACLE: AC line emulation
  - ➢ FSM: Frequency sensitive mode
  - ➢ BFSM: Bilateral frequency sensitive mode

AC Voltage Control Mode

- The AC voltage control function calculates an ΔQ based on the AC Voltage of the connected AC system



VSM	Unit	Station A	Station B	System Level Setting	Station Level Setting	System Level Setting	Engineering Level
		Both Stations					
AC Voltage_Upper Limit (U_Max)	kV	400 ... 440	400 ... 440		x	x	
AC Voltage_Lower Limit (U_Min)	kV	340 ... 400	340 ... 400		x	x	
AC Voltage_Target Setpoint @ PoC	kV	U_min ... U_max	U_min ... U_max		x	x	
AC Voltage Ramp (Release/Stop)	binary	Released / Stopper	Released / Stopper		x	x	
AC Voltage Slope Setpoint	MVAr/kV	10 ... 300	10 ... 300		x	x	
AC Voltage Deadband Setpoint	kV	0 ... 10	0 ... 10		x	x	

Key Takeaways

- HVDC market is dominated by MMC technology
- Reliability is comparable with LCC system being in the market for many decades
- Different topologies are available depending on network and operation requirements
- VSC-HVDC provides high flexibility in control modes
- VSC-HVDC is capable to operate in very weak and islanded networks
- AC grid code availability
- DC grid code under development

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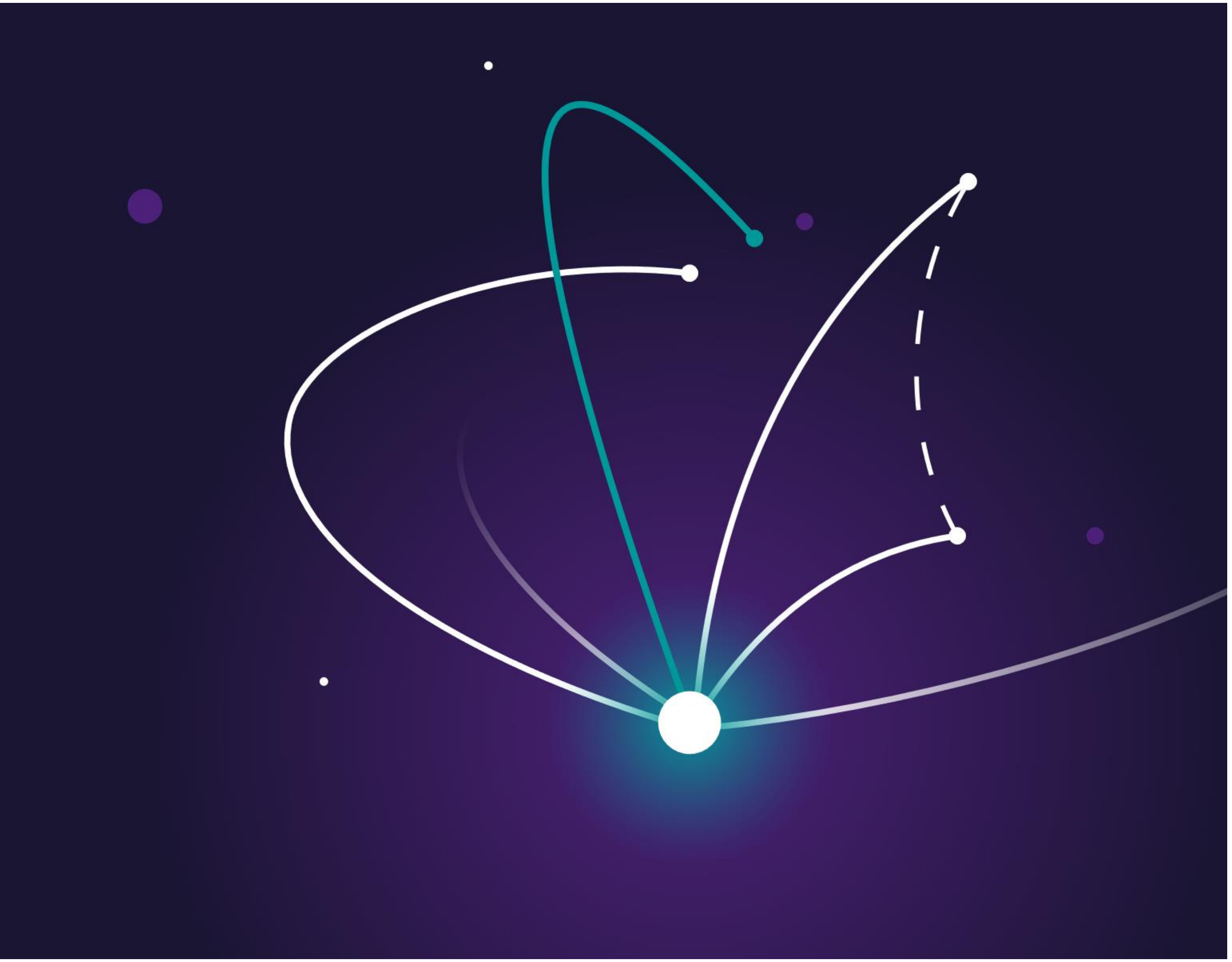

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