HVDC Development Topics

- Core HVDC Technologies
  - Conventional HVDC
  - VSC Based HVDC
- ± 800 kV HVDC
- Cost Comparison of AC & DC Transmission Alternatives
- HVDC Light
  - ± 320 kV, 1100 MW
  - Offshore
  - Multi-terminal & Overhead
- Project Examples
Core HVDC Technologies

- **HVDC Classic**
  - Current source converters
  - Line-commutated thyristor valves
  - Requires 50% reactive compensation (35% HF)
  - Converter transformers
  - Minimum short circuit capacity > 2x converter rating

- **HVDC Light**
  - Voltage source converters
  - Self-commutated IGBT valves
  - Requires no reactive power compensation (15% HF)
  - Standard transformers
  - No minimum short circuit capacity, black start
HVDC Converter Arrangements

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

**HVDC Light**
- IGBT valves
- IGBT valve stacks
- StakPaks
- Submodules
- Self commutated
HVDC Classic Control
Control of VSC Based HVDC Transmission

Principle control of HVDC-Light

AC Line Voltages OPWM
HVDC Light Plant Layout, ±150 kV, 175-555 MW

- Coolers
- Phase reactors
- Valves
- AC filter
- Cooling system
- Control and auxiliary
- DC Filter
## Cost Comparison of Transmission Alternatives

<table>
<thead>
<tr>
<th>Alternative</th>
<th>500 kV AC</th>
<th>± 500 kV</th>
<th>± 600 kV</th>
<th>± 800 kV</th>
<th>500 kV AC</th>
<th>765 kV AC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Two Single Circuits</td>
<td>HVDC Bipole</td>
<td>HVDC Bipole</td>
<td>HVDC Bipole</td>
<td>Double Circuit</td>
<td>Single Circuit</td>
</tr>
<tr>
<td>Capital Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line voltage (kV)</td>
<td>525</td>
<td>500</td>
<td>600</td>
<td>800</td>
<td>525</td>
<td>765</td>
</tr>
<tr>
<td>Rated Power (MW)</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>No. of ac line segments</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>No. of series capacitors per line segment</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total No. Series Capacitors</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Total No. AC or DC Substations</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>No. Shunt Reactors per AC line segment</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total No. Shunt Reactors</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Total No. Transformers</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. of SVC’s</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>No. Shunt Capacitors</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HVDC stations &amp; AC substations incl reactive comp</td>
<td>$366,000,000</td>
<td>$560,000,000</td>
<td>$600,000,000</td>
<td>$625,000,000</td>
<td>$366,000,000</td>
<td>$404,000,000</td>
</tr>
<tr>
<td>Transmission Line (cost/mile)</td>
<td>$1,700,000</td>
<td>$1,400,000</td>
<td>$1,456,000</td>
<td>$1,582,000</td>
<td>$1,582,000</td>
<td>$2,720,000</td>
</tr>
<tr>
<td>Transmission Line R/W (cost/mile)</td>
<td>$500,000</td>
<td>$300,000</td>
<td>$400,000</td>
<td>$500,000</td>
<td>$500,000</td>
<td>$500,000</td>
</tr>
<tr>
<td>Total line distance in miles</td>
<td>1,500</td>
<td>750</td>
<td>750</td>
<td>750</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>Transmission Line Cost</td>
<td>$3,300,000,000</td>
<td>$1,275,000,000</td>
<td>$1,392,000,000</td>
<td>$1,561,500,000</td>
<td>$2,415,000,000</td>
<td>$3,375,000,000</td>
</tr>
<tr>
<td>Total Transmission Cost + 10% contingency</td>
<td>$4,032,600,000</td>
<td>$2,018,500,000</td>
<td>$2,191,200,000</td>
<td>$2,405,150,000</td>
<td>$3,059,100,000</td>
<td>$4,156,900,000</td>
</tr>
<tr>
<td>Annual Payment, 30 years @ rate of 10%</td>
<td>$427,775,177</td>
<td>$214,120,963</td>
<td>$232,440,849</td>
<td>$255,136,504</td>
<td>$324,507,028</td>
<td>$440,960,827</td>
</tr>
<tr>
<td>Cost per kW-Yr</td>
<td>$142.59</td>
<td>$71.37</td>
<td>$77.48</td>
<td>$85.05</td>
<td>$108.17</td>
<td>$146.99</td>
</tr>
<tr>
<td>Cost per MWh @ Utilization Factor of 65%</td>
<td>$25.04</td>
<td>$12.53</td>
<td>$13.61</td>
<td>$14.94</td>
<td>$19.00</td>
<td>$25.81</td>
</tr>
<tr>
<td>No of conductors/pole/phase</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Conductor (ohms/mile) ac or dc @ temp of:</td>
<td>50</td>
<td>0.0420</td>
<td>0.0364</td>
<td>0.0364</td>
<td>0.0364</td>
<td>0.0420</td>
</tr>
<tr>
<td>Line/Pole Current (Amps)</td>
<td>1755</td>
<td>3000</td>
<td>2500</td>
<td>1875</td>
<td>1755</td>
<td>1204</td>
</tr>
<tr>
<td>Conductor current density (A/mm²)</td>
<td>0.610</td>
<td>0.695</td>
<td>0.579</td>
<td>0.435</td>
<td>0.610</td>
<td>0.419</td>
</tr>
<tr>
<td>Losses @ full load</td>
<td>291</td>
<td>209</td>
<td>159</td>
<td>109</td>
<td>291</td>
<td>137</td>
</tr>
<tr>
<td>Losses at full load in %</td>
<td>9.69%</td>
<td>6.96%</td>
<td>5.29%</td>
<td>3.63%</td>
<td>9.69%</td>
<td>4.56%</td>
</tr>
<tr>
<td>Cost of losses @ UF &amp; $/kW of:</td>
<td>65%</td>
<td>$1,500</td>
<td>$283,503,864</td>
<td>$203,705,153</td>
<td>$154,868,162</td>
<td>$106,308,654</td>
</tr>
</tbody>
</table>
Cost of transmitting 12000 MW 2000 km

Power 12000 MW
Line length 2000 km

- 800 kV AC 8 lines
- 1000 kV AC 5 lines
- 500 kV DC 4 lines
- 800 kV DC 2 lines
Comparison of overall line design

- **800 kV**
- **±600 kV**

- **1000 kV**
- **±800 kV**
## Itaipu 600 kV HVDC Line Performance

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1994</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1995</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1996</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1997</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1*</td>
<td>2</td>
<td>0</td>
<td>1*</td>
</tr>
<tr>
<td>1998</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1*</td>
<td>1</td>
<td>0</td>
<td>1*</td>
</tr>
<tr>
<td>1999</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2000</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8 year</td>
<td>24</td>
<td>4</td>
<td>9</td>
<td>33</td>
<td>3</td>
<td>8</td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>21</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Ave.</td>
<td>3</td>
<td>0.5</td>
<td>1.13</td>
<td>4.13</td>
<td>0.38</td>
<td>1</td>
<td>0.88</td>
<td>0.25</td>
<td>0.88</td>
<td>2.63</td>
<td>0.13</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*Line Tower Failures total two events

**Notes:**
- Trans = 0.659 pole faults / 100km / year
- RedV = 0.078 pole faults / 100km / year
- Perm = 0.202 pole faults / 100km / year

Isokeraunic Level 90 (Foz) to 50 (SP)

**Definitions:**
- Trans = Successful restart at full voltage
- RedV = Successful restart at reduced voltage (450 kV)
- Perm = Permanent, excluding tower failures
### Itaipu 765 kV AC Line Performance

<table>
<thead>
<tr>
<th>Year</th>
<th>Trans</th>
<th>Perm</th>
<th>Length</th>
<th>Trans</th>
<th>Perm</th>
<th>Length</th>
<th>Trans</th>
<th>Perm</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>0</td>
<td>4</td>
<td>891</td>
<td>1</td>
<td>11</td>
<td>891</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1996</td>
<td>1</td>
<td>13</td>
<td>891</td>
<td>0</td>
<td>7</td>
<td>891</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1997</td>
<td>0</td>
<td>6</td>
<td>891</td>
<td>2</td>
<td>13</td>
<td>891</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1998</td>
<td>0</td>
<td>10</td>
<td>891</td>
<td>2</td>
<td>16</td>
<td>891</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>1999</td>
<td>1</td>
<td>27</td>
<td>891</td>
<td>1</td>
<td>10</td>
<td>891</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>3</td>
<td>15</td>
<td>891</td>
<td>3</td>
<td>14</td>
<td>891</td>
<td>2</td>
<td>9</td>
<td>602</td>
</tr>
<tr>
<td>2001</td>
<td>2</td>
<td>4</td>
<td>891</td>
<td>4</td>
<td>8</td>
<td>891</td>
<td>2</td>
<td>5</td>
<td>915</td>
</tr>
<tr>
<td>2002</td>
<td>4</td>
<td>12</td>
<td>891</td>
<td>1</td>
<td>7</td>
<td>891</td>
<td>4</td>
<td>16</td>
<td>915</td>
</tr>
<tr>
<td><strong>8 year</strong></td>
<td><strong>11</strong></td>
<td><strong>91</strong></td>
<td><strong>7128</strong></td>
<td><strong>14</strong></td>
<td><strong>86</strong></td>
<td><strong>7128</strong></td>
<td><strong>8</strong></td>
<td><strong>30</strong></td>
<td><strong>2432</strong></td>
</tr>
</tbody>
</table>

*Trans = 0,198 faults / 100km / year
Perm = 1,240 faults / 100km / year

**Tower Failures due to wind:**
- 1994: 3 both circuits*
- 1997: 2 both circuits*
- 1998: 2 both circuits*

*total of 3 events

Isokeraunin Level 90 (Foz) to 50 (SP)
Three Gorges China 3000 MW

The thyristor valve hall
±800 kV, 3600 MW Converter Station
800 kV HVDC - one pole

Exposed to 800 kV dc
Long term test circuit for 800 kV HVDC
Testing for valve hall clearances
Valve Hall 800 KV HVDC
800 kV HVDC station
HVDC Light rating increase to 1100 MW

- Elements common to existing systems
  - IGBT chip
  - IGBT submodule
  - IGBT StakPak
  - IGBT module or stack
  - Control system
  - Cooling system
  - DC capacitor
- Increased dc current – six submodules per StakPak rather than four
- Increased dc voltage (150 kV to 320 kV)
  - Valve stacks comprised of IGBT modules with 26 positions arranged horizontally
  - Modules connected in series at site to reach rated voltage – elimination of valve enclosures used for the lower voltages
  - DC voltage still lower than that commonly used for conventional HVDC
- Higher ac voltage on ac filter bus – 400 kV
- Development parallels that for conventional HVDC thyristor valves
- Cable and cable accessories type tested to 320 kV, accelerated life tests to be completed this year
Power Ranges HVDC-Classic and HVDC-Light
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
- Cannot extinguish dc line fault current contribution without special provision, e.g., diode coupling for inverter
- 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
Offshore Applications of HVDC Light

Offshore Wind Farms

- Long cable transmission to shore
- Voltage regulation
- Wind generator excitation power
- Black start

Oil and Gas Production

- Long cable transmission from shore
- Feed platform load
- Variable speed compressor drives
- Voltage regulation
- Reduced weight and volume
- Reduced emissions
- Greater efficiency
- Troll – no outages since 2005!
Valhall, BP

Nyckeldata

- Valhall är BP:s största plattform I Nordsjön
- Under byggnad
- HVDC Light-systemen ska sköta all kraftmatning till plattformen
- Ger betydande miljöfördelar och minskar behovet av personal på plattformen
- 1 x 78 MW, 290 km sjökabel
- Troll: I drift sedan 2005, inga fel!
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
Estlink – full power after 19 months

Last updated: 29 Nov 2006 15:18

Consumption and production in Finland

<table>
<thead>
<tr>
<th>Consumption</th>
<th>11433 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>9483 MW</td>
</tr>
<tr>
<td>- hydro power</td>
<td>1484 MW</td>
</tr>
<tr>
<td>- nuclear power</td>
<td>2715 MW</td>
</tr>
<tr>
<td>- condensing power</td>
<td>881 MW</td>
</tr>
<tr>
<td>- district heat back pressure</td>
<td>2391 MW</td>
</tr>
<tr>
<td>- industry back pressure</td>
<td>1949 MW</td>
</tr>
<tr>
<td>- other production (estimate)</td>
<td>63 MW</td>
</tr>
<tr>
<td>Net import/export</td>
<td>1950 MW</td>
</tr>
</tbody>
</table>

Electricity price in Finland

| Elspot price area Finland       | 41.65 e/MWh |

Power balance

| Production deficit/surplus in Finland | -393 MW |
| Surplus/deficit, cumulative          | -90 MWh |
| Instantaneous freq. measurement      | 49.98 Hz |
| Time deviation                       | 6.93 s  |

Temperatures in Finland: Helsinki +6°C, Jyväskylä +7°C, Oulu +6°C, Rovaniemi +4°C
NorNed Cable HVDC Project

The longest underwater high-voltage cable in the world.

**Clients:** Statnett and TenneT

**Transmission capacity:** 700 MW

**DC Voltage:** ± 450 kV

**Length of DC cable:** 2*580 km

**Water depths:** Up to 410 m

**Project start:** January 2005

**Completion time:** Approx. three years

---

**Flat Mass-Impregnated submarine cable**
Copper profile wires, 790 mm²

**Mass Impregnated submarine cables**
Copper profile wires, 700 mm²
NorNed Cable HVDC Project *Symetric monopole*

- Rating 600 MW ± 450 kV
- Low losses 3.7%
- Continuous 700 MW
- Cable length 580 km
- No sea electrode
NorNed Cable HVDC Project

Converter valves ± 450 kV, 700 MW
120 thyristors per single valve
Totally 2880 thyristors
NorNed kabel HVDC Project

FMI Cable, 2 x 790 mm²
+/- 450 kV, 700 MW
20 mm insulation
90 kilo/meter

70 km/loading
8 joints 7-10 days/joint

24 hours/day production
2 months after order
Customer need
- Improved security of the electricity supply in South and Central Sweden
- Distance 250 miles

Alternatives
- 400 kV overhead transmission line
- Turnkey 500 – 700 MW ±300 kV underground HVDC Light system

Customer benefits with HVDC
- Shorter project time due to easier permitting (2 – 3 years)
- Increased power transfer existing a.c. lines (approx 200 MW)
- Voltage and reactive power control

Project status
- Final evaluation ongoing. Decision 2007