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

Monopolar Converter Station, 600 MW – 450 kV DC

Approximately 80 x 180 meters
HVDC Operating Configurations and Modes

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

Note: Overload shown for Intermountain Power Project
HVDC Converter Arrangements

HVDC Classic
- Thyristor valves
- Thyristor modules
- Thyristors
- Line commutated

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

Modular Back-to-Back 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
Comparison of Reactive Power Characteristics

- 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

- Coolers
- Phase reactors
- Valves
- AC filter
- Cooling system
- Control and auxiliary
- DC Filter

40 x 110 meters
HVDC Light ± 320 kV, 350-1100 MW

60 x 110 meters

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

Monopole – 1 circuit

Bipole – 2 circuits

Underground, overhead or hybrid

Optional metallic neutral or ground electrodes with metallic return

ABB
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

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**HVDC Classic Control**

![HVDC Classic Control Diagram]
Control of VSC Based HVDC Transmission

Principle control of HVDC-Light

AC Line Voltages OPWM

\[ u_{AC1}, u_{AC2} \]

DC voltage control

\[ u_{DC1}, u_{DC2} \]

Internal current control

\[ q_{ref1}, q_{ref2} \]

PWM

Internal current control

\[ i_{ref1}, i_{ref2} \]

Voltage divider

AC Filter

Smoothing reactor

Voltage PLC

Grounding switch

HVDG Transmission Overview - 9

± 800 kV HVDC Transmission

Pole equipment exposed to 800 kV dc

Long term test circuit for 800 kV HVDC

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

ABB
Cost of per MWh @ 75% Utilization

Cost Comparison for 6000 MW Transmission at 75% Utilization

- 500 kV AC 4 single circuits
- 500 kV AC 2 double circuits
- 765 kV AC 2 single circuits
- ± 500 kV 2 HVDC bipoles
- ± 800 kV 1 HVDC bipolar

Note - Transmission line, substation and HVDC converter costs based on:
- Western Regional Transmission Expansion Partnership (Frontier Line) Transmission Analysis WG: http://www.ftloutreach.com/
- Interest rate of 10%, 30 years

Full Load Losses (6000 MW Transfer)

Loss Comparison for 6000 MW Transmission

- 500 kV AC 4 single circuits
- 500 kV AC 2 double circuits
- 765 kV AC 2 single circuits
- ± 500 kV 2 HVDC bipoles
- ± 800 kV 1 HVDC bipolar

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

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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

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 voltage 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
Outaouais Asynchronous Tie- Summary

Scope
- 1250 MW HVDC B to 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

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
**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 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

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**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

Summary HVDC v HVDC Light

Conventional HVDC:
- Minimum short circuit level restriction 
  \[ S > 2 \times P_d \]
- Reactive power demand at terminals 
  \[ Q = 0.5 \times P_d \]
- 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