HVDC Transmission

- **Applications**
  - Long-distance, bulk-power OVHD transmission
  - Sea and land cable transmission
  - Asynchronous interconnections
  - Power flow control
  - Congestion relief

- **Ratings**
  - Power range up to 4000 MW at ± 500 kV
  - Power range up to 4800 MW at ± 600 kV
  - Voltage range increasing to ± 800 kV for 2009 operation
  - Power range up to 6400 MW at ± 800 kV
  - MIND Cables
**Long-Distance Bulk Power Transmission**

- **Generator Outlet Transmission**
  - More power on fewer lines
  - Improved stability
  - Lower installed cost
  - Reduced losses
  - Double circuit (bipolar line)
  - Reduced ROW
  - One line vs. two – e.g. IPP, CU, Square Butte

- **Interconnections**
  - Firm capacity
  - Bypass congestion
  - Avoid loop flow
  - No limit due to parallel paths
  - Interconnect diverse regions
# Cost Comparison of 3000 MW Transmission Systems

<table>
<thead>
<tr>
<th>Alternative</th>
<th>DC Alternatives</th>
<th>AC Alternatives</th>
<th>Hybrid AC/DC Alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>± 500 kV</td>
<td>± 500 kV 500 kV</td>
<td>± 500 kV 500 kV 765 kV</td>
</tr>
<tr>
<td></td>
<td>Bipole</td>
<td>2 x ± 500 kV</td>
<td>Bipole</td>
</tr>
<tr>
<td></td>
<td>± 600 kV Bipole</td>
<td>± 600 kV 500 kV</td>
<td>2 Single Ckt</td>
</tr>
<tr>
<td></td>
<td>± 800 kV Bipole</td>
<td>± 800 kV 500 kV</td>
<td>2 Double Ckt</td>
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<tr>
<td></td>
<td>Bipole</td>
<td>± 800 kV 765 kV</td>
<td>2 Single Ckt</td>
</tr>
<tr>
<td></td>
<td>Bipole</td>
<td>Bipole</td>
<td>AC+DC</td>
</tr>
<tr>
<td>Capital Cost</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Rated Power (MW)</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
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<tr>
<td></td>
<td>4000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Station costs</td>
<td>$420</td>
<td>$680</td>
<td>$465</td>
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<tr>
<td>Transmission line</td>
<td>$1.60</td>
<td>$1.60</td>
<td>$1.80</td>
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<tr>
<td>Transmission Line</td>
<td>$1,200</td>
<td>$2,400</td>
<td>$1,350</td>
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<tr>
<td>Total Line Cost</td>
<td>$1,620</td>
<td>$3,080</td>
<td>$1,815</td>
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<tr>
<td></td>
<td>$3,542</td>
<td>$2,942</td>
<td>$4,830</td>
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<td></td>
<td>$1,620</td>
<td>$1,802</td>
<td>$3,422</td>
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<tr>
<td>Annual Payment, 30 years @10%</td>
<td>$172</td>
<td>$327</td>
<td>$193</td>
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<tr>
<td>Cost per kW-Yr</td>
<td>$57.28</td>
<td>$81.68</td>
<td>$64.18</td>
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<td>$125.24</td>
<td>$104.03</td>
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<td>$7.69</td>
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<td>$16.82</td>
<td>$13.97</td>
<td>$22.93</td>
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<tr>
<td>Losses @ full load</td>
<td>193</td>
<td>134</td>
<td>148</td>
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<tr>
<td></td>
<td>208</td>
<td>208</td>
<td>139</td>
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<tr>
<td>Losses at full load</td>
<td>6.44%</td>
<td>3.35%</td>
<td>4.93%</td>
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<tr>
<td></td>
<td>6.93%</td>
<td>6.93%</td>
<td>4.62%</td>
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<tr>
<td>Capitalized cost</td>
<td>$246</td>
<td>$171</td>
<td>$188</td>
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<tr>
<td>Capital costs @ $1500 kW (M$)</td>
<td>$265</td>
<td>$265</td>
<td>$177</td>
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<td>Parameters:</td>
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<tr>
<td>Interest rate %</td>
<td>10%</td>
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<td></td>
</tr>
<tr>
<td>Capitalized cost of losses $/kW</td>
<td>$1,500</td>
<td>$1,500</td>
<td>$1,500</td>
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<tr>
<td>Note:</td>
<td></td>
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<tr>
<td>AC current assumes 94% pf</td>
<td></td>
<td></td>
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<tr>
<td>Full load converter station losses = 0.75% per station</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total substation losses (transformers, reactors) assumed = 0.5% of rated power</td>
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</tbody>
</table>
Comparison to Rail Transport of Coal

- 3000 MW power plant
- Coal haul distance 900 miles
- Fuel – sub-bituminous coal 8500 BTU/lb
- Plant heat rate – 8500 BTU/kWh, 85% load factor
- 3 unit trains per day (100, 100 ton cars/train)
- Annual hauling cost $560 M at $50 per ton
  - $186 per kW-yr
  - $25 per MWh
  - 20 million gallons of diesel fuel per year
    @ 500 net ton miles per gallon
- Subject to escalation, congestion
- Cannot deliver energy from renewable resources
The HVDC Classic Converter Station

Converter station

Transmission line or cable

AC bus

Shunt capacitors or other reactive equipment

DC filter

AC filters

Smoothing reactor

Converter

Control system

Telecommunication
The HVDC Classic Converter Station

HVDC-CSC

AC Filters

Converter Transformers

DC Filters

AC

Indoor

Outdoor

Thyristor Valves

DC
HVDC Converter Station Design

- Shunt Capacitor Banks
- AC Filter Banks
- Converter Building
- AC Switchyard
- DC Switchyard
HVDC Classic Control
Asynchronous Interconnections

- Economic
  - Firm transactions
  - Shared reserves
  - Increase diversity
  - Economy energy trade

- Reliability
  - Emergency power support
  - Mutual assistance
  - Isolate disturbances
  - ‘Fire-wall’ against cascading outages
  - Reserve sharing

HVDC in North America
The CCC* Converter Station

*Capacitively-commutated converter station

Transmission Line, Cable or Back-Back

Weaker Systems
Back-to-Back
100 - 550 MW

AC bus

Contune AC filters

Converter

Smoothing reactor

DC filter

Telecommunication

Control system

Commutation capacitors
Modular Back-to-Back CCC Asynchronous Tie
HVDC Light Transmission – Voltage Source Converters

Applications
- Underground and sea cable transmission
- Off-shore - platforms, islands
- Urban in-feed
- Constrained ROW
- Virtual generator for replacement of RMR generation
- Integration of remote renewable generation
- Improved voltage stability

Ratings
- Power range 50-1100 MW
- Voltages ± 80, ± 150 and ± 300 kV
- Extruded cables with prefabricated joints
HVDC Light Station

Converter station

Voltage Source(d)
Converter - VSC

Phase Reactor

AC bus

Dry DC Capacitor

AC filters

DC Capacitor

Transmission Cable

Control system

Strong or Weak Systems
Dynamic Voltage Control
Underground Transmission
Up to ±150kV, 550MW
Up to ±300kV, 1100MW

IGBT Valves
HVDC Converter Arrangements

Conventional HVDC

VSC Based HVDC
Underground Cable Systems with HVDC Light

**Economic**
- No distance limitation
- Full utilization – no reactive power
- Two cables vs three cables for AC
- Light, flexible and simpler design
- Timely permitting
- No induced circulating currents
- Half the losses
- Easier transport and installation

**Reliability**
- No cable overloads possible
- Dynamic reactive power support
- Congestion relief
- Isolate disturbances
- Share ROW without increasing exposure
- Black-start capability
HVDC Light Converter Station

HVDC-VSC

AC

Outdoor

Indoor

DC

IGBT Valves
HVDC Transmission with Voltage Source Converters

Simplified Single Line Diagram (SLD)
HVDC Light Converter Station

- Coolers
- IGBT Valve Enclosures
- Phase Reactors
- AC Filters
Control of VSC Based HVDC Transmission

Principle control of HVDC-Light

AC Line Voltages OPWM
Offshore Applications of HVDC Light
Comparison of Reactive Power Characteristics