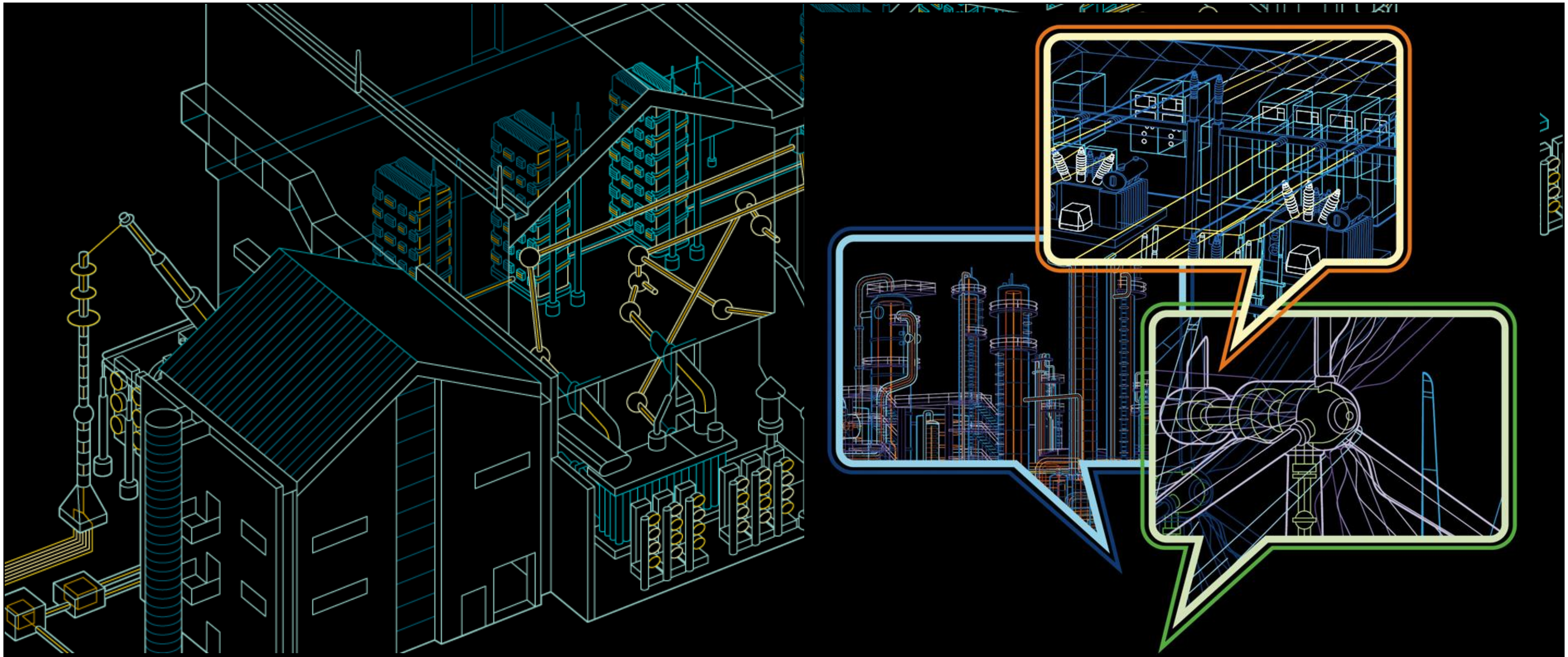
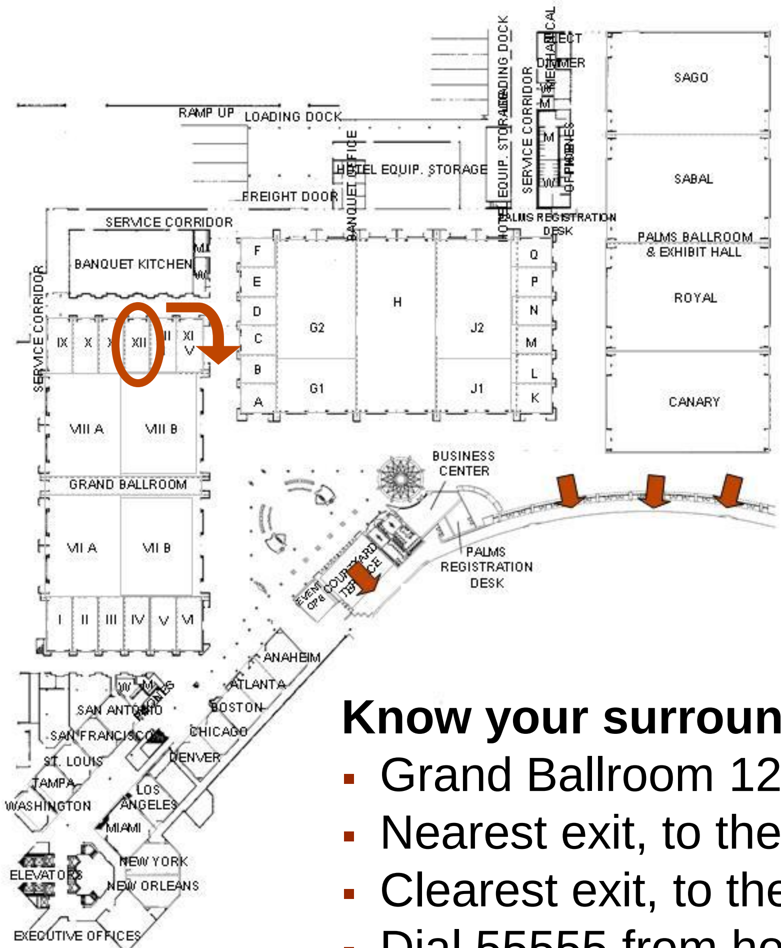
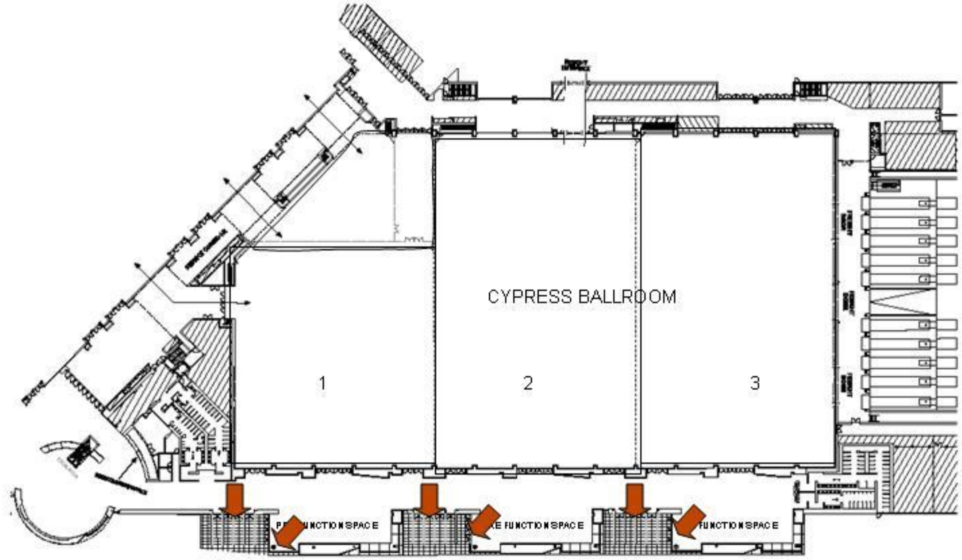


ABB Automation & Power World: April 18-21, 2011, Michael Bahrman P.E.

WPS-117-1
Why the strong growth in HVDC?

Your safety is important to us
Convention Center exits in case of an emergency





Know your surroundings:

- Grand Ballroom 12
- Nearest exit, to the right, then left out through the service corridor
- Clearest exit, to the right, then right out through the main doors
- Dial 55555 from house phone in case of emergency

Why the strong growth in HVDC transmission?
Topics

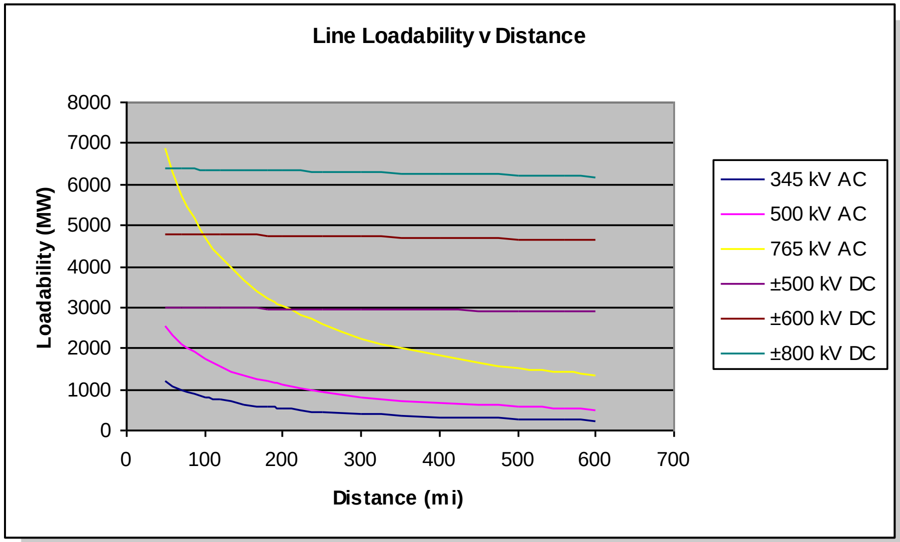
- A look back
- Transmission characteristics
- HVDC applications
- Enabling technologies
- Economics & efficiencies
- Additional drivers
- Today's expanded HVDC market
- A look forward
- Q & A

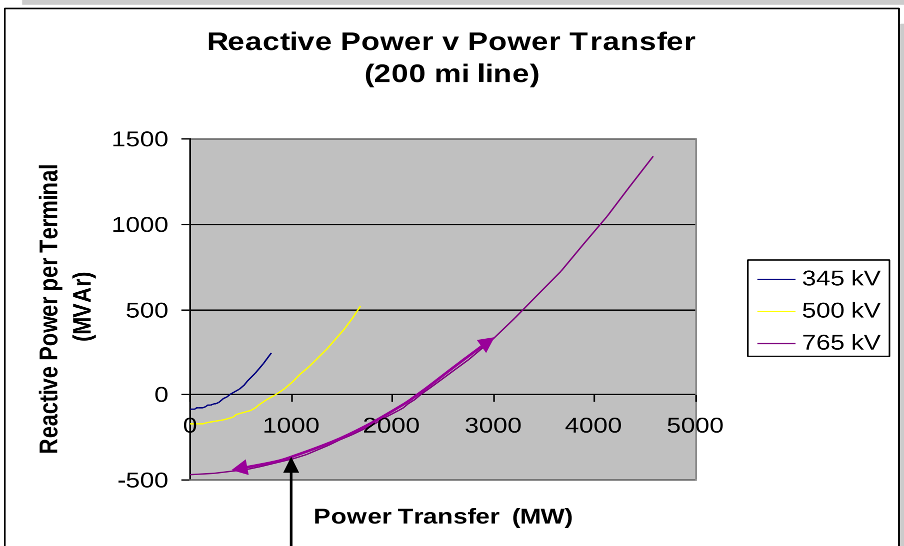
Technical evolution – some firsts at their time by ABB Innovation factors into HVDC market growth




- 1954 – first commercial HVDC with Hg arc valves
- 1970 – first thyristor valves
- 1980 – highest power (6300MW) / voltage (± 600kV) Itaipu, first use of μP
- 1994 – longest submarine cable (250km), Baltic Cable
- 1997 – first commercial VSC-based transmission, (HVDC Light^{TM})
- 2002 – longest underground cable project (180km), Murraylink HVDC Light^{TM}
- 2005 – first power from shore, Troll A HVDC Light^{TM}
- 2009 – first offshore wind, BorWin1 HVDC Light^{TM}
- 2009 – first overhead with VSC HVDC Light^{TM}, Caprivi Link
- 2010 – first ± 800kV, 6400 MW, Xiangjiaba – Shanghai
- 2010 – 4th generation HVDC Light^{TM}, higher ratings, lower losses

Transmission line delivery capability v distance
AC line capacity diminishes with distance*





Reactive power variation of 800 MVAr per 100 mi, 0.2-1.3 SIL

AC line distance effects:

- Intermediate switching stations, e.g. every ~200-250 mi max segment due to TOV, TRV, voltage profile
- Lower stability limits (voltage, angle)
- Increase stability limits & mitigate parallel flow with FACTS: SVC & SC
- Variable reactive demand
- Parallel flow issues more prevalent

DC line distance effects:

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

* St Clair Curve

Attributes of HVDC transmission

- Controllable – bypass congestion
- Higher power on fewer less-expensive lines, better utilization of resources
- No stability distance limitation
- Lower losses
- Facilitates integration of remote diverse resources with less impact on existing grid
- No limit to underground or sea cable length
- No significant fault current contribution
- Asynchronous, ‘firewall’ against cascading outages
- Up to 6400 MW on a bipolar (double circuit) line
- Up to ~1000 MW on a cable circuit

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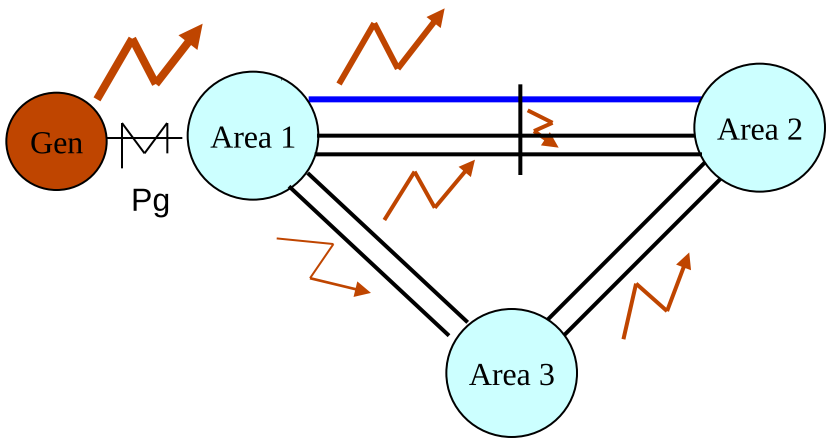
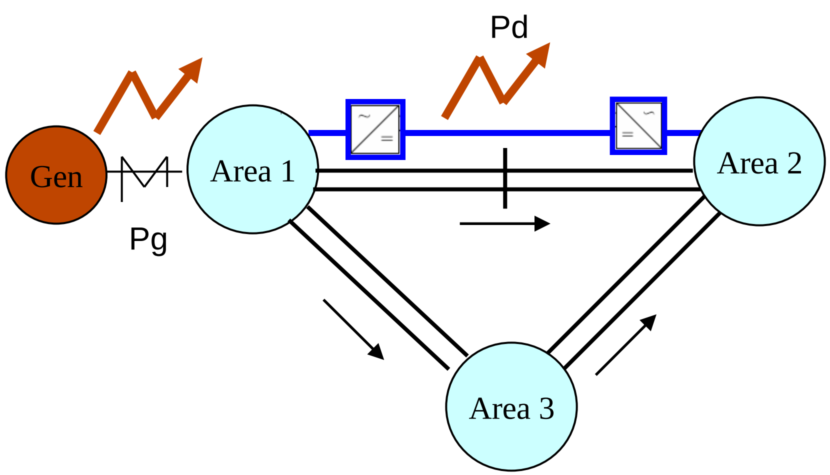
Indirect v Direct Control – AC v DC



AC Transmission:

- Power flow from generation distributes per line characteristics (impedance) & phase angle (generation dispatch)
- Variable generation gives variable flow on all paths
- May be limited due to congestion
- New resources add cumulatively clogging existing paths
- Flow controlled indirectly by generation schedule often at sub-optimal dispatch



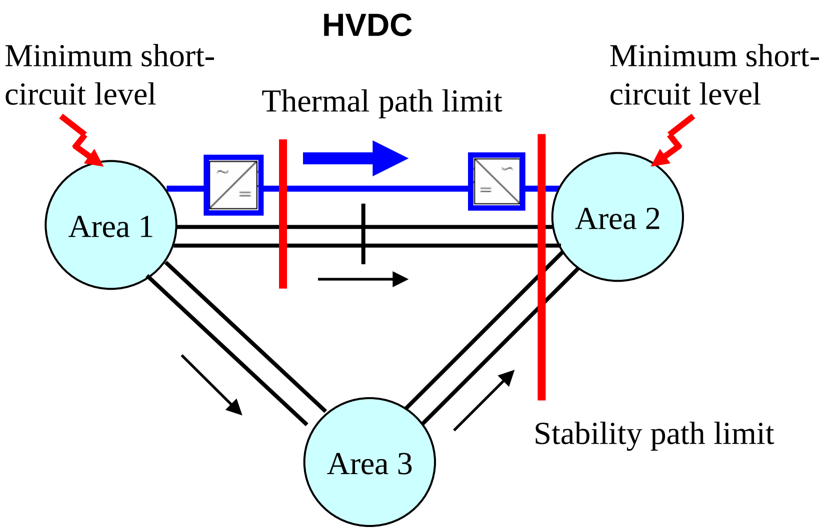
HVDC Transmission:

- Controlled power flow adds flexibility
- Pd = Σ Pg + P schedule or k * Pg, e.g.
- Transfers do not burden underlying grid
- Permits optimal power flow
- Bypasses congestion
- More firm

HVDC applications

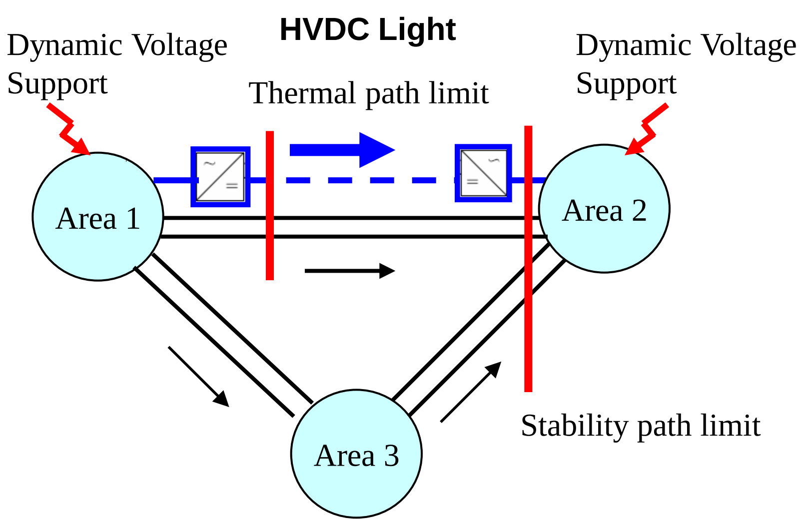
- Long distance, bulk power transmission
- Long distance underground and submarine cables
- Asynchronous interconnections
- Power to / from shore
- Weak system operation with dynamic voltage support for increased transfer on interconnecting ac and black start
- Fault current limitation

Converter Technology
HVDC and HVDC Light



Conventional HVDC - CSC:

- Minimum short circuit level restriction ($S_{MVA} > 2 \times Pd$)
- Induction wind generation contribution to short circuit and voltage support limited
- Reactive power demand and compensation at terminals
- Higher ratings, greater economies of scale, more efficient



HVDC Light - VSC:

- No minimum short circuit levels
- No filters or reactive power demand
- Dynamic reactive voltage support (virtual generator, Q ~= 0.5 x Pr)
- Leverage ac capacity by voltage support
- Conducive for but not limited to underground cable transmission

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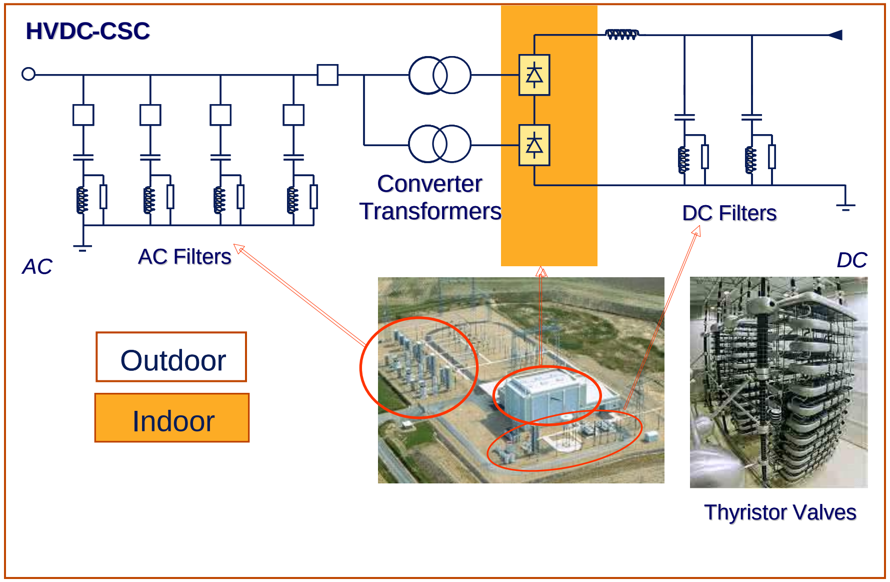
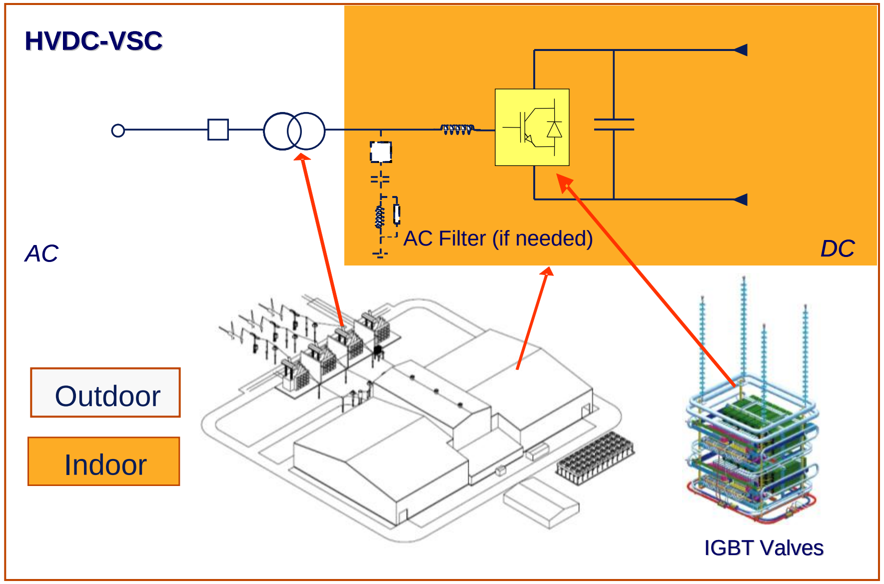
Core HVDC technologies





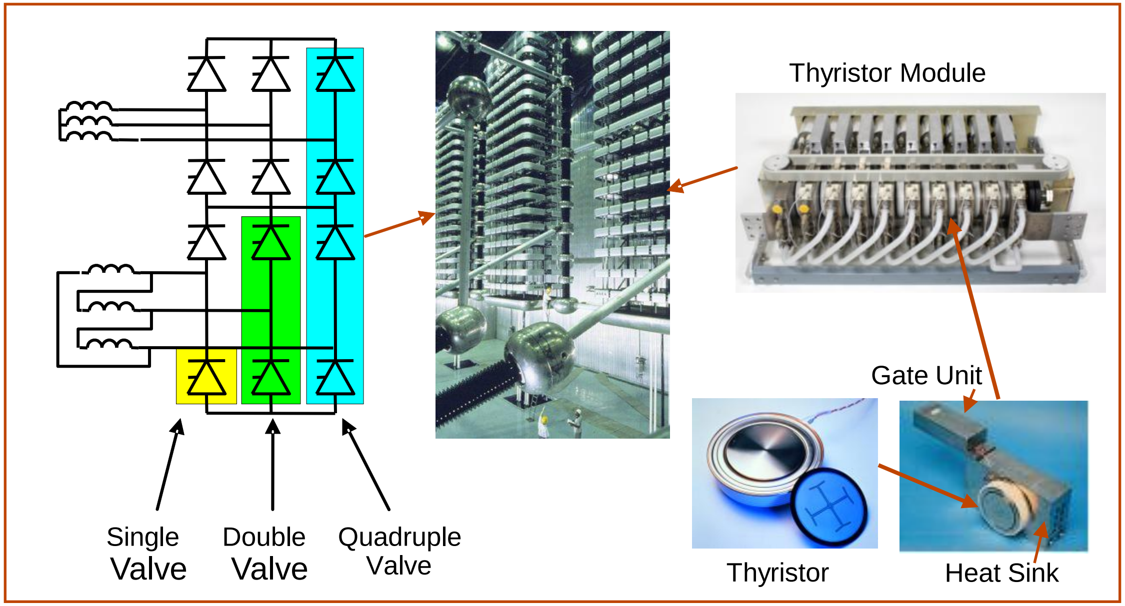
HVDC Classic

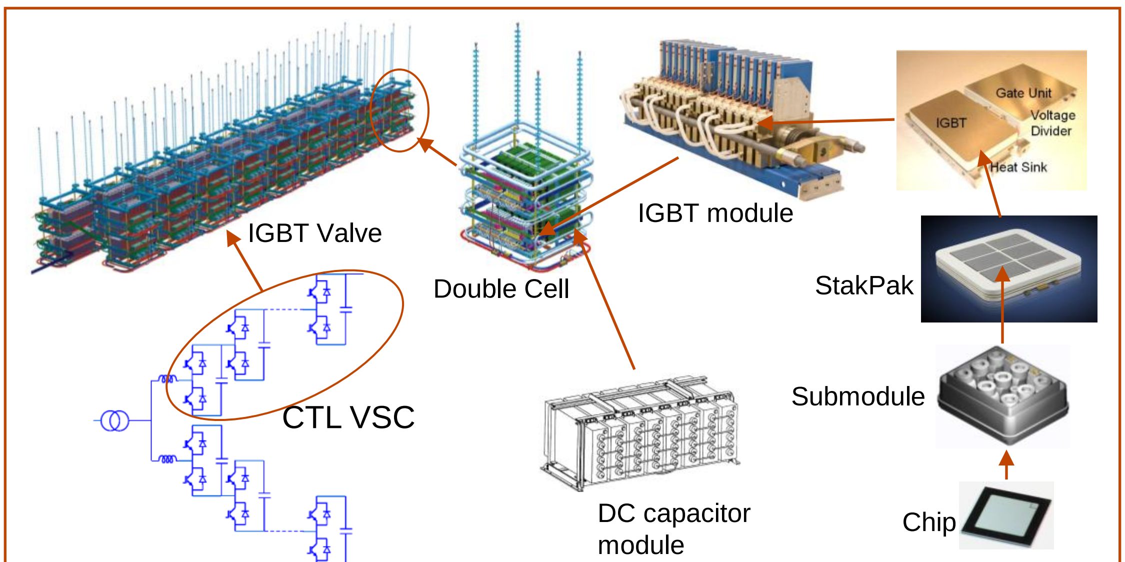
- Current source converters (CSC)
- Line-commutated converter (LCC) with thyristor valves
- Requires 50% reactive compensation (35% HF)
- Converter transformers
- Minimum short circuit capacity > 2 x Pd, > 1.3 x Pd with capacitor commuted converter (CCC)

HVDC Light 4G

- Voltage source converters (VSC)
- Self-commutated with IGBT valves
- Cascaded two level converters (CTL)
- Requires no reactive power compensation (~0-15% HF as required)
- Virtual generator at receiving end: P,Q
- Standard transformers
- Weak system, black start
- Radial wind outlet regardless of type of wind T-G, off-shore or isolated from grid
- U/G or OVHD

HVDC Converter Arrangements





HVDC Classic

- Current source converter
- Thyristor valves
- Thyristor modules
- Thyristors
- Electrically triggered
- Line commutated

HVDC Light 4G

- Voltage source converter
- Cascade two-level converters
- DC capacitor modules
- IGBT valve modules
- StakPaks
- Safe short circuit failure mode
- Submodules
- Self commutated

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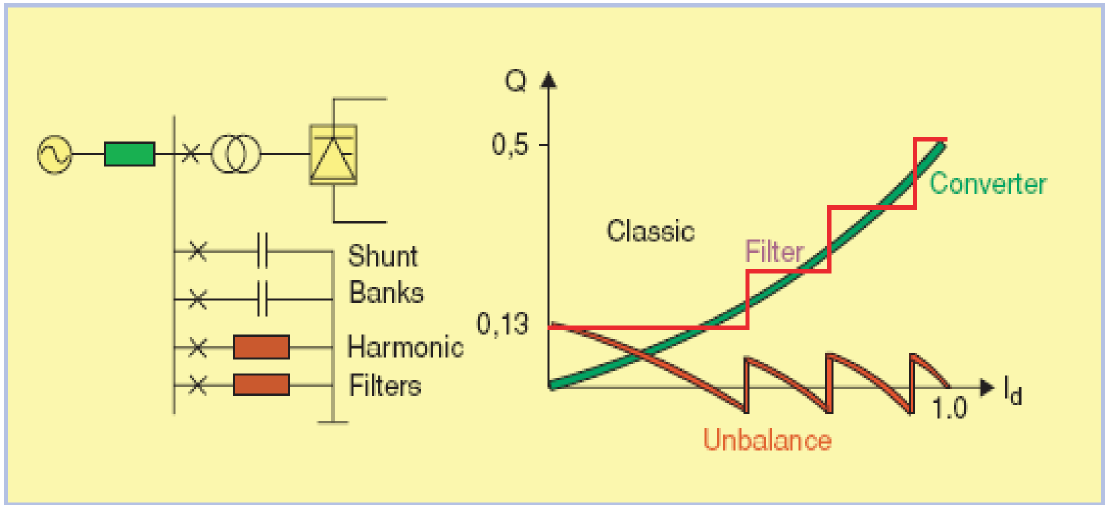
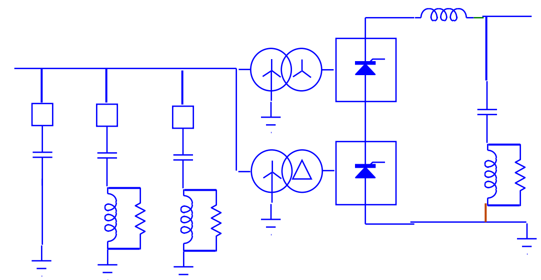
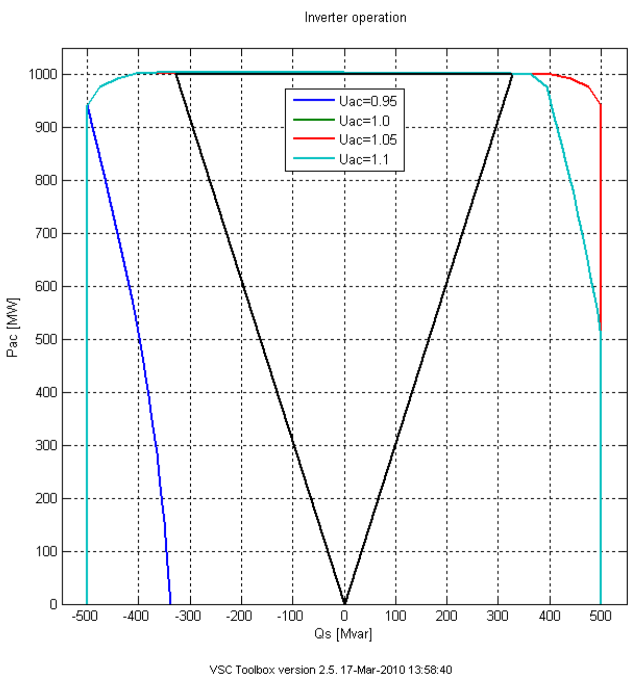
Comparison of Reactive Power Characteristics



HVDC Classic:

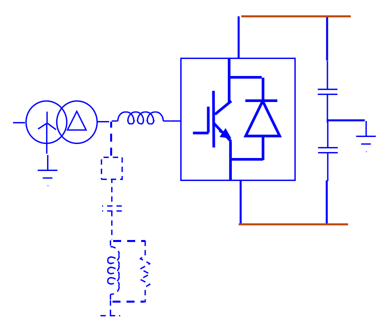
Reactive compensation by switched filters and shunt capacitor banks



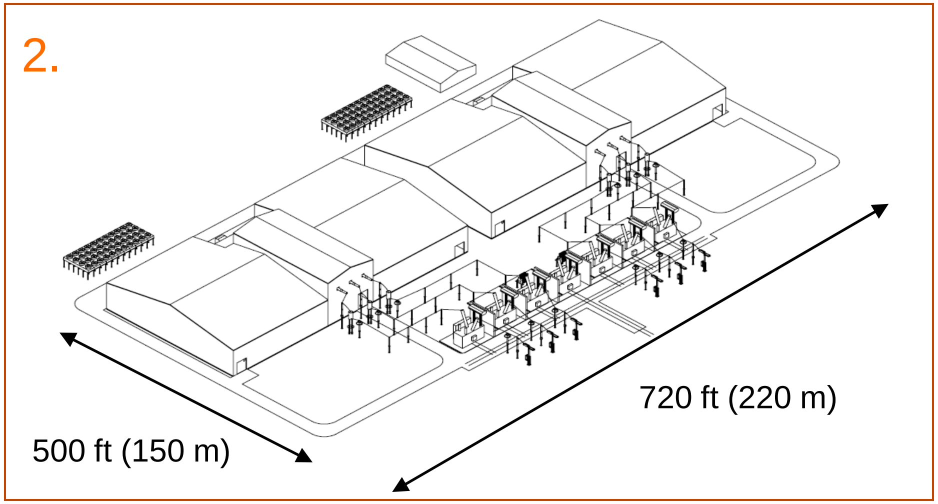


HVDC Light:

No reactive compensation necessary, STATCOM with dynamic range ~ 0.5Pd/+0.5Pd MVar below 90% p.f. (black “v-shaped” lines represent 95% power factor)

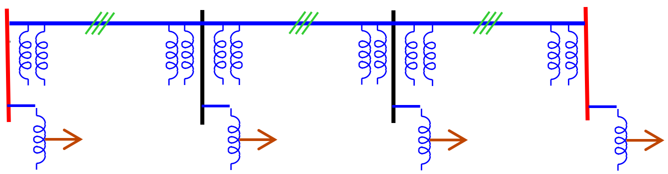


How big is a 2000 MW HVDC converter station?

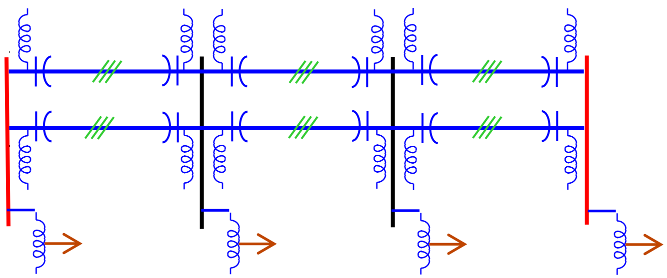


1. 2000 MW HVDC, 26.2 acres (10.6 hectares), system dependent
2. 2000 MW HVDC Light, 8.2 acres (3.3 hectares), system independent
3. Walmart Supercenter, 31.5 acres (12.8 hectares)

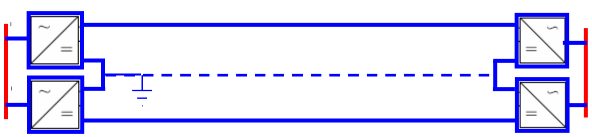
Transmission alternatives and HVDC configurations 3000 MW steady state capacity



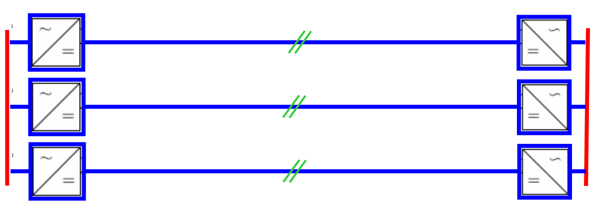
765 kV circuit



2 x 500 kV circuits with series comp

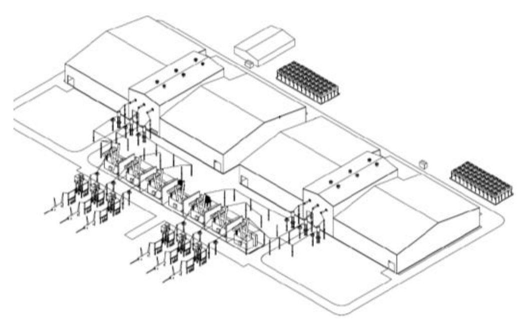


±500/600 kV HVDC/HVDC Light bipole

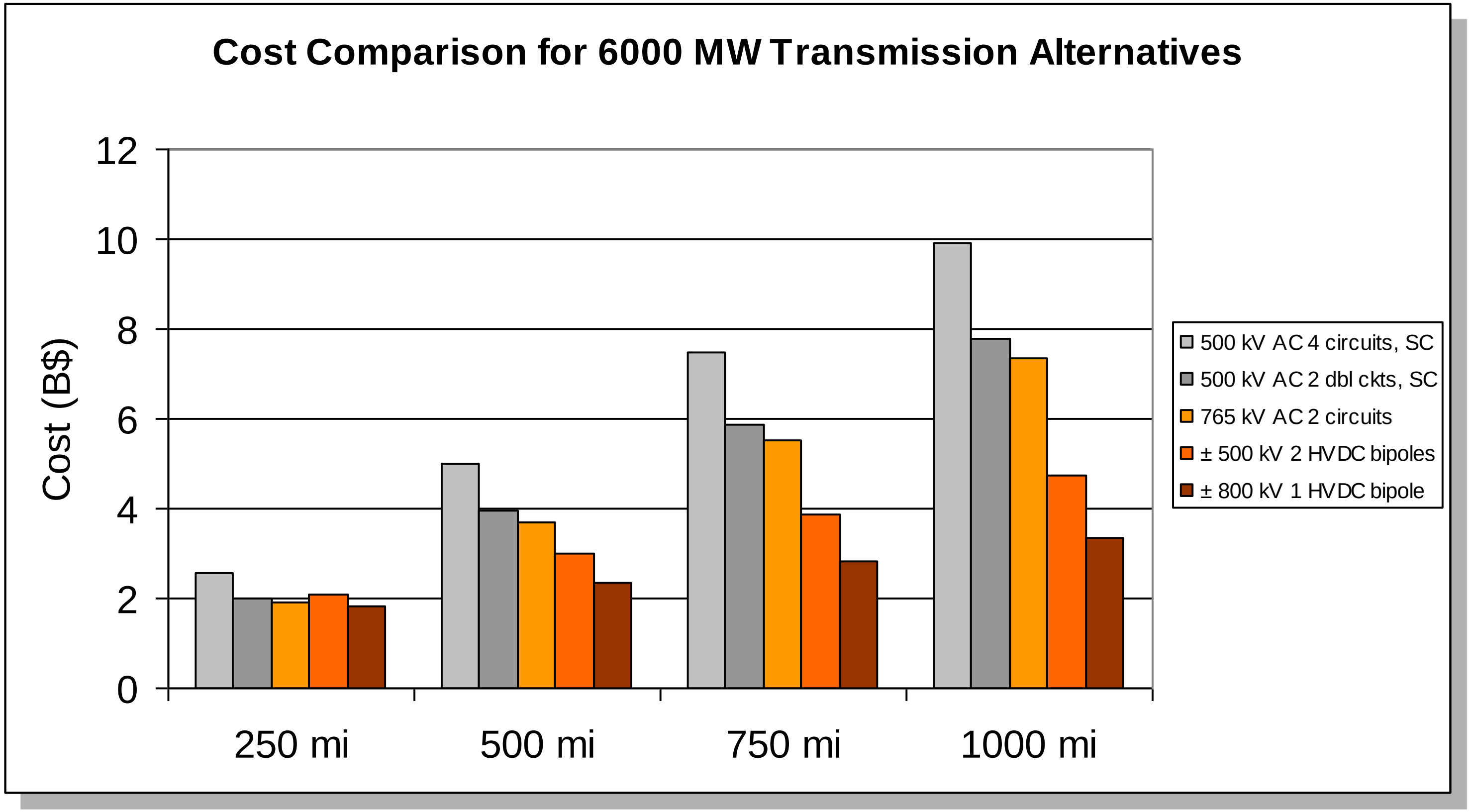


3 x ±320 kV HVDC Light tripole

OVHD / UG or hybrid



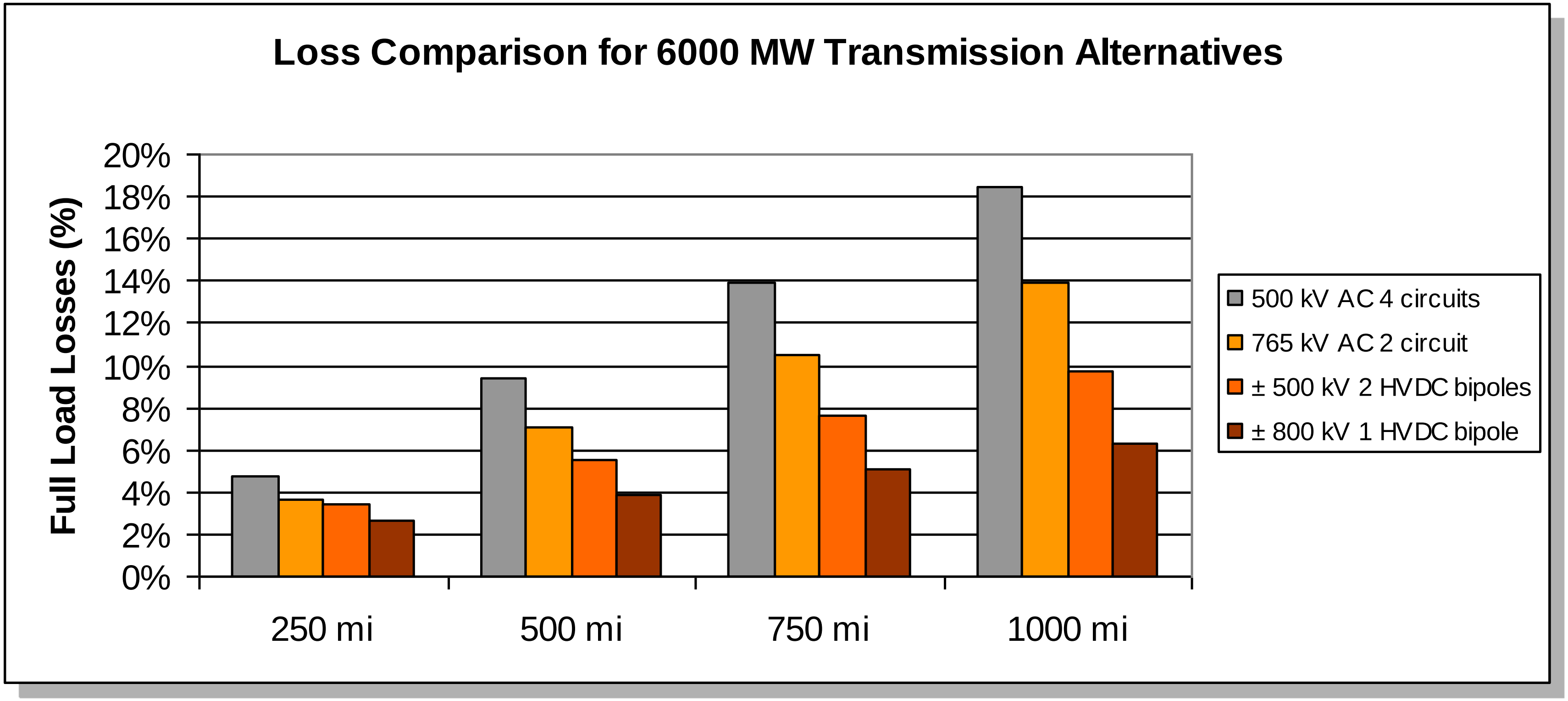
Comparative costs for 6000 MW transmission Intermediate S/S and reactive comp every 400 km



Notes:

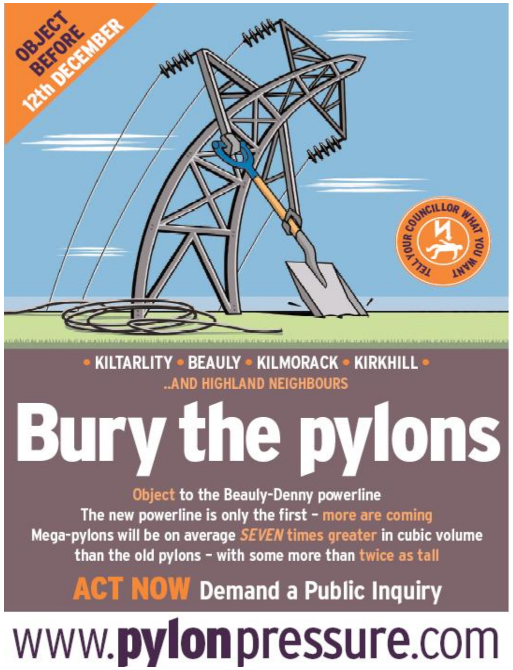
- Series compensated ac lines loaded to ~ 2 x SIL,
- 765 kV loaded to ~ 1.3 x SIL or ~ steady state stability limit for 200 mi line segment per St Clair curve
- Transmission line and substation costs based on Frontier Line transmission subcommittee, NTAC, WREZ and ERCOT CREZ unit cost data.
- Lines loaded to their steady state stability limits

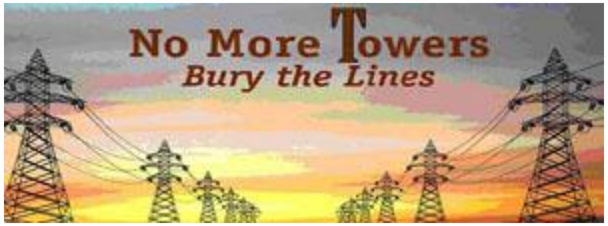
Transmission Alternatives Loss Comparison: 6000 MW
Line losses + converter and S/S losses @ full load



Note: AC and DC line conductors chosen for comparable current densities, higher no. conductor bundles for higher voltage.

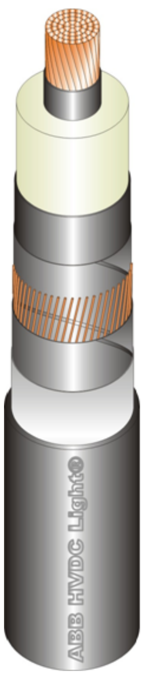
The NIMBY effect . . .
Organized opposition and protracted routing delays



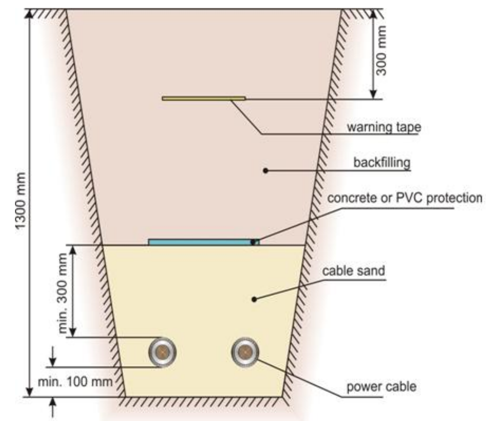


HVDC Light XLPE cables to 320 kV, 1000 MW
Two cables per symmetrical monopole circuit

- More information at WPS-125-1, Session 10



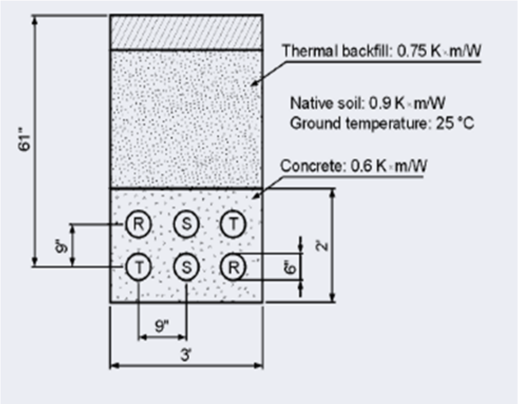
Conductor material:	Copper or Aluminum
Conductor screen material:	Conductive PE
Insulation type/material:	Dry cured triple extruded HVDC polymer
Insulation screen:	Conductive PE
Bedding:	Conductive swelling tapes
Metallic screen:	Copper wires
Bedding:	Conductive swelling tapes
Radial moisture barrier:	Aluminum-PE laminate
Outer jacket:	Polyethylene



Direct burial:

Advantages – less costly civil construction, easier cable installation, less thermo-mechanical stresses on joints, etc.

Disadvantages – arguably less mechanical protection against dig-ins and external damage to the cables.



Duct bank system:

Advantages – solid mechanical protection against dig-ins and external damage to the cables. (Important characteristic in roads and in areas with other utilities close by.)

Disadvantages – costly civil construction, more difficult cable pulling, higher thermo-mechanical stresses on joints, etc.

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HVDC projects with ABB technology

- **47 HVDC Classic Projects**
- **11 HVDC Upgrade Projects**
- **16 HVDC Light Projects**

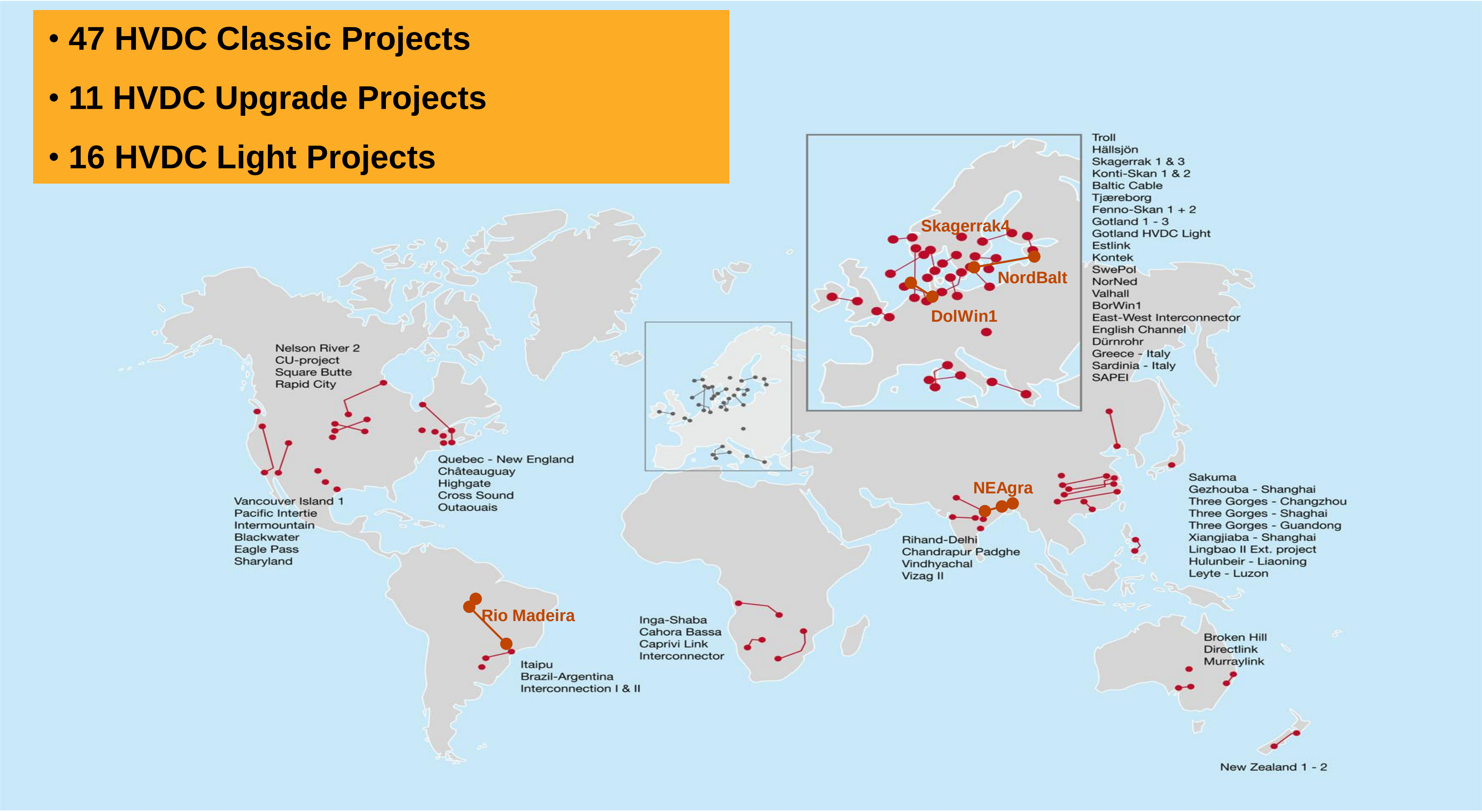
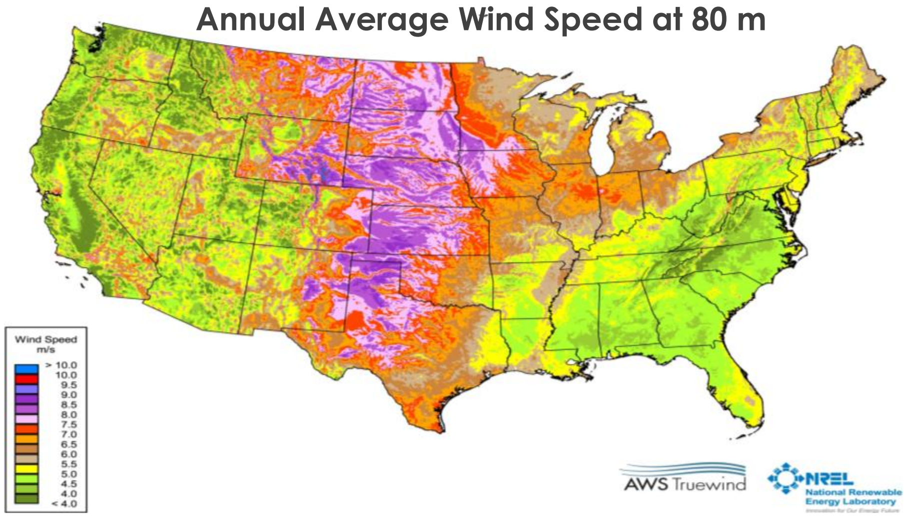
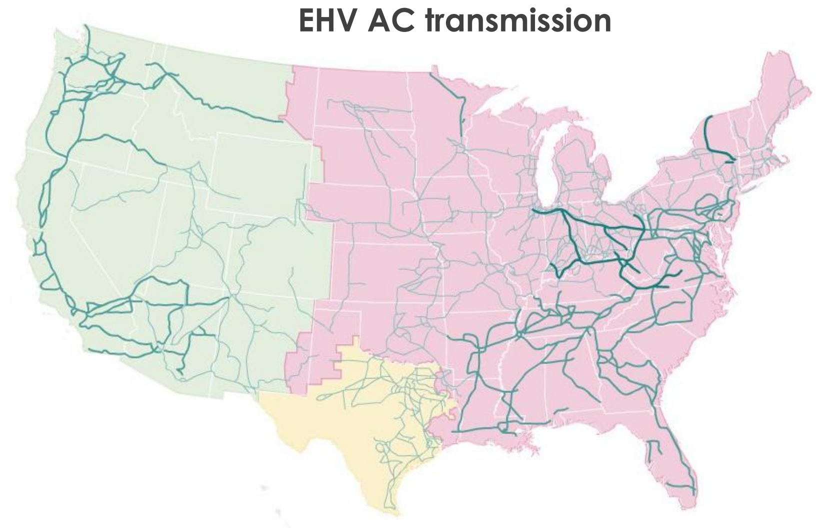
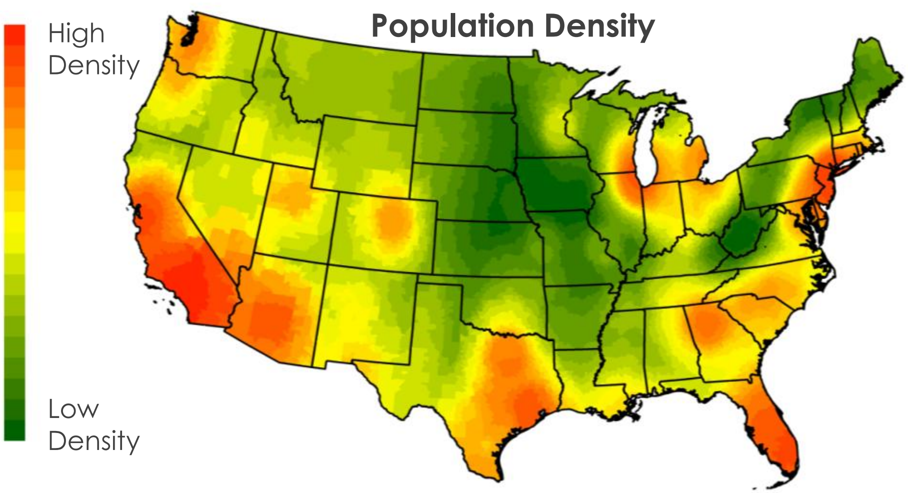


ABB has delivered 53 % of all commissioned HVDC projects
Source: Cigre statistic 2009

Resource distribution, demographics and EHV grid

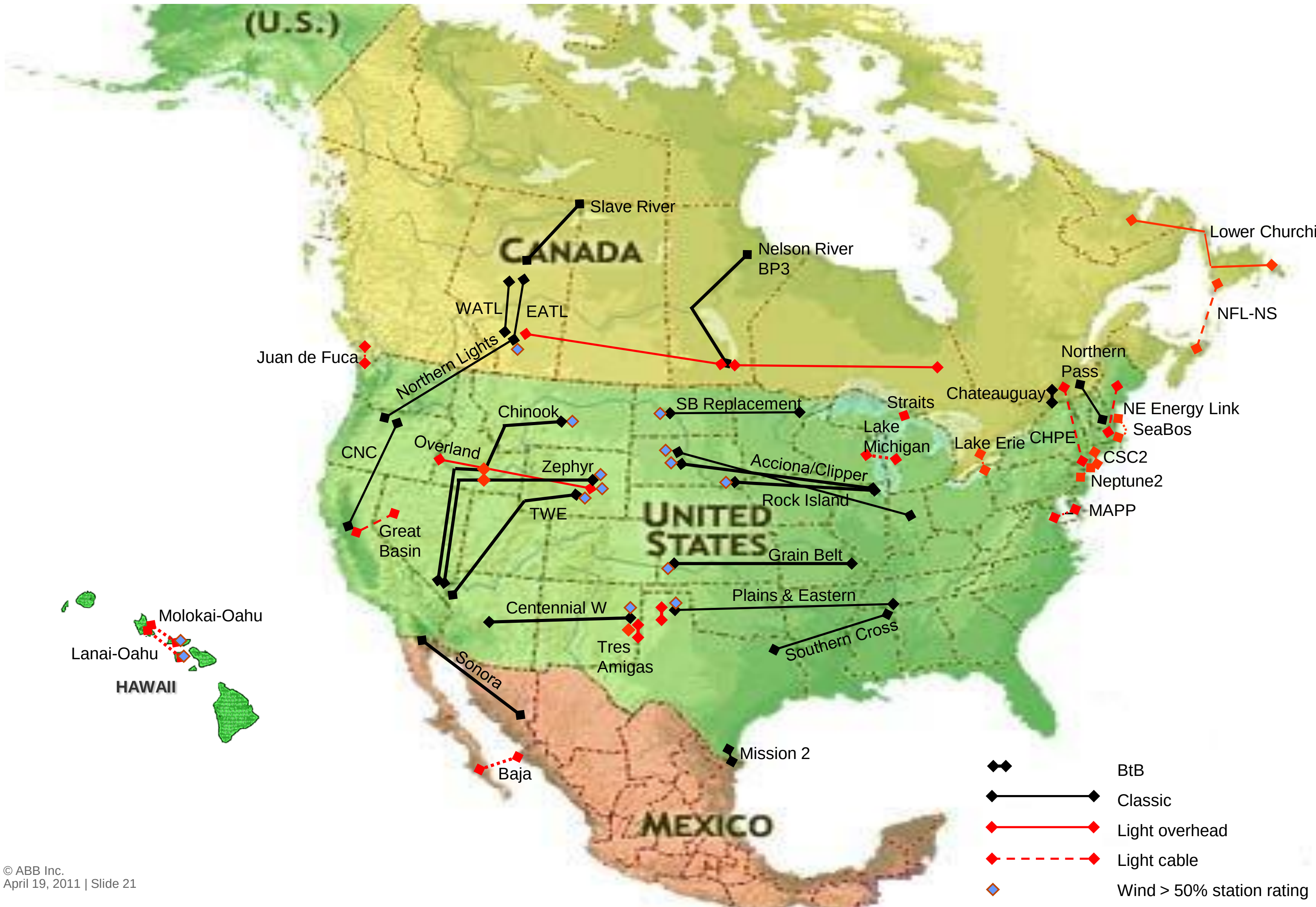






U.S. Census Bureau

Proposed HVDC projects in North America
Market drivers exemplified



A look forward
Trends in HVDC transmission

- Higher power and voltage ratings
- Smaller station footprint
- Greater efficiencies
- Fast DC breakers
- DC grids / networks
- Increased use for underground transmission
- Increased use for accessing renewable generation both on and off-shore - required for meeting RPS
- Non-traditional uses, maximizing power transfer on available corridors, either overhead or underground
- Stay tuned!

Q & A
Reminders Automation & Power World 2011

- Please be sure to complete the workshop evaluation
- Professional Development Hours (PDHs) and Continuing Education Credits (CEUs):
  - You will receive a link via e-mail to print certificates for all the workshops you have attended during Automation & Power World 2011.
  - BE SURE YOU HAVE YOUR BADGE SCANNED for each workshop you attend. If you do not have your badge scanned you will not be able to obtain PDHs or CEUs.

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