High Voltage Direct Current (HVDC)

Technology Solutions for Integration of Renewable Resources

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Grid Modernization and Transmission Capacity Expansion Needs

Grid Modernization and Transmission Capacity Expansion Needs

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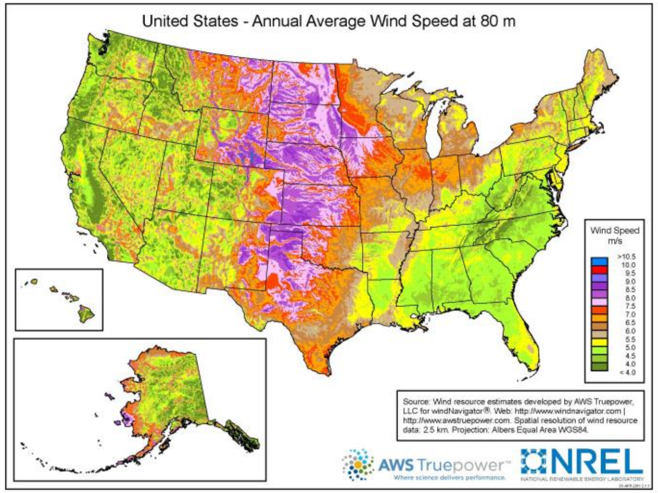

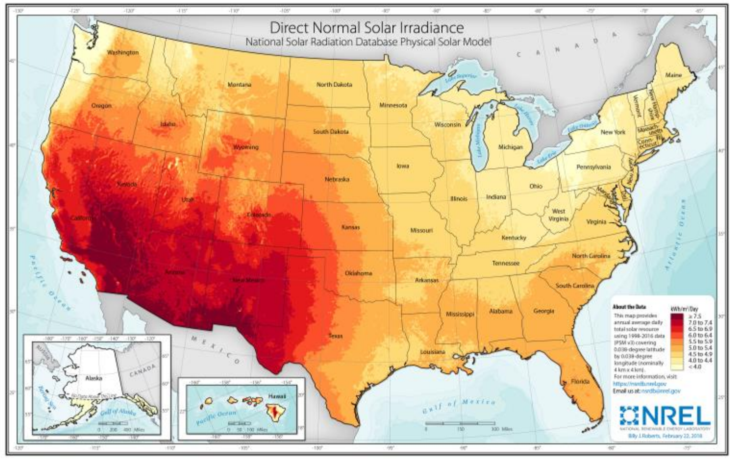

- The most favorable conditions for development of large-scale onshore wind and solar based generation in the United States are in rural areas of the Midwest and Southwest.
- These areas are generally far removed from large population centers and loads.
- New electric transmission capacity will be needed to support reliable delivery of renewable energy from remote areas to major population and load centers.
- Traditional transmission expansion proposals often experience fierce public opposition that hinder or impede permitting of new lines.
- Factors commonly cited against construction of new overhead transmission lines include:
  - ✓ Environmental (e.g., impacts on animal life and plants from clearing of new corridors)
  - ✓ Aesthetics
  - ✓ EMF

Grid Modernization and Transmission Capacity Expansion Needs

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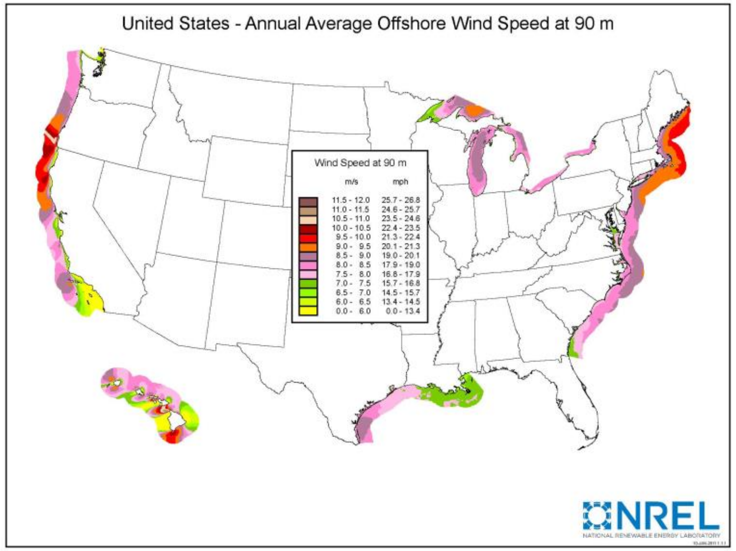

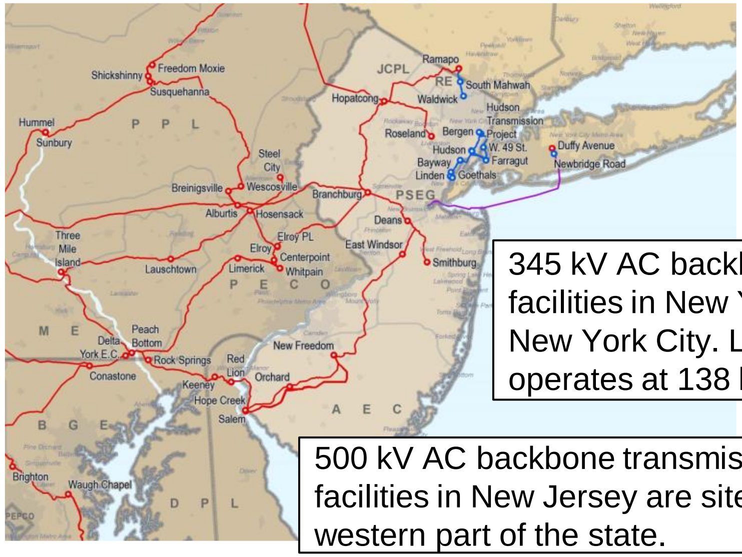

345 kV AC backbone transmission facilities in New York State end in New York City. Long Island grid operates at 138 kV or below.

500 kV AC backbone transmission facilities in New Jersey are sited in western part of the state.

- States with ambitious plans for development of large-scale offshore wind facilities (e.g., Massachusetts, New York and New Jersey) have few existing transmission facilities located near shore that are capable to receiving power from large offshore wind farms.
- In both New York and New Jersey, the existing transmission backbone systems and associated substations are located away from anticipated landing sites for export cables from planned new offshore wind facilities.
- Major new backbone transmission facilities will be needed onshore and/or offshore to facilitate development of large offshore wind facilities and support public policies to reduce green-house gas emissions.
- Siting and construction of major new overhead transmission lines near the shores of Long Island or the mid-Atlantic coast seems highly unlikely.

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Impacts of Retirement of Traditional Fossil-Fuel Based and Nuclear Generation Facilities

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- Fossil-fuel and nuclear based generators sited close to major load centers typically supply or absorb significant amounts of reactive power to maintain grid voltage profiles, system stability and reliable power supply to the loads.
- Turbines and generators also provide inertia that supports the power frequency and reliable power delivery during grid disturbances.
- When fossil-fuel and nuclear based generation near major load centers retire, reactive capacity deficits and reduced system inertia can cause reliability issues that reduce transmission capacity of existing transmission facilities.

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Why Consider HVDC over Conventional AC Transmission?

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Why Consider HVDC over Conventional AC Transmission?

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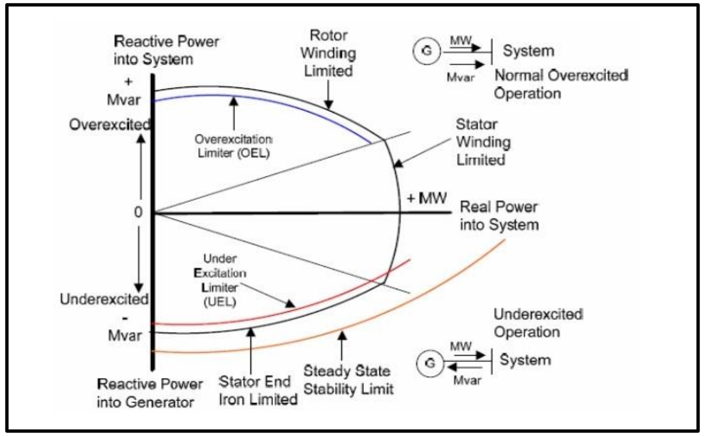
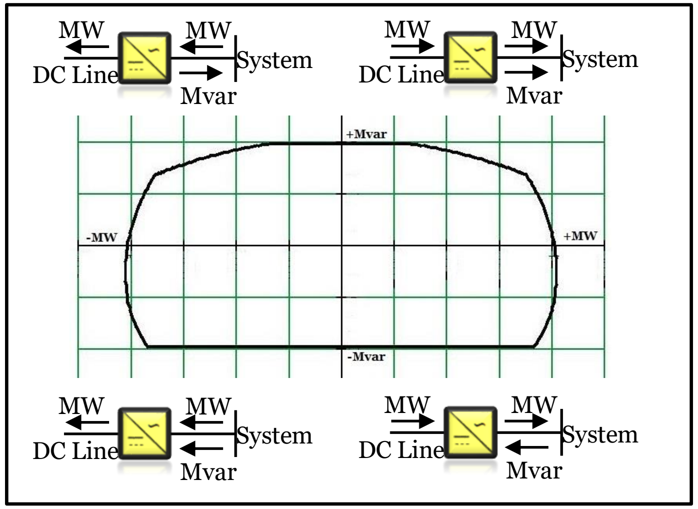
Performance Characteristics | Reactive Power Support and Black-Start



Typical P-Q Curve for Fossil Fuel based Generators



Typical P-Q Curve for VSC Based HVDC Stations

- Voltage source converter ("VSC") based HVDC links can deliver renewable energy from remote renewable wind, solar and hydroelectric resources and make such deliveries appear to the grid as supply from a local generator sited at the receiving end of the transmission corridor.
  - ***No Inadvertent Power Flows:*** The converter stations control the power flow on an HVDC link to the desired dispatch and there is no risk of inadvertent flows overloading other parallel transmission facilities
  - ***Improved Grid Performance***: VSC based HVDC stations provide dynamic and continuous reactive power support (approx. ±50% of real power capacity rating) for real power transfers in both directions on the DC line.
  - ***Improved Grid Resilience***: VSC based HVDC stations are capable of quickly black-starting the AC grid at the receiving end of the DC transmission corridor using power supply from remote generation resources located at the sending end of the line.

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HVDC Projects Around the World

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North America

- SunZia
- CHPE
- Chateauguay
- Maritime Link
- Quebec – New England Upgrade
- CU Upgrade
- Madawaska Upgrade
- Celilo Upgrade
- Highgate Upgrade
- Railroad DC Tile
- Oklaunion
- Mackinac
- IPP Upgrade
- Blackwater Upgrade
- Outaouais
- Sharyland
- Rapic City
- Cross Sound
- Eagle Pass
- Quebec – New England
- Pacific Intertie Expansion
- IPP Intermountain – Adelanto
- Pacific Intertie Upgrade
- Madawaska
- Highgate
- Chateauguay Upgrade
- CU project
- Square Butte Upgrade
- Eel River Upgrade
- Pacific Intertie
- Vancouver Island Pole 1 & 2
- Nelson River 3, Bipole
- EATL
- WATL
- Nelson River 1 & 2
- McNeill
- Lower Churchill
- Trans Bay Cable
- Hudson
- Neptune RTS
- Lamar
- Celilo Valve Replacement
- Sylmar East Valve
- Welsh 1995/2017
- Virginia Smith/Sidney
- Square Butte
- Eel River
- Eddy County BtB
- Stegall BtB

South America

- Itaipu
- Rio Madeira Back-to-back
- Rio Madeira
- Brazil – Argentina
- Interconnection I & II
- Rio Madeira
- Melo
- Rivera HVDC Brazil
- Acaray

Africa

- Saudi-Egypt
- Caprivi Link
- Inga – Kolwezi Upgrade
- Cahora Bassa, Songo
- Apollo Upgrade
- Inga – Kolwezi
- Cahora Bassa
- Cahora Bassa
- Ethiopia – Kenya HVDC Interconnector

Europe

- Hornsea 3
- Shetland
- Dogger Bank C
- Dogger Bank A&B
- IFA2
- Nordlink
- North-sea Link
- Caithness – Moray
- Kriegers Flak Cgs
- Johan Svedrup
- Gotland Upgrade
- Kontek Upgrade
- Troll 1 & 2
- Troll 3 & 4
- Borwin 1
- Dolwin 1
- Dolwin 2
- Dolwin 5
- Åland
- Nordbalt
- Litpol Link
- East West Interconnector
- Sapei
- Valhall
- Norned
- Estlink
- Italy – Greece
- Tjæreborg
- Swepol
- Gotland Light
- Hällsjön
- Kontek
- Baltic Cable
- Fennoskan 1 & 2
- Dürnohr
- Skagerrak 1-3
- Skagerrak 4
- Gotland 1-3
- Konti-skan 1 & 2
- English Channel
- Borwin 3,5
- Konti-Skan 1 Cable
- SACOI
- Western HVDC Link
- EstLink 2
- COMETA
- BritNed
- Storebælt
- Moyle Interconnector
- Etzenricht
- Wien-Suedost
- Dürnrohr
- Borwin 2
- Dolwin 3
- Helwin 1
- Helwin 2
- INELFE
- Sylwin 1
- MONITA
- Italy-France

Asia

- Project Lightning
- Higashi-Shimizu
- Jeju 3
- Changji-Guquan
- Raigarh-Pugalur
- North-East Agra
- Jinping – Sunan
- Hülünbeir – Liaoning
- Qinghai-Tibet
- Yunnan-Guangxi
- Lingboa li Extension
- Xiangjiaba – Shanghai
- Three Gorges – Shanghai
- Vizag Li
- Three Gorges – Guangdong
- Three Gorges – Changzhou
- Xiluodu-Zhexi
- Hami-Zhengzhou
- Lingzhou-Shaoxing
- Jinbei-Nanjing
- Jiuquan-Hunan
- Shanghaimiao-Shandong
- Ximeng-Taizhou
- Dianxibei-Guangdong
- Zhalute-Qingzhou
- Chapad
- Rihand-Delhi
- Gezhouba – Shanghai
- Vindyachai
- Sakuma
- Champa-Kurukshetra I/2
- Zhangbei
- Leyte-Luzon
- Buk-Dangjin-Godeok
- Jeju-Jindo
- Nindong-Shandong
- 3G-Shanghai 2
- GCCIA
- Lingbao 2
- China-Russia
- Sasaram
- Jeju-Haenam
- Chandrapur
- Nuozhadu – Guangdong
- Xiluodu – Guangdong
- Back-to-Back Bangladesh
- Mundra – Haryana
- Ballia – Bhiwadi
- Yunnan – Guangdong
- Guizhou – Guangdong II
- Guizhou – Guangdong
- East-South Inter connector II and Upgrade
- Thailand-Malaysia
- Tianshengqiao – Guangzhou
- Wudongde-Guangdong-Guangxi
- YU-E

Australia and Oceania

- Murraylink
- Directlink
- NewZealand 1
- NewZealand 2
- Broken Hill
- Inter-Island link Pole 3
- Basslink

Project executed by Hitachi Energy - Project delivered by other suppliers

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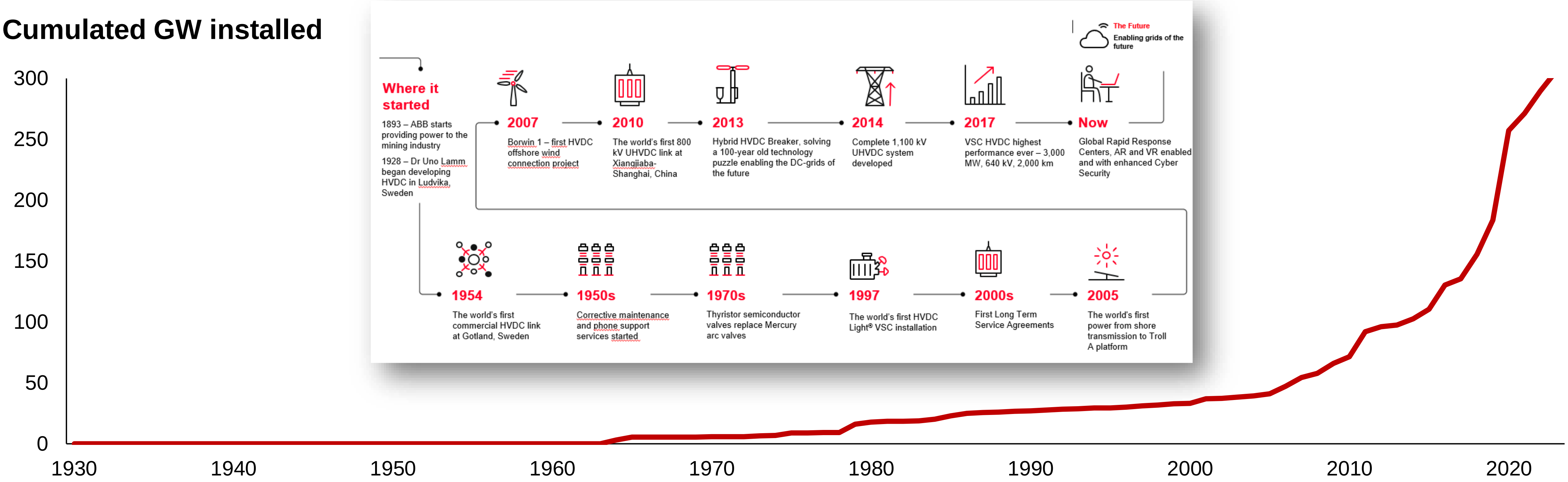
HVDC Growth

Cumulated GW installed



1928

Dr Uno Lamm began developing HVDC in Ludvika, Sweden

1954

The world's first commercial HVDC link at Gotland, Sweden

1970s

Mercury arc valves replaced with thyristor valves

1997

The world's first VSC HVDC installation

2017

VSC HVDC highest performance ever – 3,550 MW, 640 kV

Exponential growth has been driven by Technical developments and Grid transformation needs

Why Consider HVDC over Conventional AC Transmission?

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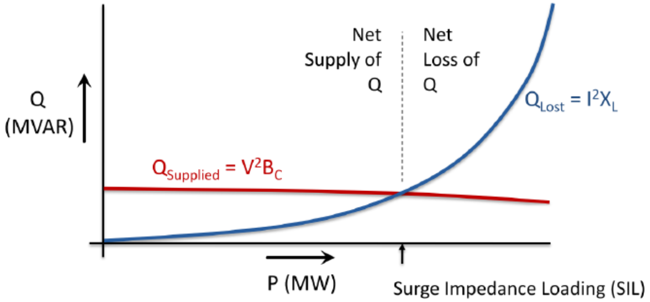
Characteristics of DC and AC Lines

Typical surge impedance loading:

- 230 kV: 200 MW
- 345 kV: 420 MW
- 500 kV: 950 MW



- HVDC lines cost less and require less space:
  - 2 versus 3 insulated conductors
- Lower losses in HVDC lines:
  - No reactive power flows
  - No skin effect (R_{DC} for conductors is lower than R_{AC})
- Transmission capacity of long AC lines is constrained by voltage and transient stability limits
  - HVDC lines are constrained by thermal limits only
- EMF - No fluctuating magnetic field in HVDC line corridors
  - No risk of induced currents in co-located infrastructure

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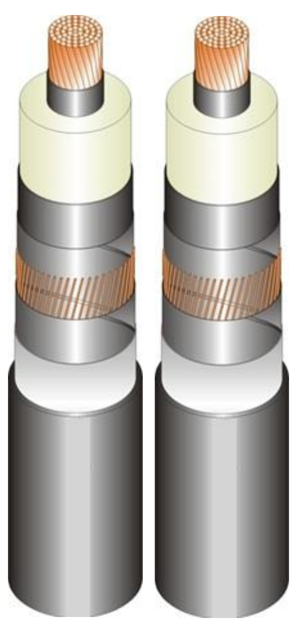
Why Consider HVDC over Conventional AC Transmission?

Transmission Technology Deployment | New Invisible High-Capacity Transmission Lines



Underground DC Cable Circuit

Submarine DC Cable Circuit

- The practical length of a high-voltage AC cable link is limited by the 60 Hz charging current caused by the inherent electrical capacitance of the cable
  - The cable capacitance increases linearly with the length of the cable
  - HVDC cables only carry charging current during initial energization of the circuit
- Continued R&D over the past two decades has produced high-capacity polymer (XLPE) insulated DC cables that facilitate construction of very long and invisible high-capacity transmission lines.
  - New transmission lines onshore can be all underground or a hybrid of overhead and underground construction to mitigate siting issues and public concerns
- Underground segments can be sited in existing infrastructure corridors (e.g., existing overhead line corridors, roads, railroads, pipelines, etc.) to avoid disturbing or impacting previously undeveloped land.

1999	2002	2012	2007-2009	2015	2016	2023	2014-2018
Sweden	Australia	Ireland-Wales	Type and PQ tests	Germany	Sweden-Lithuania	United Kingdom	Type and PQ tests
160 kV (±80 kV)	300 kV (±150 kV)	400 kV (±200 kV)	640 kV (±320 kV)	640 kV (±320 kV)	600 kV (±300 kV)	640 kV (±320 kV)	1050 kV (±525 kV)
50 MW	220 MW	500 MW	up to 1100 MW	800 MW	700 MW	1200 MW	up to 2000 MW
43 miles UG	112 miles UG	46 miles UG		60 miles UG	31 miles UG	20 miles UG	1280 kV (±640 kV)
		116 miles subsea		47 miles subsea	248 miles subsea	80 miles subsea	up to 2400 MW

Why Consider HVDC over Conventional AC Transmission?

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Installation of high-capacity submarine DC cable system in the North Sea

Installation of high capacity XLPE insulated DC cable system in rural area in Germany

Two DC power cable cores and fiber-optic cable

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HVDC Configurations and Converter Technologies

Typical HVDC Transmission System Configurations

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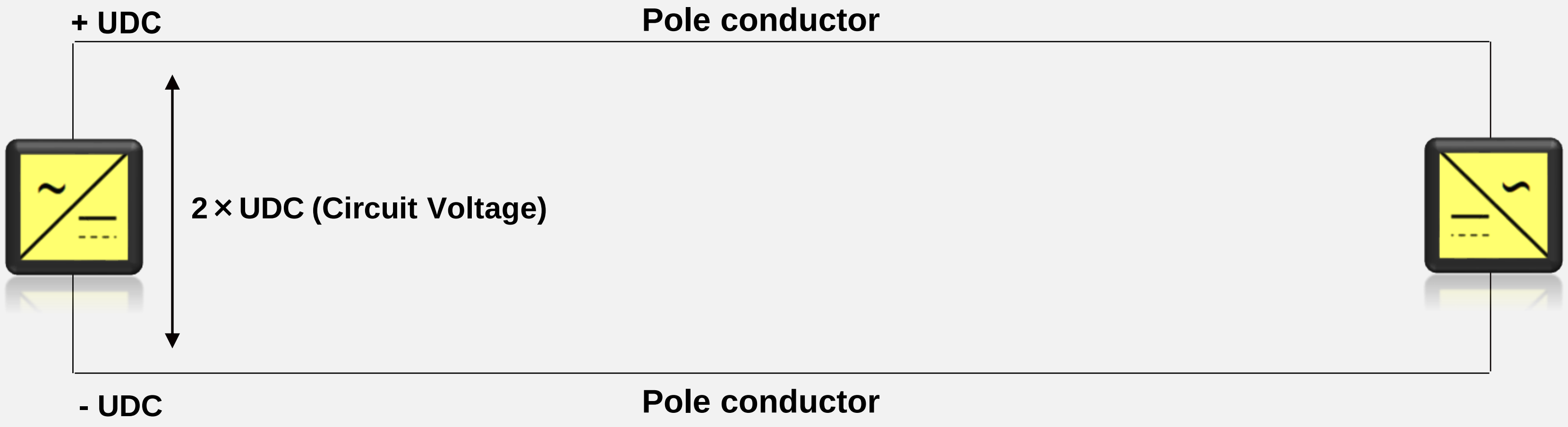
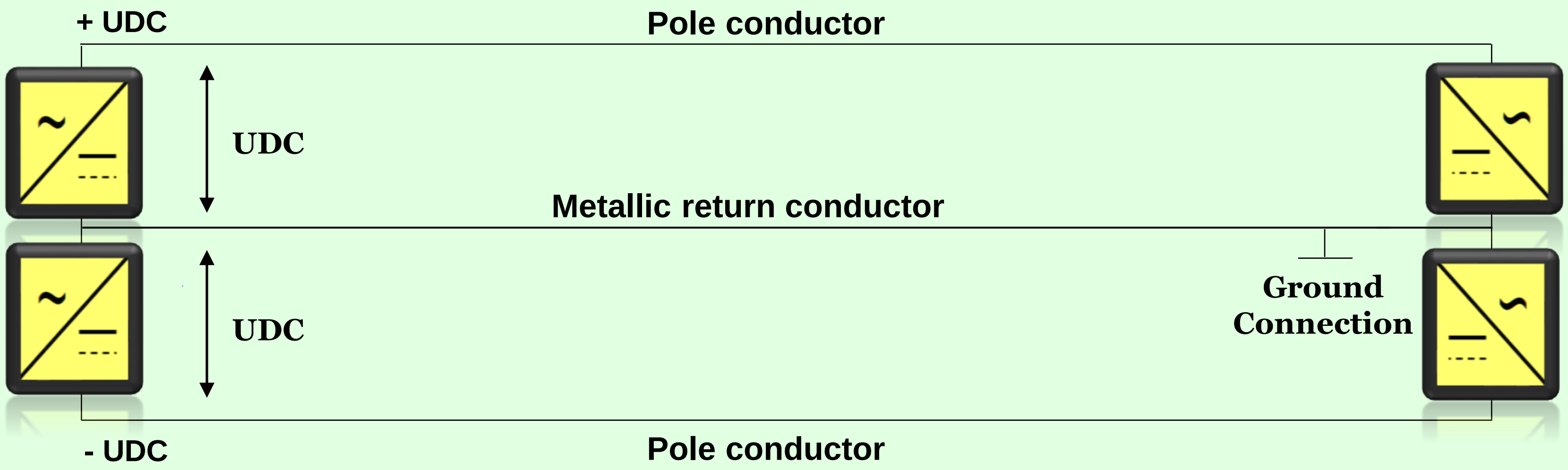


<u>Symmetric Monopole Configuration</u>

- Traditional configuration for long DC cable systems
- Examples in the United States:
  - Cross Sound Cable
  - Champlain Hudson Power Express



<u>Bipolar Configuration</u>

- Traditional configuration for long DC overhead lines
- Equivalent to double-circuit AC line
- Examples in the United States:
  - Pacific DC Intertie
  - Intermountain Power Project
  - SunZia

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HVDC Converter Technologies

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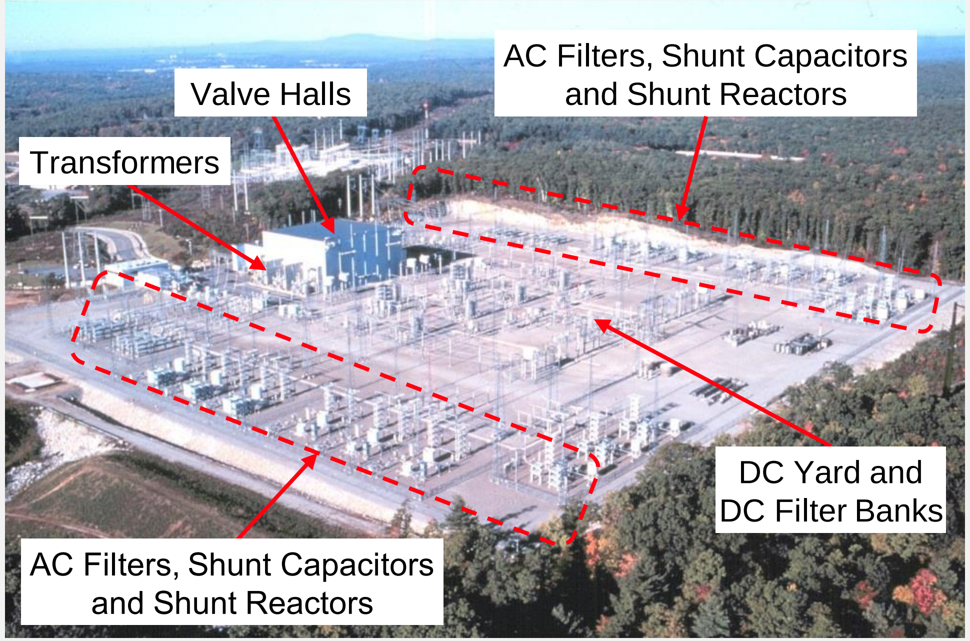
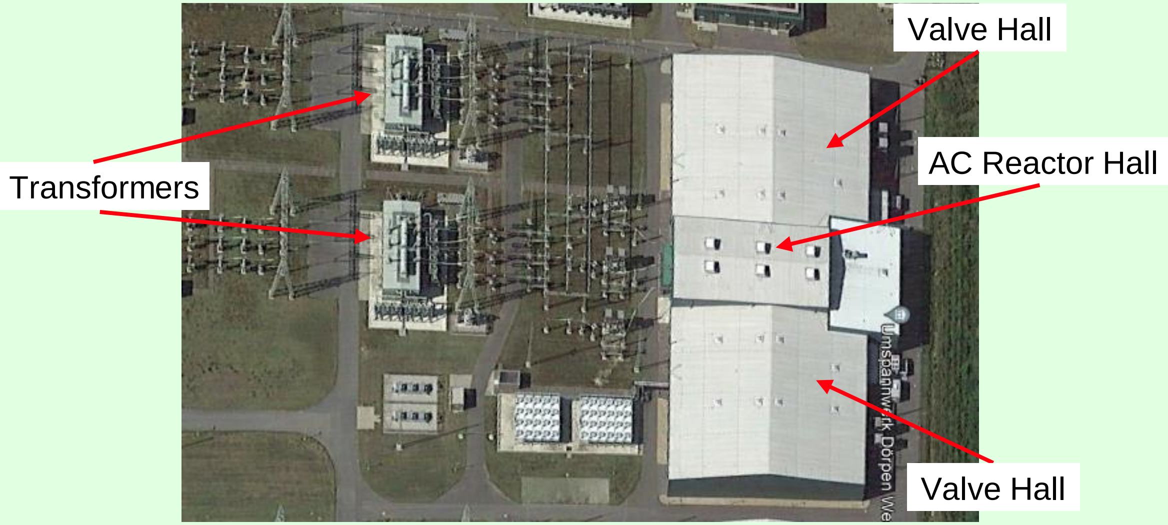
HVDC Stations with Line Commutated Converters (LCCs)

- Capacity ratings up to 12000 MW, ±1,100 kV
- Generation of harmonics – Large complex AC filter banks required to meet power quality requirements
- Reactive power demand (approx. 50% of power capacity rating) is typically supplied by switchable AC filters and shunt elements located in the converter station
- Thyristor based valves – power dispatch between 10% and 100%
- System strength at interconnection point essential for HVDC system stability (short circuit MVA ≥ 2.5×P_{DC})



HVDC Stations with Voltage Source Converters (VSCs)

- Capacity ratings up to 3500 MW, ±640 kV
- Modular multi-level converter (MMC) technology eliminates the need for complex AC and DC filter banks
- Reactive power and AC voltage support to the grid – Voltage source converter based HVDC stations can provide static and dynamic VAr support
- Transistor based valves – power dispatch between 0% and 100%
- Black start capability
- Much smaller footprint than for line commutated converters
- The industry is rapidly moving towards increased use of voltage source converter technology



HVDC VSC Stations | Converter Valve Designs

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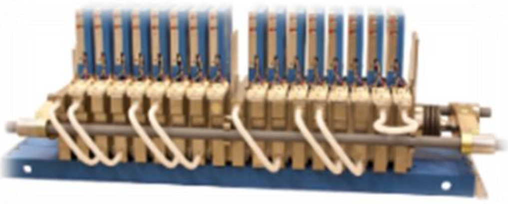
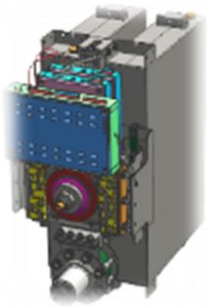
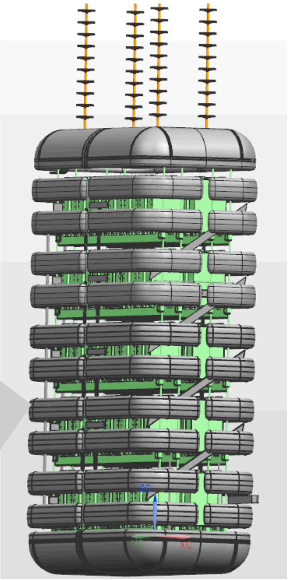
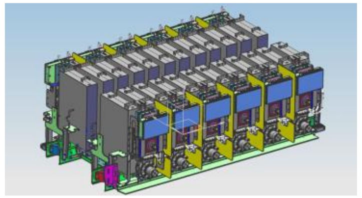
VSC Valve Design Developments

- Lower losses
- Safety
- Optimized size
- Cost efficient







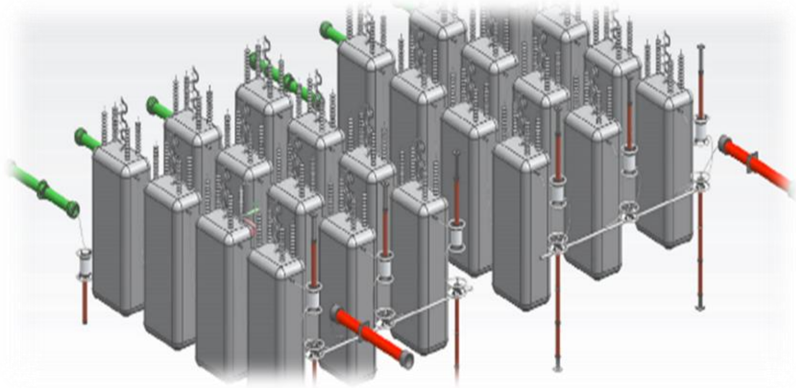


Two Level Converters (TLC)

Cascaded Two Level Converters (CTLC)

Modular Multilevel Converters (MMC)

Inside the Valve Hall



The DC voltage rating determines how many valve structures are needed per arm inside the valve hall

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HVDC VSC Stations | DC Voltages and Capacity Ratings

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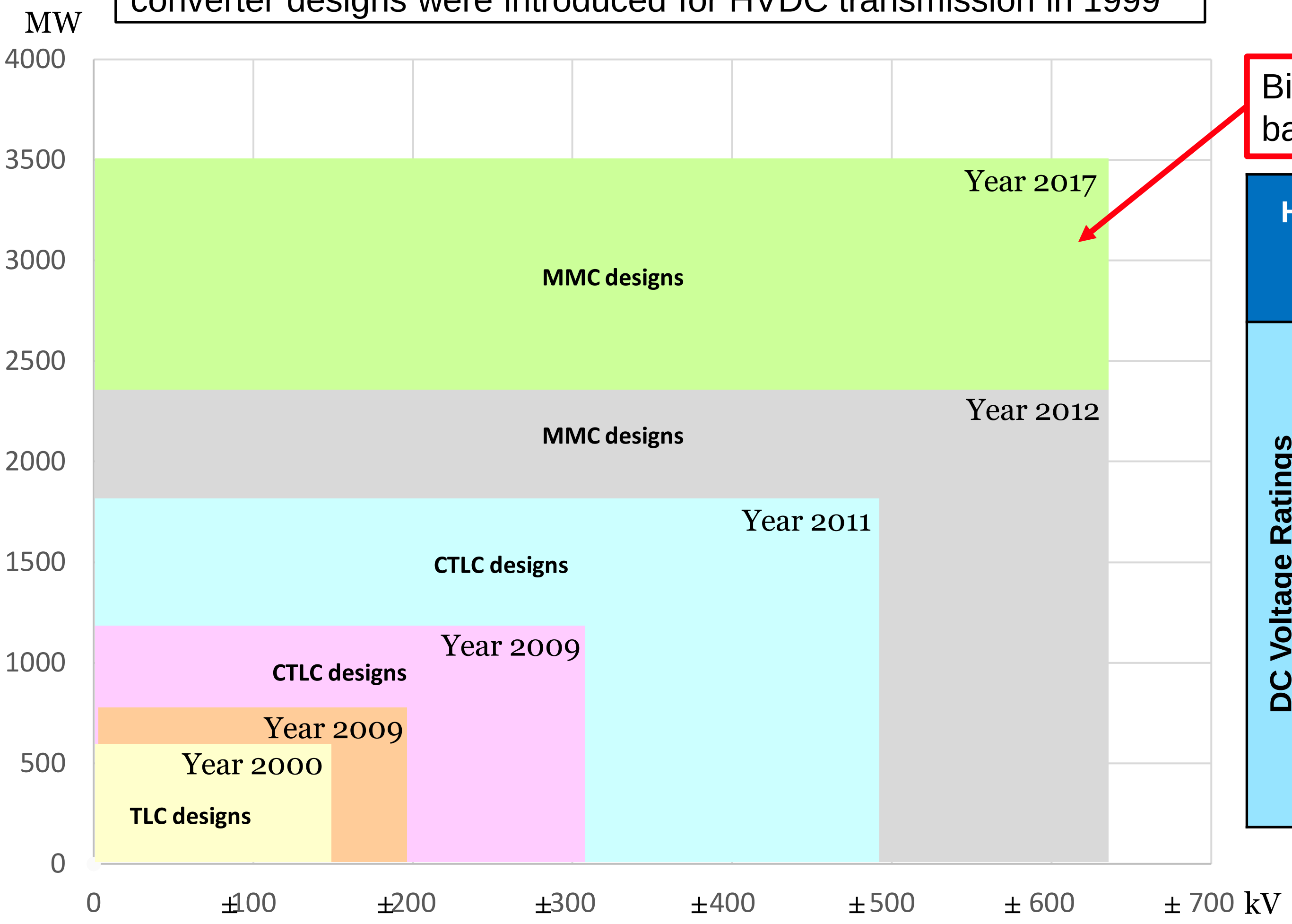
Insulated Gate Bipolar Transistor (IGBT) based voltage source converter designs were introduced for HVDC transmission in 1999



Bi-Mode Insulated Gate Transistor (BIGT) based designs launched in 2017

HVDC Light® Base Modules		DC Current Ratings			
		617 A_{dc}	1233 A_{dc}	1850 A_{dc}	2775 A_{dc} (*)
DC Voltage Ratings	±80 kV_{dc}	M1 99 MW	M2 197 MW	M3 296 MW	M3x 444 MW
	±150 kV_{dc}	M4 185 MW	M5 370 MW	M6 555 MW	M6x 833 MW
	±320 kV_{dc}	M7 395 MW	M8 789 MW	M9 1184 MW	M9x 1776 MW
	±500 kV_{dc}	M10 617 MW	M11 1233 MW	M12 1850 MW	M12x 2775 MW
	±640 kV_{dc}	M13 789 MW	M14 1579 MW	M15 2368 MW	M15x 3552 MW

(*) Note: The DC current rating can be increased above 2775 Amps by project specific optimization of the voltage source converter valve design

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HVDC VSC Stations | Typical Station Layout

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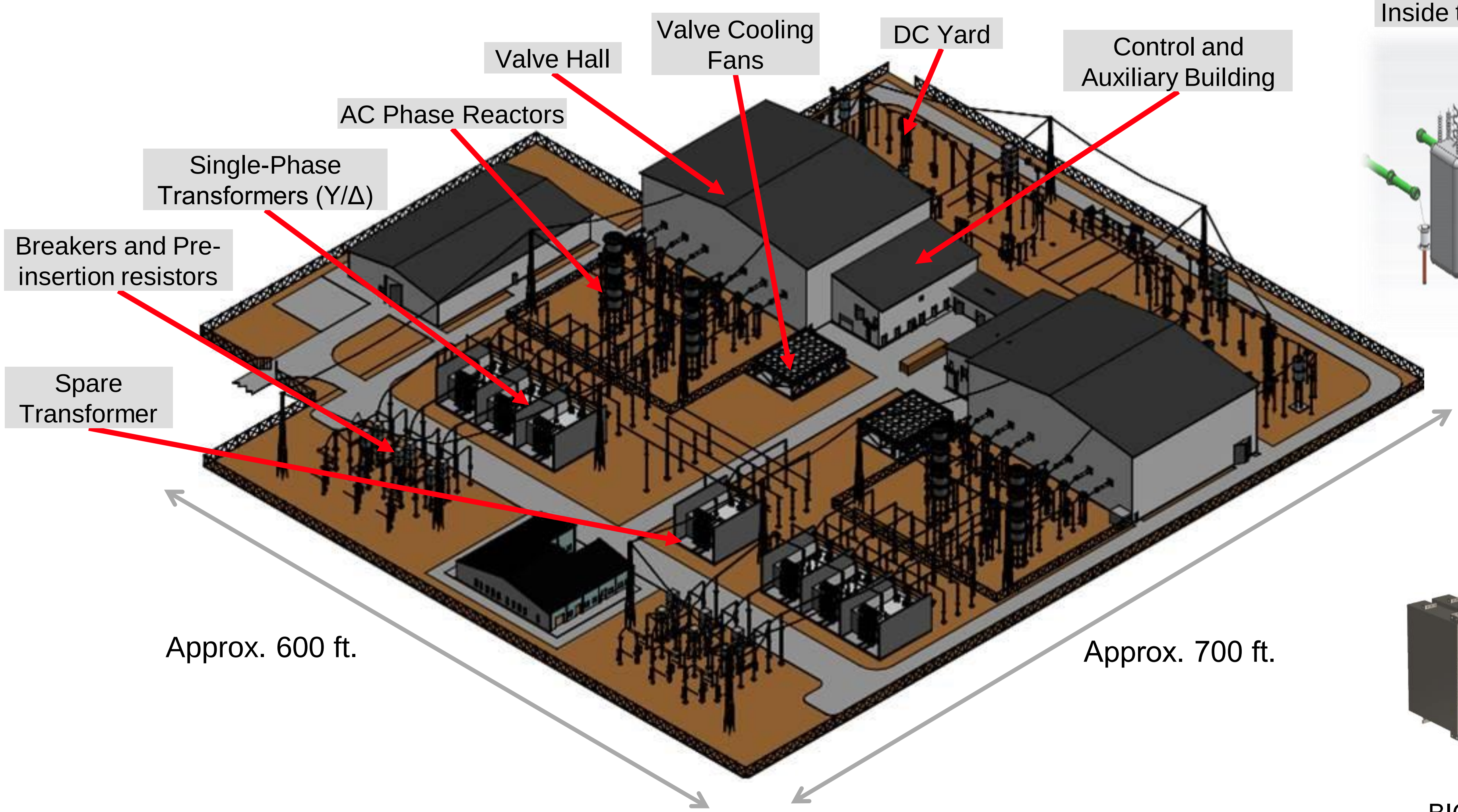
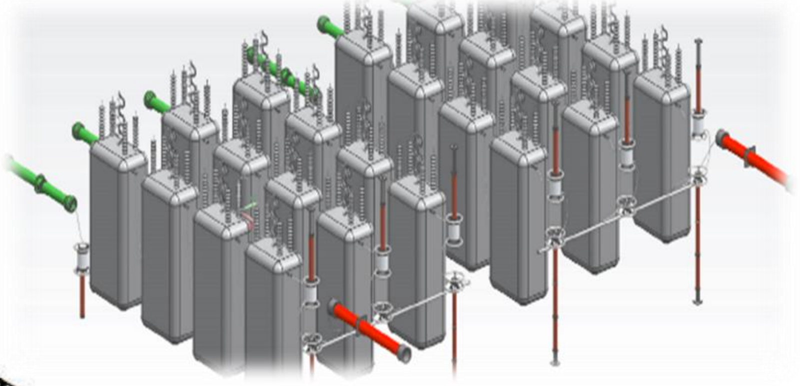
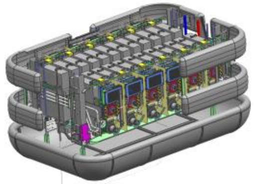
±525 kV, 3000 MW, Bipolar HVDC VSC Station



Inside the Valve Hall



BIGT cell



12 BIGT cells per layer

5 layers per structure

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HVDC VSC Stations | Typical Station Layout

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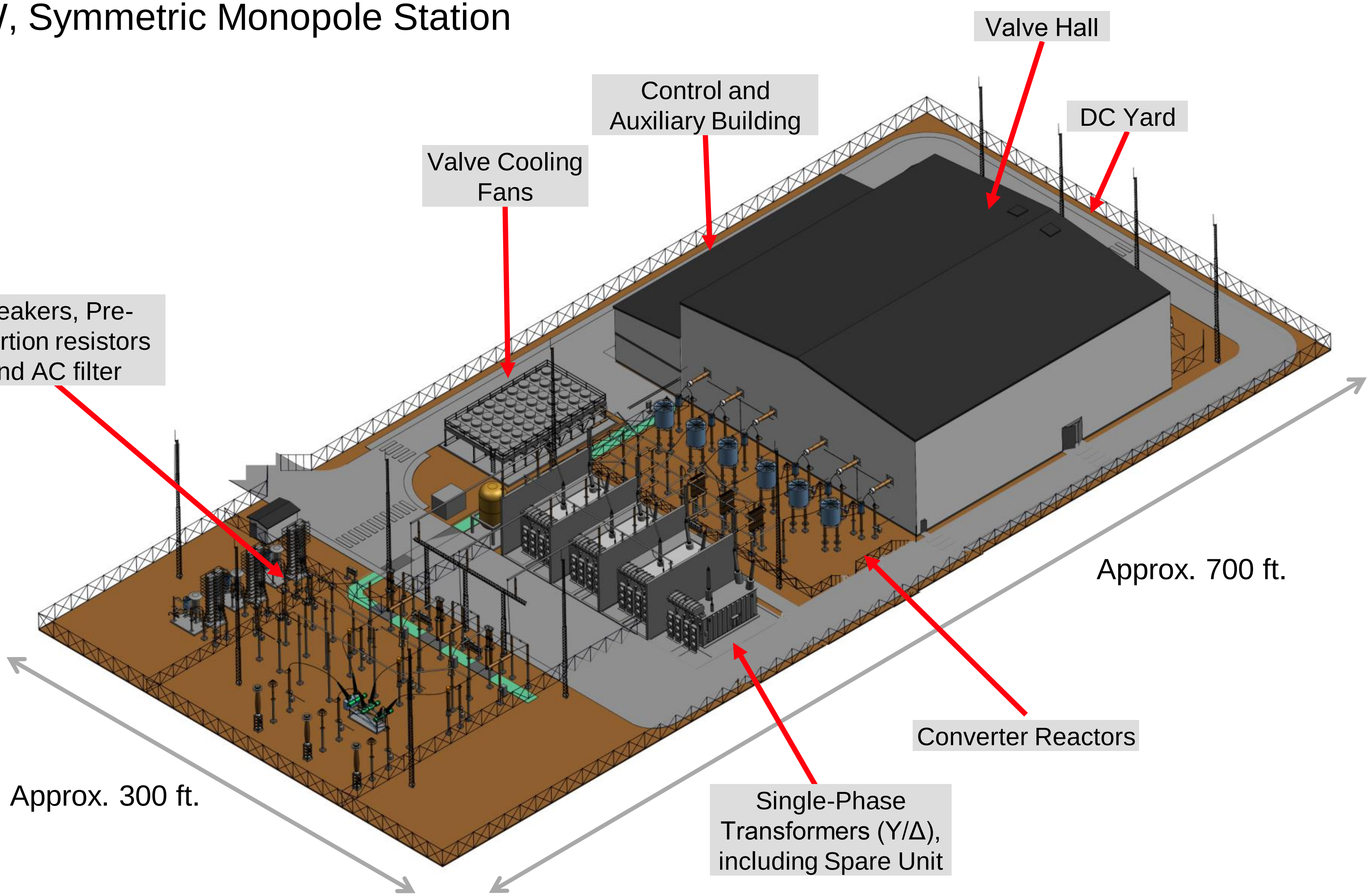
±320 kV, 1200 MW, Symmetric Monopole Station



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HVDC VSC Stations | Power Losses

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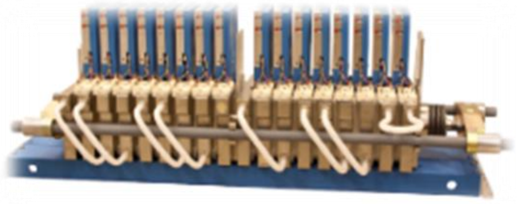
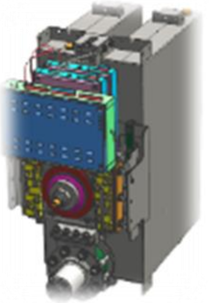
Line Commutated Converters Versus HVDC Light® Voltage Source Converters

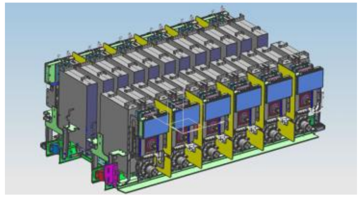
Two-Level Converter (TLC) Designs



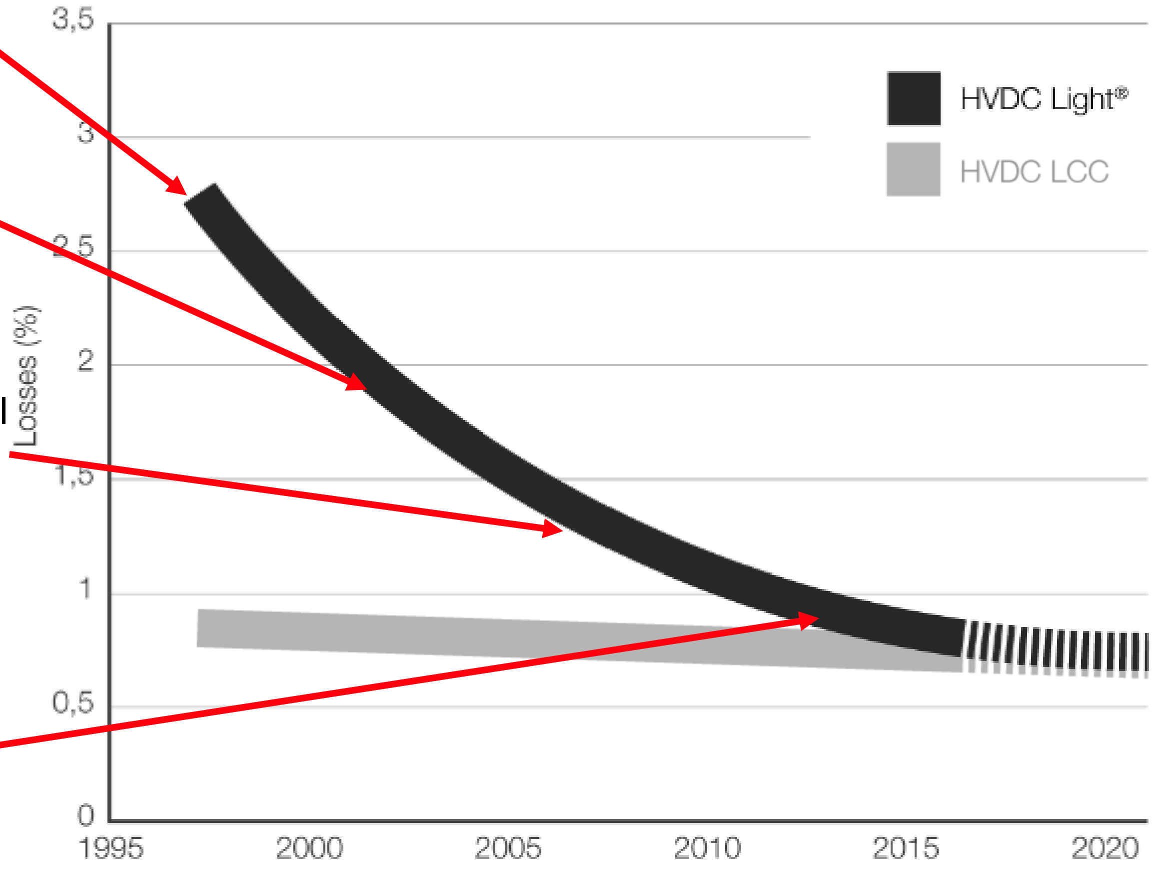
Three-Level Converter (TLC) Designs

Cascaded Two Level Converter (CTLC) Designs





Modular Multilevel Converter (MMC) Designs



Approx. 0.7% per station

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HVDC Reference Projects – Line Commutated Converter Technology

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Pacific DC Intertie | Continuous Development

1970: 1440 MW, ±400 kV

1985: PI Upgrade, 2000 MW, ±500 kV

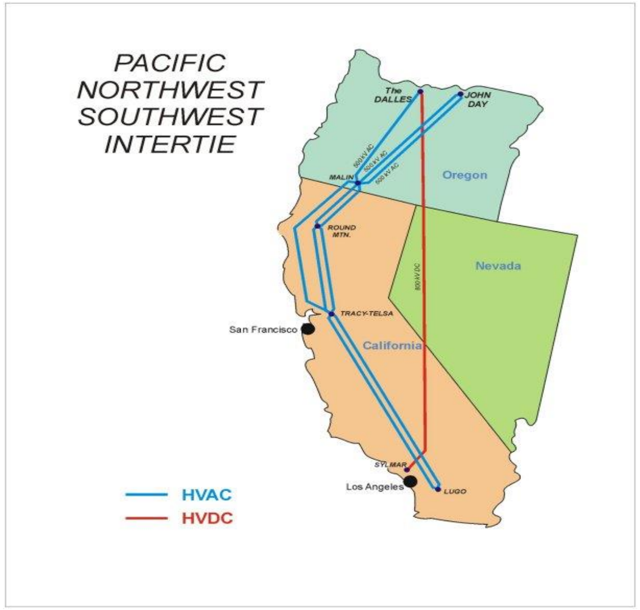
1989: PI Expansion, 3100 MW, ±500 kV

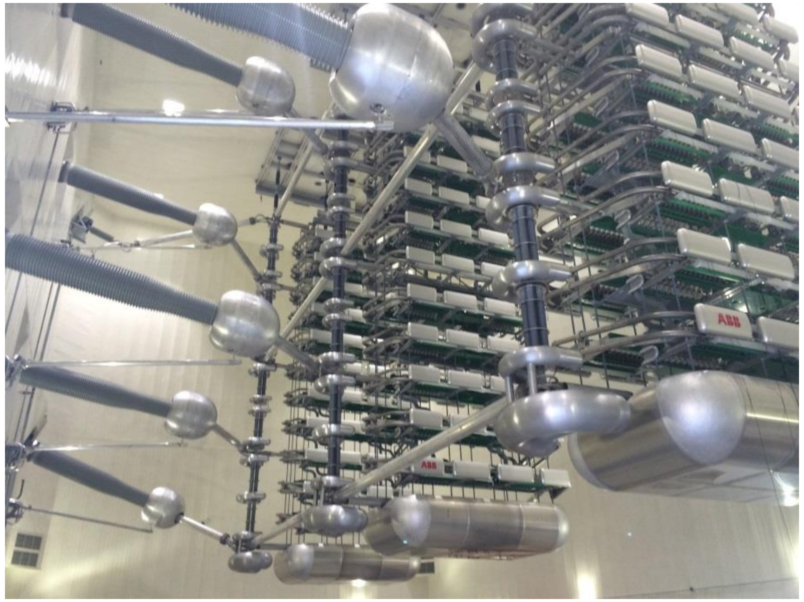
2004: Sylmar Upgrade

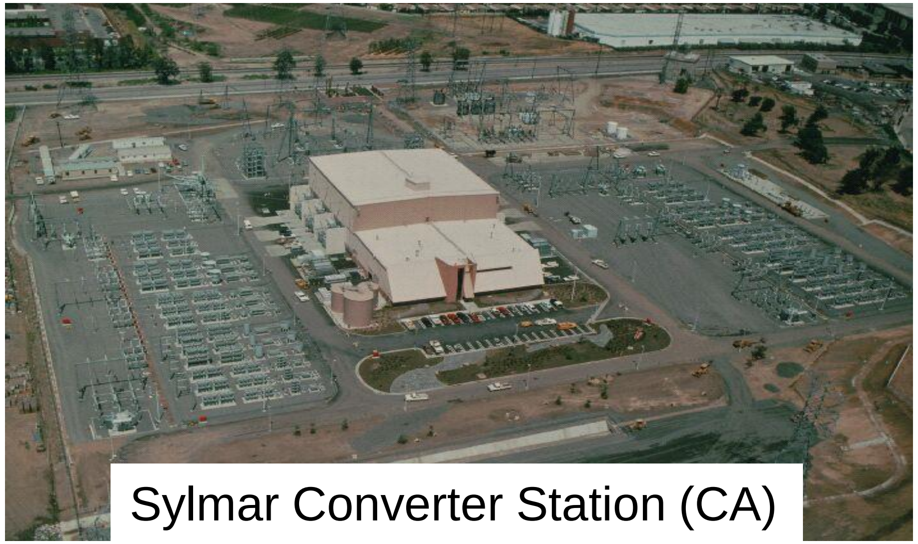
2016: Celilo Upgrade, 3800 MW, ±560 kV

2020: Sylmar Upgrade, 3220 MW

Celilo Converter Station (OR)







Sylmar Converter Station (CA)

Quebec – New England HVDC Link (First Multi-Terminal System)

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LCC Stations | Quebec and Massachusetts

Main Data			
	Radisson (QE)	Nicolet (QE)	Sandy Pond (MA)
Commissioning Year:	1990	1992	1990
Control Upgrade (Year):	2016	2016	2016
Power Capacity Rating:	2250 MW	2138 MW	1800 MW
No. of Poles:	2	2	2
AC Voltage:	315 kV	230 kV	345 kV
Rated DC Voltage:	±500 kV	±475 kV	±450 kV

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CU HVDC Link

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LCC Stations | North Dakota and Minnesota

Main Data	
In-Service Year:	1979 | Major Upgrade in 2019
Upgrade award | In-service	Dec. 2015 | May 2019
Power Capacity Rating:	1000 MW
No. of Poles:	2
AC Voltage:	230 kV (North Dakota)
	345 kV (Minnesota)
DC Voltage:	±400 kV
Type of DC System:	Overhead Line

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HVDC Reference Projects – Voltage Source Converter Technology

Cross Sound Cable

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First VSC-Based HVDC Link in the United States | Connecticut and Long Island

Main Data	
Commissioning Year:	**2002**
Power Capacity Rating:	**330 MW**
No. of Poles:	**1 (Symmetric Monopole)**
AC Voltage:	**345 kV (Connecticut)** **138 kV (Long Island)**
DC Voltage:	**±150 kV**
Type of DC System:	**Submarine Cable Link**
Route Length:	**25 miles**

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Mackinac

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First VSC-Based HVDC Back-to-Back Station in the World | Michigan

Main Data	
Commissioning Year:	**2014**
Power Capacity Rating:	**200 MW**
No. of Poles:	**1 (Symmetric Monopole)**
AC Voltage:	**138 kV (Both Sides)**
DC Voltage:	**±71 kV**
Type of DC System:	**Back-to-Back Station**

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Champlain Hudson Power Express (CHPE)

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VSC-Based HVDC Link | Quebec to New York City

Main Data	
Commissioning Year:	**2025**
Power Capacity Rating:	**1250 MW**
No. of Poles:	**1**
AC Voltage:	**735 kV (Quebec)**
	345 kV (New York City)
DC Voltage:	**±400 kV**
Type of DC System:	**Cable Link**
Route Length:	**191 miles Submarine Cable**
	182 miles Underground Cable

The CHPE Link will interconnect the Quebec and NYISO markets and provide increased security of power supply and other benefits for both regions

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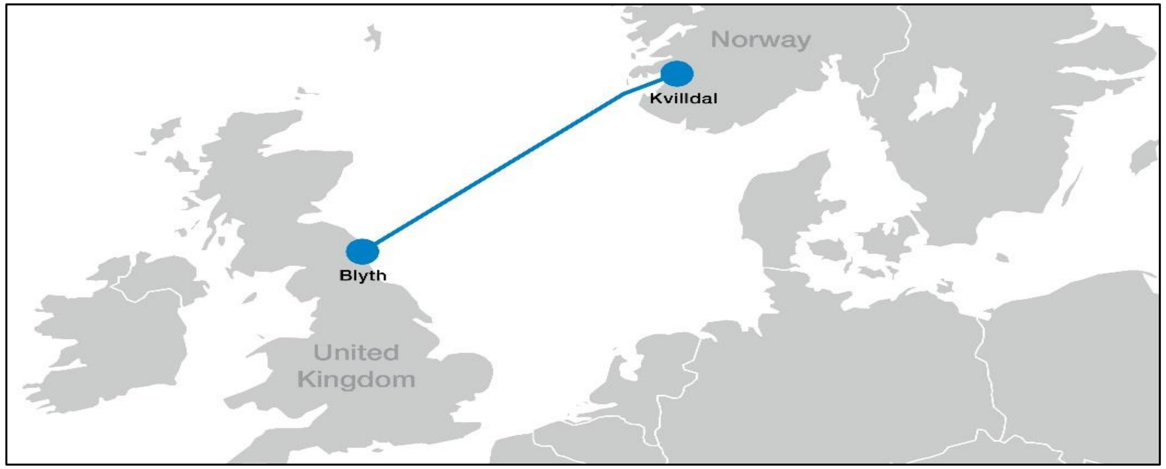
North Sea Link

HVDC VSC Stations | Norway and United Kingdom

Main Data	
Commissioning Year:	**2021**
Power Capacity Rating:	**1400 MW**
No. of Poles:	**2**
AC Voltage:	**400 kV (Norway)**
	400 kV (United Kingdom)
DC Voltage:	**±525 kV**
Type of DC System:	**Submarine Cable Link**
Route Length:	**454 miles**



The North Sea Link will interconnect the Nordic and British markets and provide increased security of power supply and other benefits for both regions

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SunZia Southwest Transmission Project

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Commissioning Year: 2025

"We are proud to be advancing a sustainable energy future for all in the southwestern United States, enabling Pattern Energy to integrate emission-free electricity into the regional grid serving Arizona and Southern California."

Niklas Persson
Managing Director, BU Grid Integration

Challenge

To overcome the geographical mismatch between high-quality wind resources in rural New Mexico and major load centers in southwestern United States.

Solution

±525 kV, 3000 MW, HVDC link based on Hitachi Energy's HVDC Light® VSC technology. HVDC Light® station in New Mexico will operate as grid forming facility and includes two 1,500 MW AC choppers (dynamic braking systems).

Impact

Increased availability of wind energy in the large population centers in the southwestern United States and major reduction in CO_2 emissions.

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Dolwin 1 and 2 – Offshore Wind Interconnections

HVDC VSC Stations | Offshore wind power from the North Sea to mainland Germany

Main Data		
	Dolwin 1	**Dolwin 2**
Commissioning Year:	**2015**	**2017**
Power Capacity Rating:	**800 MW**	**916 MW**
No. of Poles:	**1 (Symmetric Monopole)**	**1 (Symmetric Monopole)**
AC Voltage:	**155 kV (Off-Shore)**	**155 kV (Off-Shore)**
	380 kV (On-Shore)	**380 kV (On-Shore)**
DC Voltage:	**±320 kV**	**±320 kV**
Type of DC System:	**Cable Link | VSC Stations**	**Cable Link | VSC Stations**
Route Length:	**47 miles Submarine Cable**	**28 miles Submarine Cable**
	56 miles Upland Cable	**56 miles Upland Cable**

Offshore Wind Interconnections

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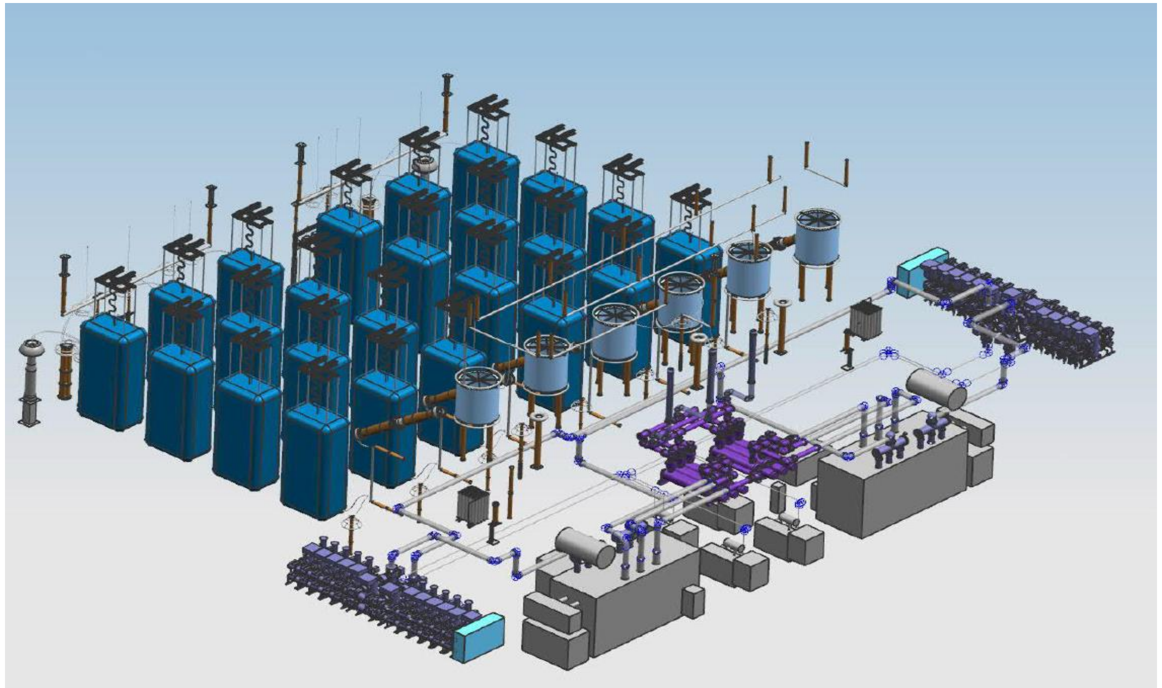
Offshore layout – ±320 kV, 1200 MW

- 66 kV GIS
- Power transformers
- 400 kV GIS
- Converter phase reactors
- Valve arrangement



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