IEEE PES T&D

Conference & Exposition

April 22, 2008

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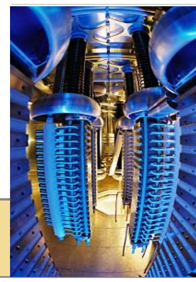


HVDC Transmission Overview

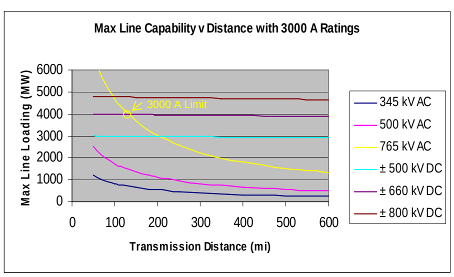
Topics

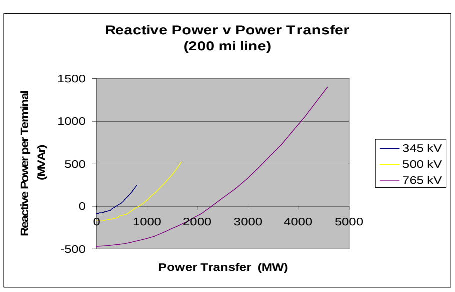
- HVDC Transmission Characteristics
- Transmission Distance Effects
- Core HVDC Technologies
  - Conventional HVDC
  - VSC-based HVDC
- High Power HVDC Transmission
- Comparison of HVDC & EHV Transmission
- Applications
- HVDC Project Examples
- Summary

Characteristics of HVDC Transmission

- Controllable - power injected where needed
- Bypass congested circuits – no inadvertent flow
- Facilitates integration of remote diverse resources
- Higher power, fewer lines, lower losses, no intermediate S/S needed
- Two circuits on less expensive line
- No stability distance limitation
- Reactive power demand limited to terminals
- Narrower ROW, no EMF constraints
- No limit to underground cable length
- Asynchronous, ‘firewall’ against cascading outages

Transmission Line Delivery Capability





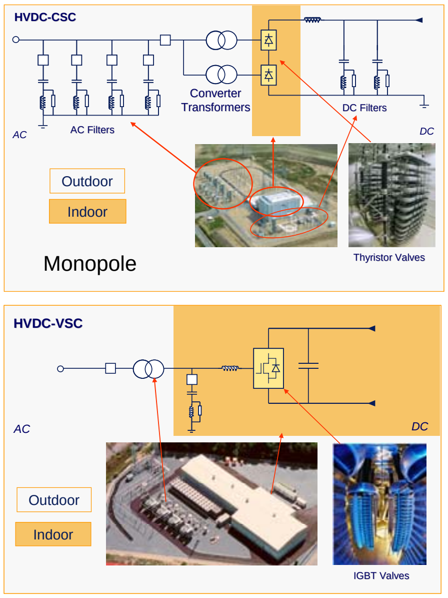
AC line distance effects:

- Intermediate switching stations, e.g. every ~250 mi maximum
- Lower stability limits (voltage, angle)
- Increase stability limits & mitigate parallel flow with FACTS: SVC & SC
- Higher reactive demand with load
- Higher charging at light load
- Parallel flow issues more prevalent
- Thermal limit remains the same

DC line distance effects:

- No distance effect on stability (voltage, angle)
- No need for intermediate stations
- No parallel flow issues due to control
- Minor change in short circuit levels
- No increase in reactive power demand

Core HVDC Technologies

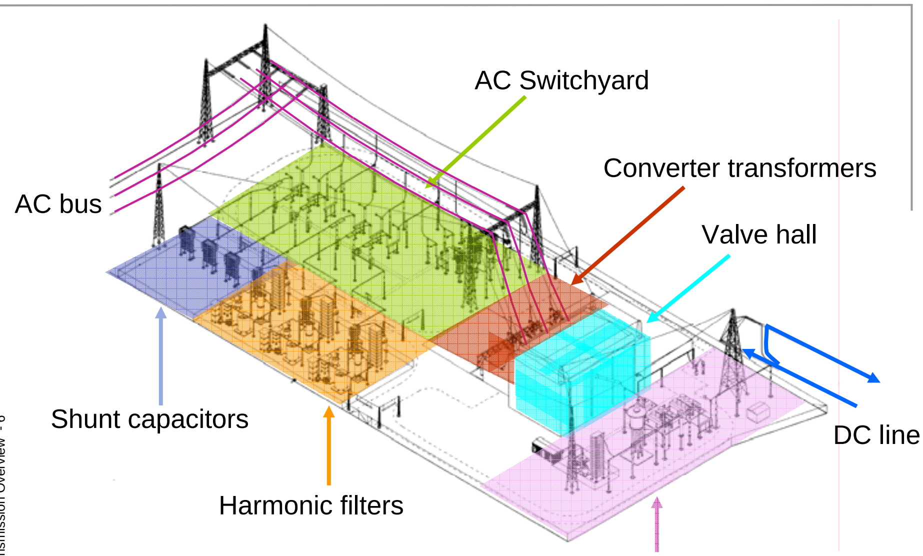


HVDC Classic
- Current source converters
- Line-commutated thyristor valves
- Requires 50% reactive compensation (35% harmonic filter)
- Converter transformers
- Minimum short circuit capacity > 2x converter rating, > 1.3x with capacitor commutation

HVDC Light
- Voltage sourced converters
- Self-commutated IGBT valves
- Requires no reactive power compensation (~15% HF)
- Standard transformers
- Weak system, black start
- U/G or OVHD
- Radial wind outlet regardless of type of wind T-G
- More compact

HVDC Transmission Overview - 5

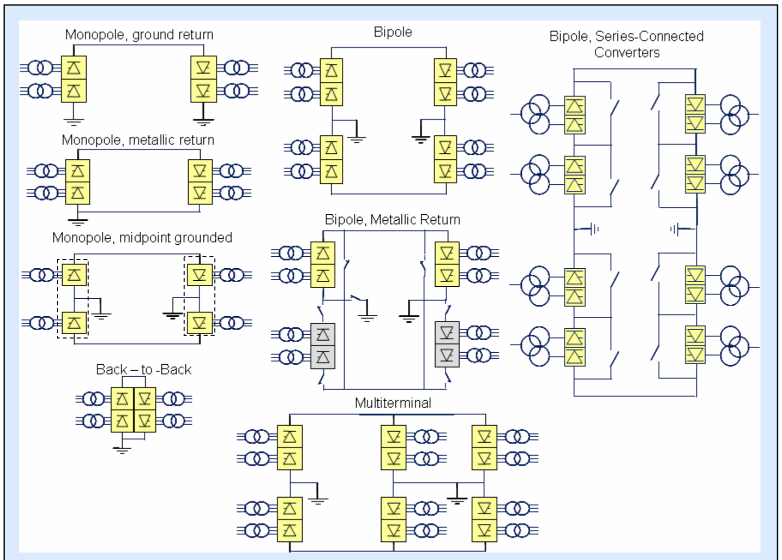
Monopolar Converter Station, 600 MW – 450 kV DC



Approximately 80 x 180 meters

HVDC Transmission Overview - 6

HVDC Operating Configurations and Modes



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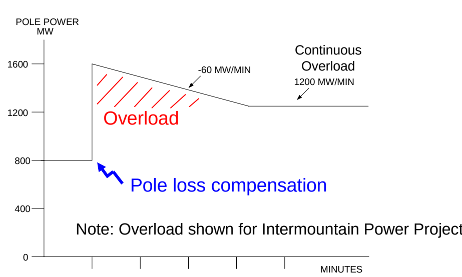
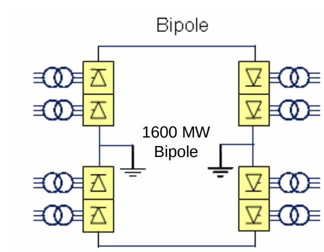
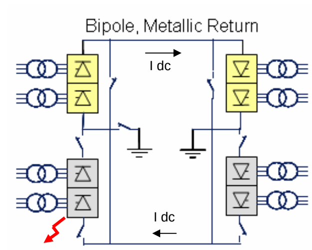
HVDC Bipole – Contingency Operation Example

Metallic Return Operation:

- Loss of pole converter or line insulation degraded
- Isolate converters on faulty pole
- Close pole shorting switches at each end on faulty pole
- Open metallic return transfer breaker in dc electrode line
- Reverse sequence and restart pole to restore balanced bipolar operation







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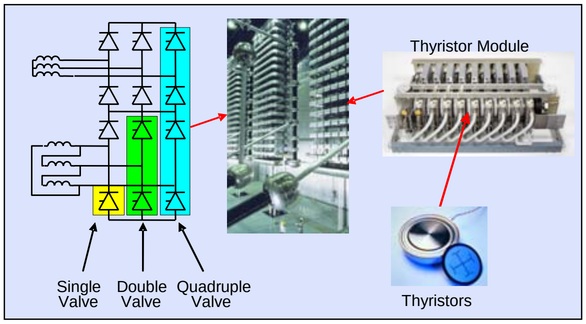
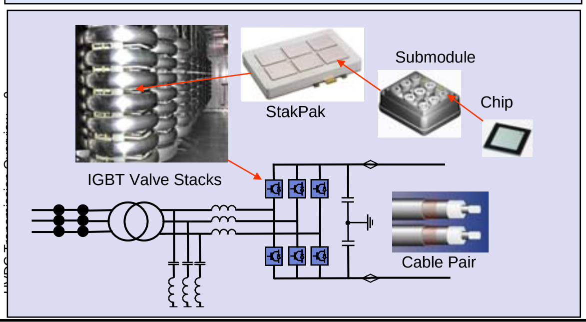
HVDC Converter Arrangements





HVDC Classic

- Thyristor valves
- Thyristor modules
- Thyristors
- Line commutated

HVDC Light

- IGBT valves
- IGBT valve stacks
- StakPaks
- Submodules
- Self commutated

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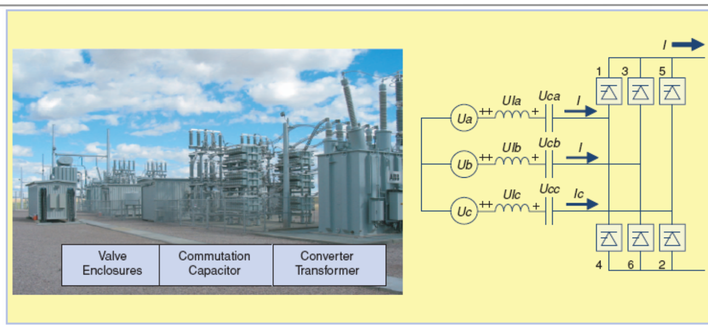
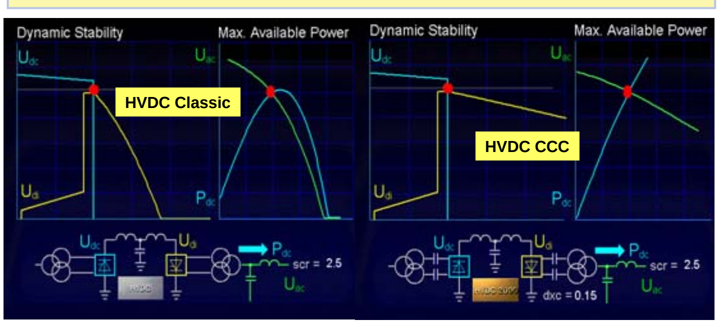
Modular Back-toBack CCC Asynchronous Tie





- Improved stability for weak systems due to commutation capacitor
- Higher power for given location
- Simplified reactive power control
- Garibi: 4x550 MW
- Rapid City Tie: 2x100 MW
- Modular design for shorter construction time
- Least expensive, most efficient asynchronous tie technology

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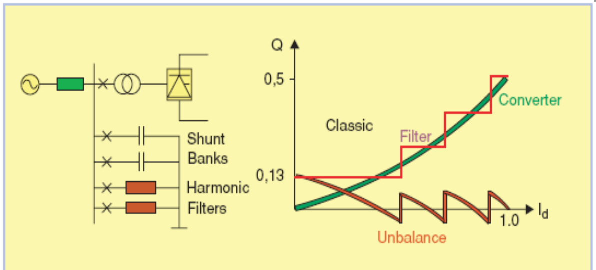
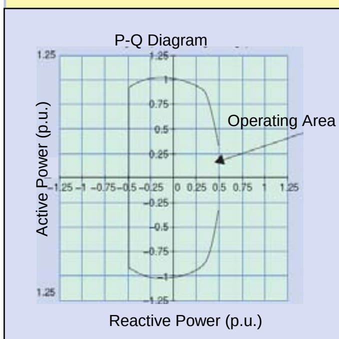
HVDC Transmission Overview - 10

Comparison of Reactive Power Characteristics

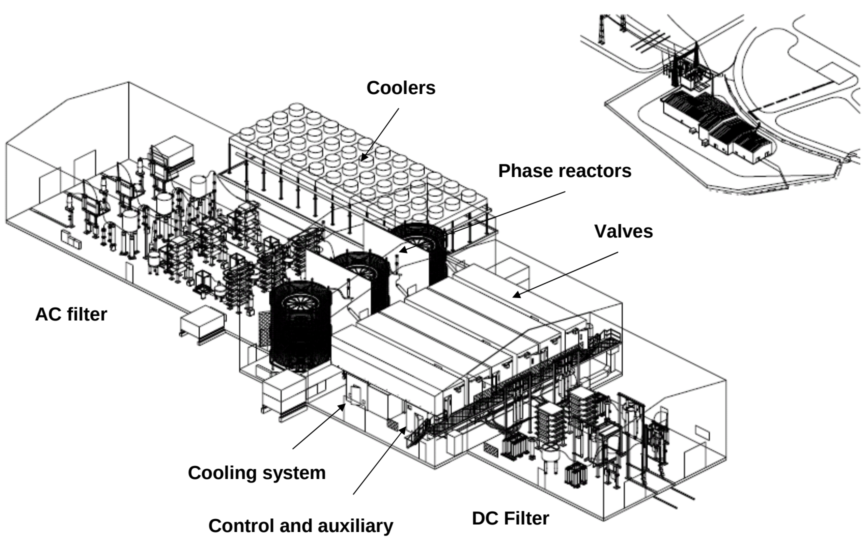




HVDC VSC Operating Range

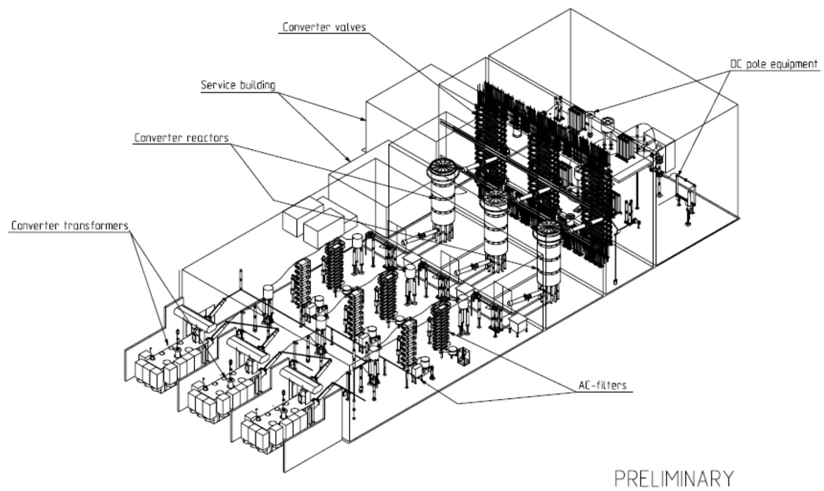
- Conventional HVDC – HVDC Classic (~ SVC with TCR+FC, -0.5Pd / +0 MVAr)
- VSC Based HVDC – HVDC Light (~ STATCOM, -0.5Pd/+0.5Pd MVar)

HVDC Light , ±150 kV, 175- 555 MW



40 x 110 meters

HVDC Light ± 320 kV, 350-1100 MW

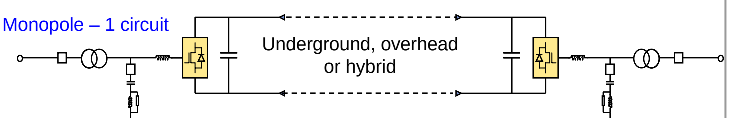


60 x 110 meters

Power Ranges HVDC-Light, ~ ± 50% VAr Support

± 320 kV Double Monopole

Monopole – 1 circuit

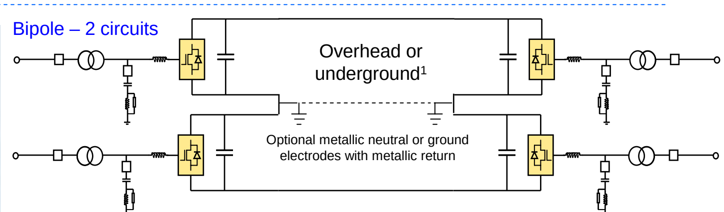


HVDC Light for Underground or Overhead Transmission

Transmission Voltage	Power Rating in MVA v Current and Voltage Rating					
	500 A ac		1000 A ac		1500 A ac	
	627 A dc		1233 A dc		1881 A dc	
± 80 kV dc	M1	101	M2	199	M3	304
± 150 kV dc	M4	190	M5	373	M6	570
± 320 kV dc	M7	380	M8	747	M9	1140

± 640 kV Bipole

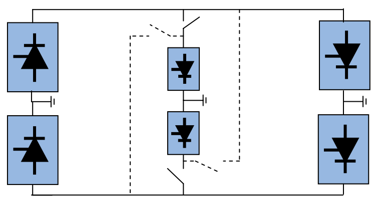
Bipole – 2 circuits



HVDC Light for Overhead Transmission

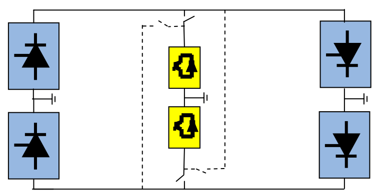
Transmission Voltage	Power Rating in MVA v Current and Voltage Rating					
	500 A ac		1000 A ac		1500 A ac	
	593 A dc		1186 A dc		1779 A dc	
± 160 kV dc	M1-B	190	M2-B	380	M3-B	569
± 320 kV dc	M4-B	380	M5-B	759	M6-B	1139
± 640 kV dc	M7-B	759	M8-B	1518	M9-B	2277

Tapping OVHD HVDC with Large VSC Converters



HVDC Tap

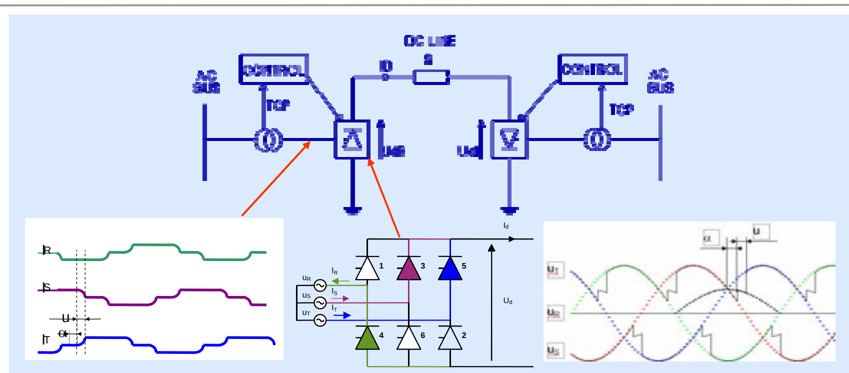
- Reverse power by polarity reversal
- Electronic clearing of dc line faults
- Fast isolation of faulty converters
- Reactive power constraints
- Momentary interruption due to CF at tap
- Limitations on tap rating, location and recovery rate due to stability

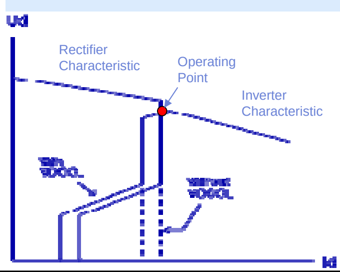


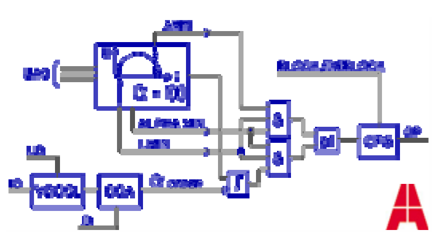
HVDC Light Tap

- Polarity reversal if main link is bidirectional
- DC line fault current contribution extinguished with special provision
- No interruption to main power transfer due to CF at tap
- Less limitations on tap rating and location
- Cascade VSC connection for lower tap rating
- No reactive power constraints
- Improved voltage stability
- Up to ± 640 kV

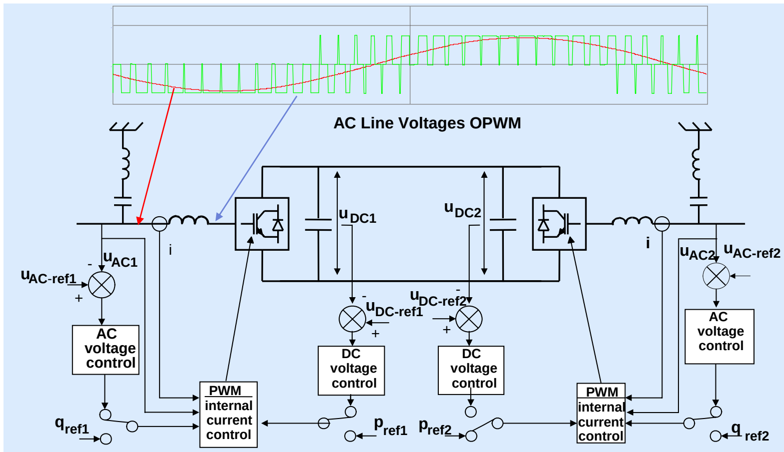
HVDC Classic Control





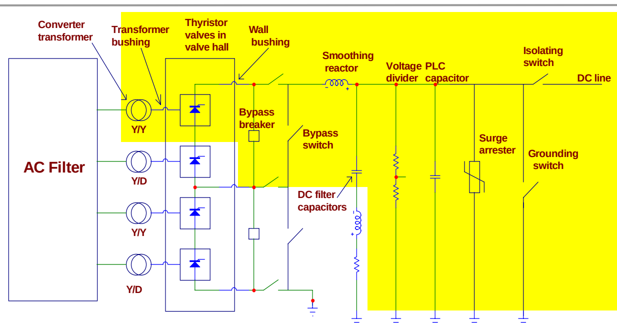


Control of VSC Based HVDC Transmission



Principle control of HVDC-Light

± 800 kV HVDC Transmission

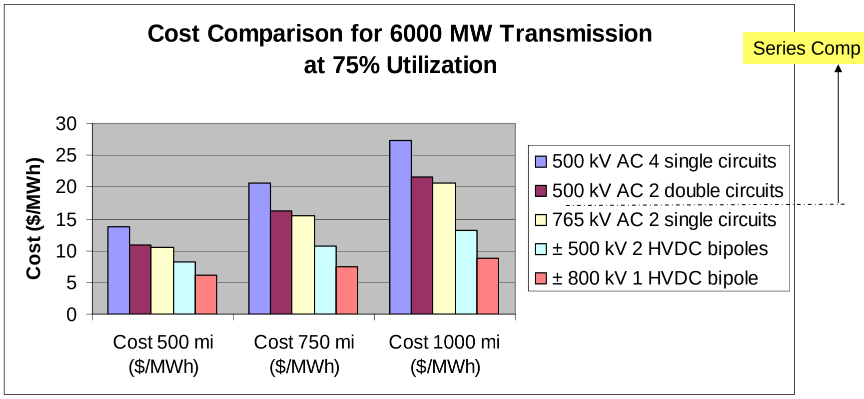


Pole equipment exposed to 800 kV dc

Long term test circut for 800 kV HVDC

± 800 kV, 6400 MW (4 x 1600) HVDC Link

Cost of per MWh @ 75% Utilization



Note - Transmission line, substation and HVDC converter costs based on:
- Western Regional Transmission Expansion Partnership (Frontier Line) Transmission Analysis WG: http://www.ftloutreach.com/
- Northwest Power Pool, Northwest Transmission Assessment Committee, CNC Options Analysis Tool www.nwpp.org/ntac/pdf/CNC_Options_Analysis_Tool_-_2006.xls
- Interest rate of 10%, 30 years

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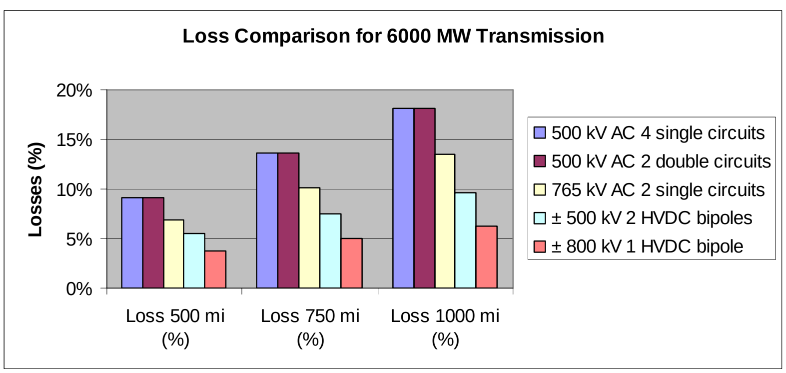
Full Load Losses (6000 MW Transfer)



Note - Conductor areas based on comparable current densities, operating temperatures and power factors.

HVDC Transmission Overview - 20

HVDC Transmission Applications

HVDC Applications

- Long-distance, bulk-power transmission
- Sea cable transmission with MIND cables
- Asynchronous interconnections
- Power flow control
- Congestion relief
- Higher power ratings, economies of scale

HVDC Light

- Underground & sea cable transmission with extruded polymer cables and molded joints
- Weak system applications
- Off-shore - platforms, islands, wind
- Urban in-feed, reduced footprint
- Constrained ROW – overhead or underground
- Virtual generator for replacement of RMR generation
- Integration of remote renewable generation
- Improved voltage stability

Estlink – HVDC Light between Estonia & Finland

Client:	Nordic Energy Link, Estonia
Contract signed:	April 2005
In service:	November 2006
Project duration:	19 months
Capacity:	350 MW, 365 MW low ambient
AC voltage:	330 kV at Harku
	400 kV at Espoo
DC voltage:	±150 kV
DC cable length:	2 x 105 km (31 km land)
Converters:	2 level, OPWM
Special features:	Black start Estonia, no diesel
Rationale:	Electricity trade
	Asynchronous Tie
	Long cable crossing
	Dynamic voltage support
	Black start

Bulk Power Transmission: Three Gorges - Shanghai

- Rated power: 3000 MW
- DC voltage: ± 500 kV
- Configuration: Bipolar
- Transmission: 1060 km
- Improved stability, lower cost, lower losses, fewer lines

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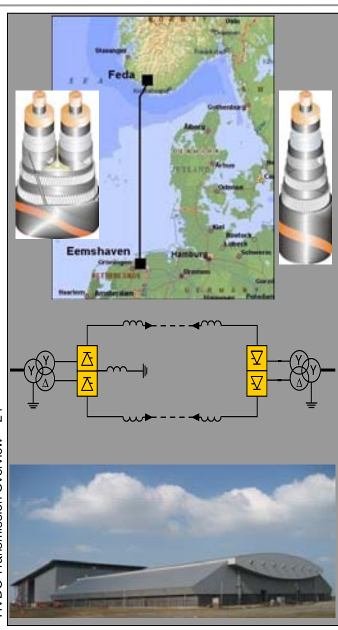
Submarine Cable: NorNed Cable HVDC Project



Scope

- 700 MW HVDC cable interconnection Norway - Netherlands
- ± 450 kV monopole mid-point ground (900 kV converters)
- Cable length: 2 x 580 km
- Sea depth: up to 480 meters
- 400 kV ac voltage at Eemshaven
- 300 kV ac volgage at Freda

Project Basis

- Customer: Statnett (NOR), Tennet (NLD)
- Asynchronous networks, long cable
- Power control suits markets
- Links system with energy storage (hydro reservoirs) with system supplied with thermal and wind generation

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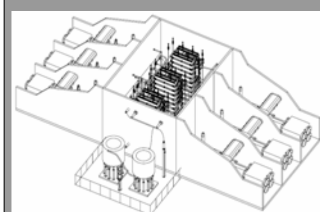
Outaouais Asynchronous Tie- Summary



Scope

- 1250 MW HVDC B t B Interconnection Québec-Ontario
- Two independent converters of 625 MVA
- Includes 14 x 250 MVA 1-phase converter transformers

Project Basis

- Customer: Hydro-Québec (HQ)
- Project to export power from Québec to Ontario (Hydro Québec and Hydro One)
- Ontario gets access to clean hydroelectric power during peak times and decreases dependency on coal from US
- HQ sells at peak and buys at low (pump storage)
- Provides stability and reliability to both grids

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Valhall - Redevelopment Project

Description

- One HVDC Light station off-shore and one on-shore
- 292 km HVDC Cable
- Builds on Troll A power from shore project (PFS)

Main data

- P = 78 MW
- U_{DC} = -150 / 0 kV
- U_{AC} = 11 kV on offshore and 300 kV onshore

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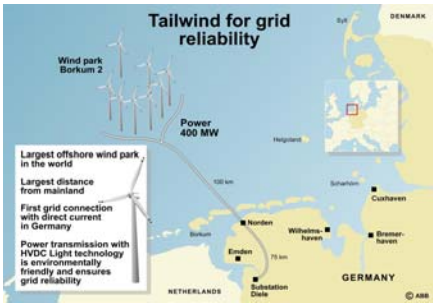
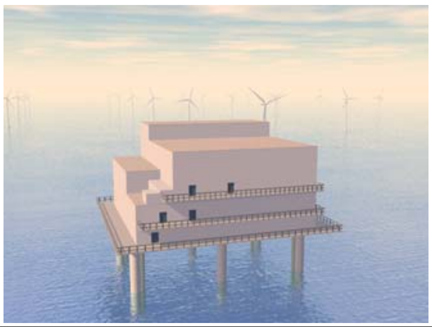
Borkum 2, E.ON Netz





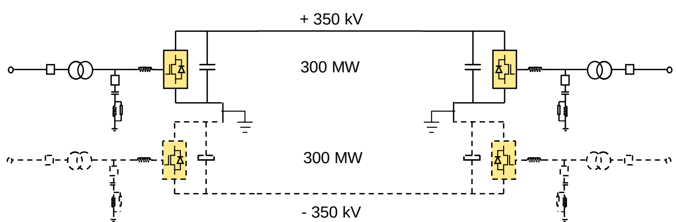
Scope

- 400 MW HVDC Light Offshore Wind, North Sea - Germany
- ±150 kV HVDC Light Cables (route = 130 km by sea + 75 km by land)
- Serves 80 x 5 MW offshore wind turbine generators
- Builds upon HVDC Light experience with wind generation at Tjaerborg and Gotland
- Controls collector system ac voltage and frequency

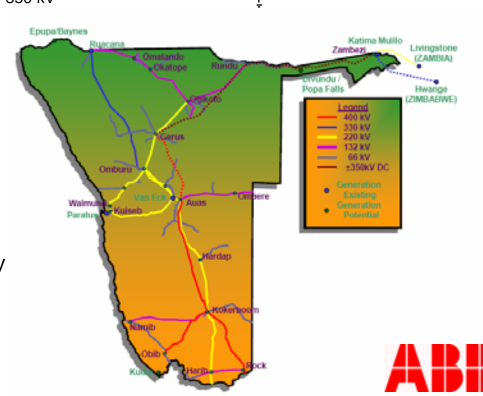
Project Basis

- Customer: E.ON Netz GmbH
- Project serves 80 x 5 MW offshore wind turbine generators
- Germany gets gets access to clean wind power with higher capacity factor than land based wind generation
- Provides stability and reliability to receiving system
- 24 month delivery time
- Saves 1.5 M tons CO2/year

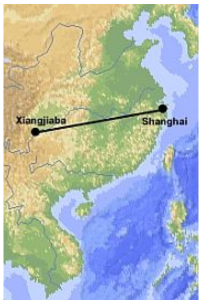
Caprivi Link, NamPower



- 300 MW, 350 kV HVDC Light Monopole with ground electrodes
- Expandable to 600 MW, ± 350 kV Bipole
- ± 350 kV HVDC Overhead Line
- Links Caprivi region of NE Namibia with power network of central Namibia and interconnects with Zambia, Zimbabwe, DR Congo, Mozambique
- Improves voltage stability and reliability
- Length of 970 km DC and 280 km (400kV) AC



Xiangjiaba - Shanghai ± 800 kV UHVDC Project



Scope

- Power: 6400 MW (4 x 1600 MW converters)
- ± 800 kV DC transmission voltage
- System and design engineering
- Supply and installation of two ± 800 kV converter stations including 800 kV HVDC power transformers and switchgear
- Valves use 6 inch thyristors and advanced control equipment

Project Basis

- Customer: State Grid Corporation of China
- Project delivers 6400 MW of Hydro Power from Xiangjiaba Power Plant in SW China
- Length: 2071 km (1286 mi), surpasses 1700 km Inga-Shaba as world's longest
- Pole 1 commissioned in 2010, pole 2 in 2011
- AC voltage: 525 kV at both ends

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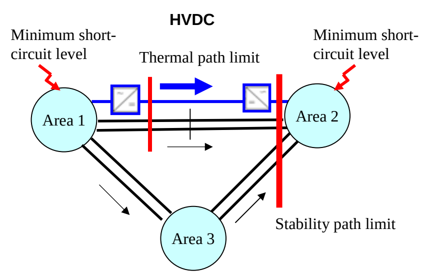
Summary HVDC v HVDC Light

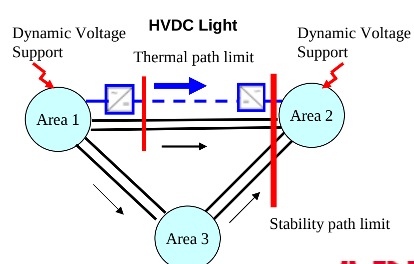
Conventional HVDC:

- Minimum short circuit level restriction (S > 2 x Pd)
- Reactive power demand at terminals (Q = 0.5 x Pd)
- Reactive compensation at terminals
- Higher ratings possible
- Greater economies of scale



HVDC Light:

- No minimum short circuit levels
- No reactive power demand
- Dynamic reactive voltage support (virtual generator)
- Leverage ac capacity by voltage support
- Conducive for but not limited to underground cable transmission



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