High Voltage DC Transmission Technical and Economical Aspects

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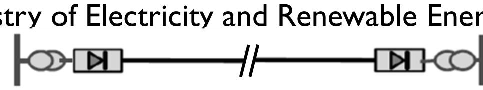

History of HVDC Technology

1. Electromechanical (Thury) Systems
2. Mercury Arc Valves
3. Thyristor Valves
4. Voltage Source Converters (VSC)
5. Capacitor-Commutated Converters (CCC)

Electromechanical (Thury) Systems

- First power transmission between Miesbach-Munich in 1882, 1.5 kW
- Thury System: series-connected motor-generator sets used. (Swiss engineer Rene Thury 1860 –1938: the king of HVDC)
- Moutiers-Lyon system for 8600 kW of hydroelectric power a distance of 124 miles, including 6 miles of underground cable.
- The system used 8 series-connected generators with dual commutators, 1906-1936.

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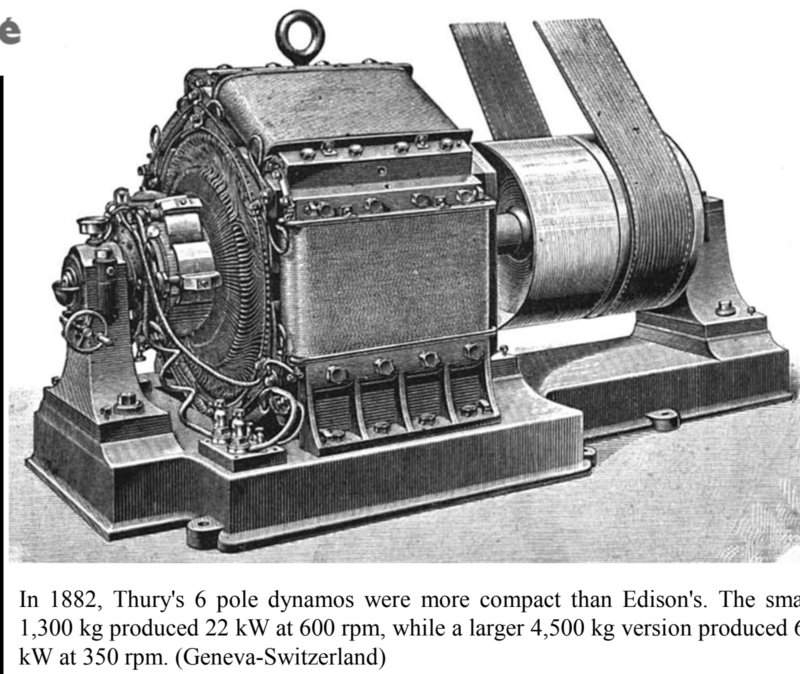

In 1882, Thury's 6 pole dynamos were more compact than Edison's. The small 1,300 kg produced 22 kW at 600 rpm, while a larger 4,500 kg version produced 66 kW at 350 rpm. (Geneva-Switzerland)

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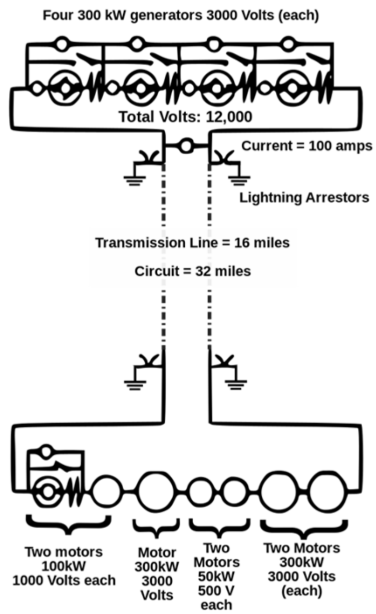

Diagram of a Thury System balancing voltage of supply with voltage of load
The first system using Rene Thury's system was installed in 1889.

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Mercury Arc Valves

- Between 1920 to 1940
- In 1932 GE tested first mercury-vapor vaves (12kV DC transmission line Mechanicville, NewYork).
- Elbe projects in Berlin in 1941(60 MW, +/- 200 kV, 115 km buried cable link)
- Fully static mercury arc valve to commercial service in 1954.

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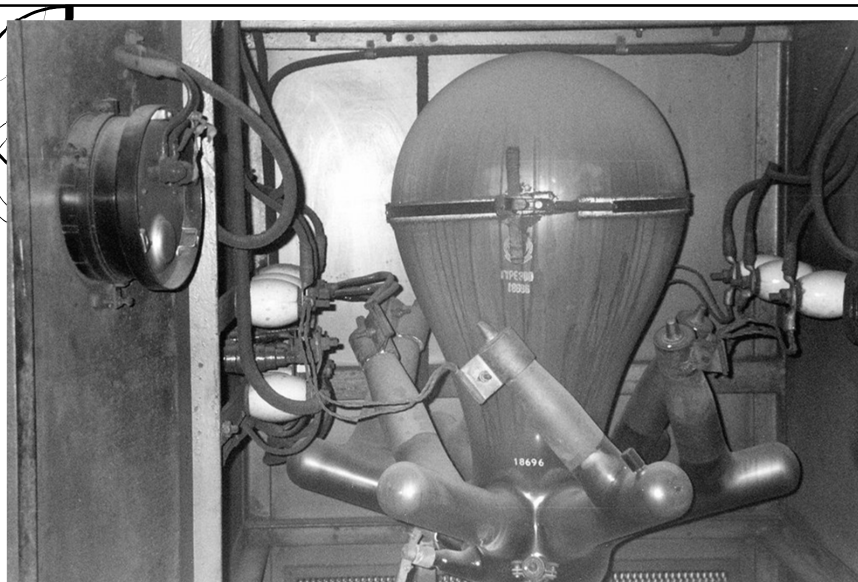

n the 1920s, economical conversion to and from HVDC egan to be possible with glass bulb mercury arc rectifiers, ut this help came too late for the Thury system.

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HVDC in 1971: this 150 kV Mercury Arc Valves converted AC hydropower volt age for transmission to distant cities from Manitoba Hydro generators (Radisson Converter Station).

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Thyristor Valves

- Since 1976, new HVDC systems have used only solid state devices, Thyristor Valves.
- The thyristor had impressive advantages:

➢ Very reliable

➢ Fail safe failure mode

➢ Compact design

In 1979 a thyristor based HVDC connection beteen Cahora Bssa and Johannesburg, 1410 km, ± 533 kV, 1920 MW was turned on.

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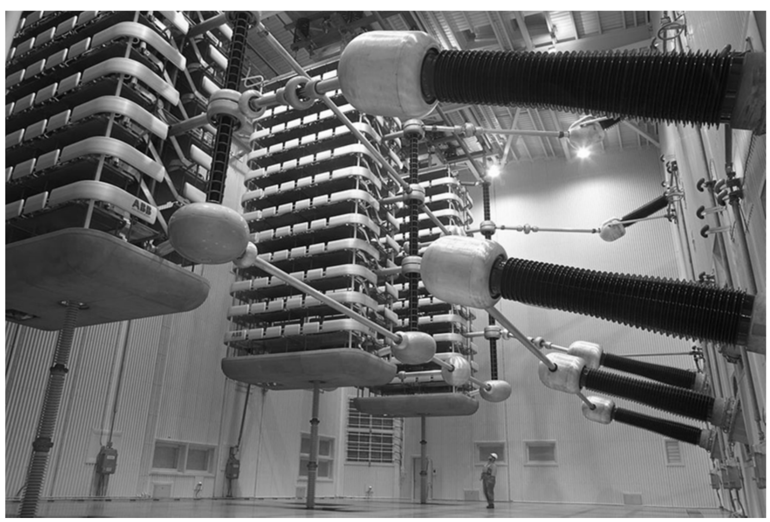

Thyristor valve stacks for Pole 2 of the HVDC Inter-Island between the North and South Islands of New Zealand. The man at the bottom gives scale to the size of the valves.

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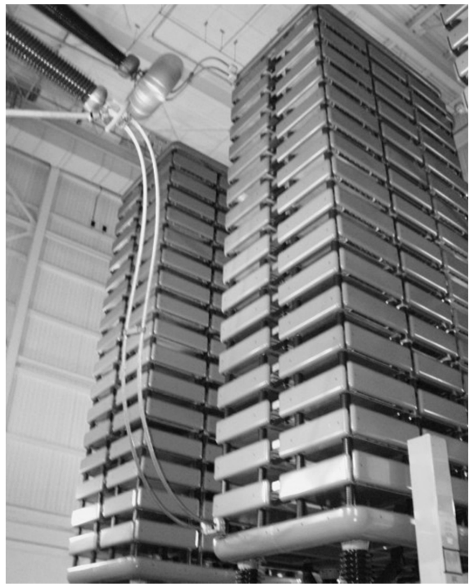

Valve hall containing thyristor valve stacks used for long-distance transmission of power from Manitoba Hydro dams

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- In August 1987 the Swedish Asea and the Swiss BBC Brown Boveri announced that the two companies were to merge under the name Asea Brown Boveri - ABB.
- Asea's history, however, dates back to 1883.
- BBC Brown Boveri was founded in 1891.

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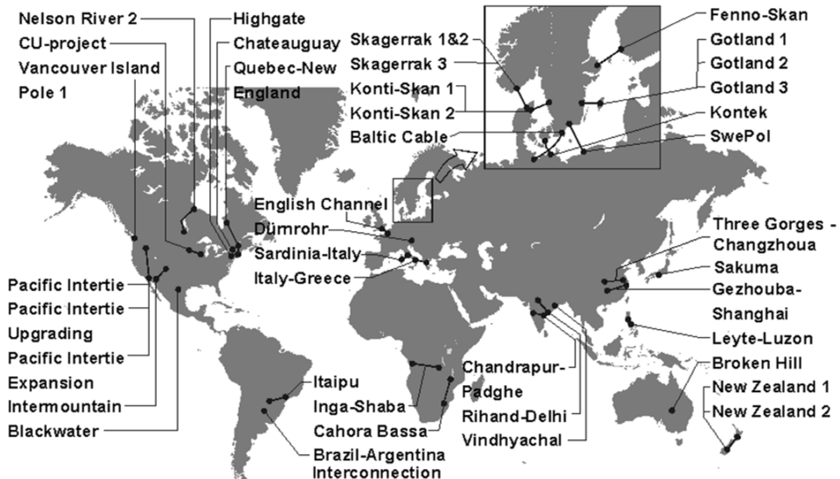
HVDC is well established, transmitting 75 GW world wide, mainly remote hydro- and geothermal power



Source: ABB

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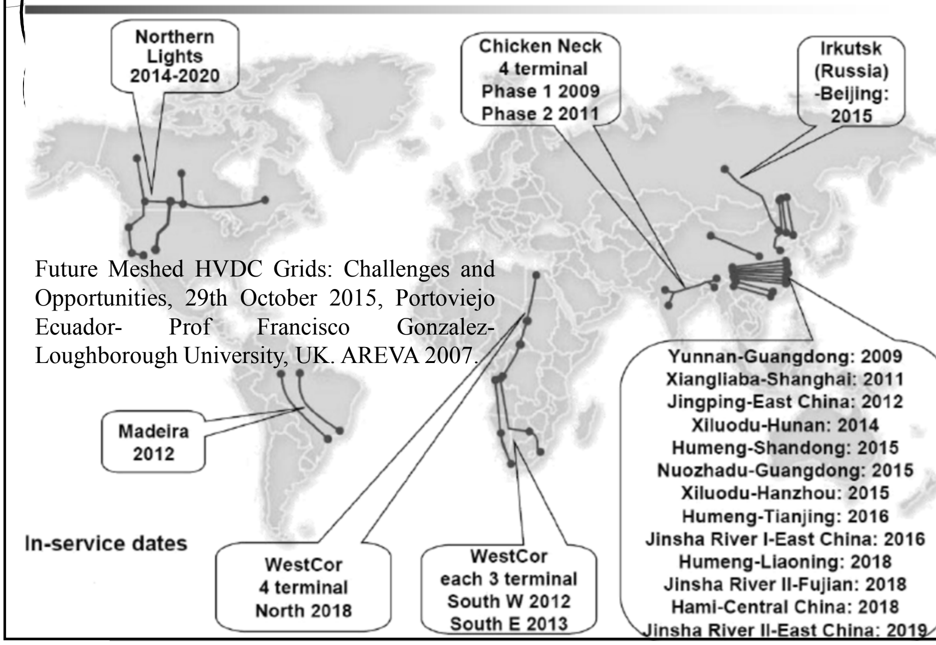
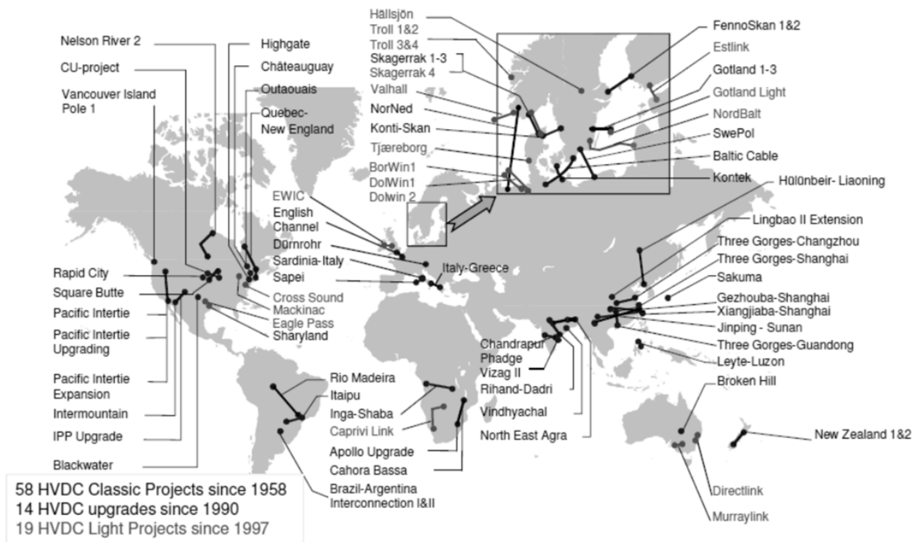
UHVDC Prospects 600kV-800kV



Future Meshed HVDC Grids: Challenges and Opportunities, 29th October 2015, Portoviejo Ecuador- Prof Francisco Gonzalez-Loughborough University, UK. AREVA 2007.

ABB has more than half of the145 HVDC projects
The track record of a global leader



22 April 2013 | Slide 9

ABB

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cigré

- Some 110 new high voltage direct current (HVDC) lines are planned or are currently under construction and will be completed worldwide by 2020, according to a recent report from Navigant Research.
- Approximately 300 gigawatts (GW) of new HVDC transmission capacity will be added between 2015 and 2020, including nearly 200 GW in China alone."

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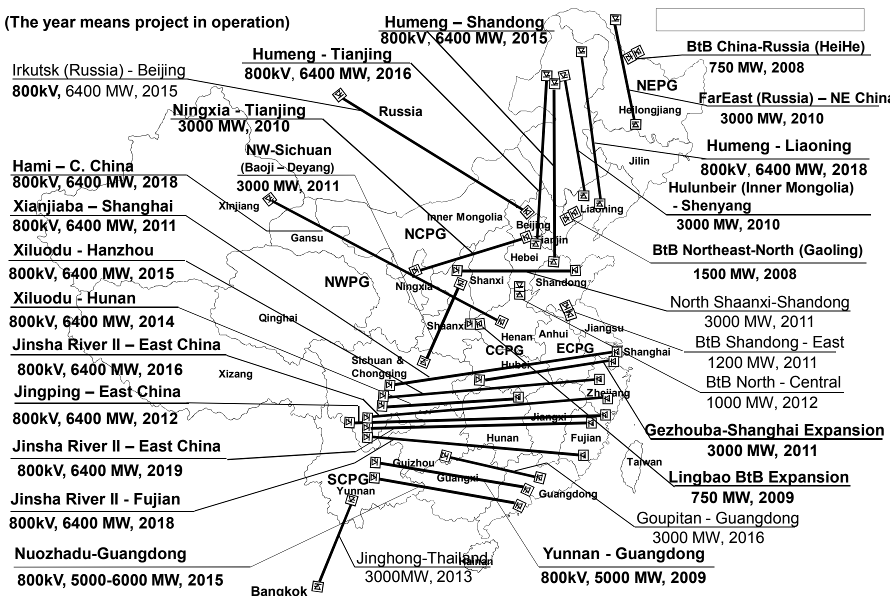
HVDC projects in China 2020

(The year means project in operation)



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UHVDC Projects in Operation

Projects	DC voltage (kV)	Rated power (MW)	DC current (A)	Line length (km)
Xiangjiaba-Shanghai	±800	6400	4000	1907
Jinpin-Sunan	±800	7200	4500	2051
Haminan-Zhengzhou	±800	8000	5000	2192
Xiluodu-Zhejiang	±800	8000	5000	1653

UHVDC Projects under Construction

Projects	DC voltage (kV)	Rated power (MW)	DC current (A)	Line length (km)
Lingzhou-Shaoxing	±800	8000	5000	2000
Jiuquan-Hunan	±800	8000	5000	2300
Jinbei-Nanjing	±800	8000	5000	1100

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UHVDC Projects under plan

Projects	DC voltage (kV)	Rated power (MW)	Rated DC current (A)	Line length (km)	Operation
Ximeng-Taizhou	±800	10000	6250	1620	2017
Shanghaimiao-Shandong	±800	10000	6250	1235	2017
Zhundong-Wannan	±1100	12000	5500	3340	2018

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UHVDC Projects under plan

Project	Rated DC voltage（kV）	Rated power (MW)	Rated DC current (A)	Line length (km)	Operation
Zhalute-Qingzhou	±800	10000	6250	1450	2018
Yazhong-Nanchang	±800	10000	6250	1400	2018
Zhundong-Chengdu	±1100	12000	5500	2600	2018

Why HVDC Transmission?

(a) More power can be transmitted per conductor per circuit.

(b) Use of Ground Return Possible

(c) Smaller Tower Size

(d) Higher Capacity available for cables

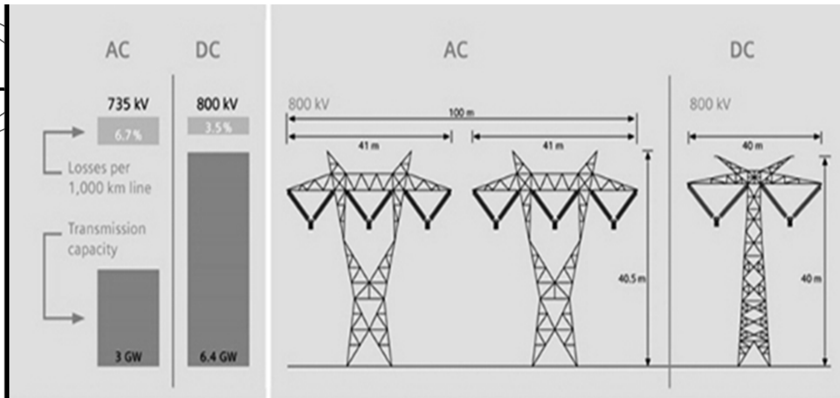
(e) No skin effect

(g) No Stability Problem

(h) Asynchronous interconnection possible

(i) Lower short circuit fault levels (Smoothing Reactor)

(j) Tie line power is easily controlled



UHV DC- More than 50% reduction in right -of-way requirements

UHV DC- A significant reduction in transmission losses

The 800 kV UHVDC transmission system has an efficiency rating of 94 % and uses significantly less land than traditional technologies

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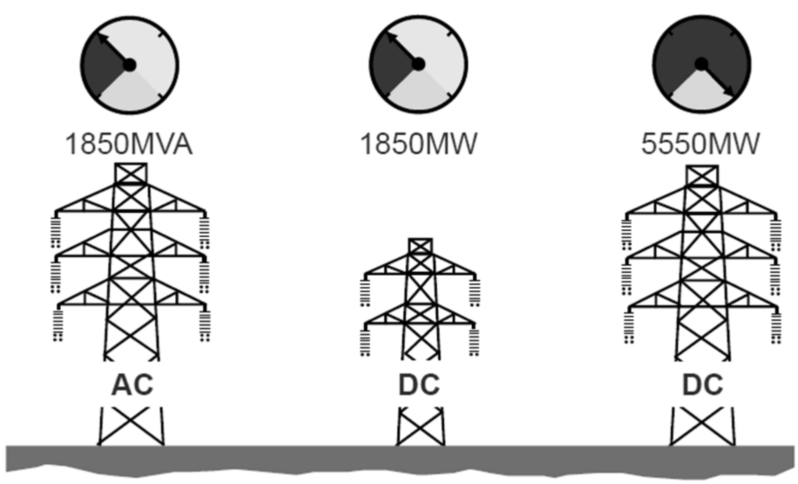
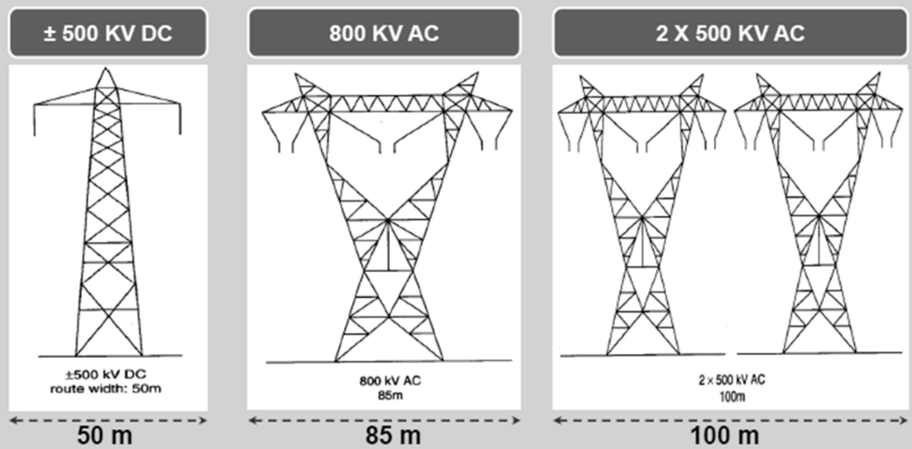
More Power Per Tower



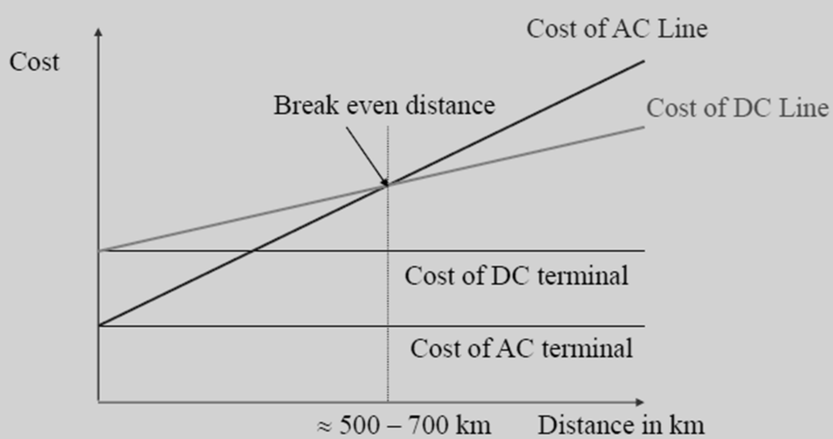
Up to 3 Times More Power

Right of Way Comparisons

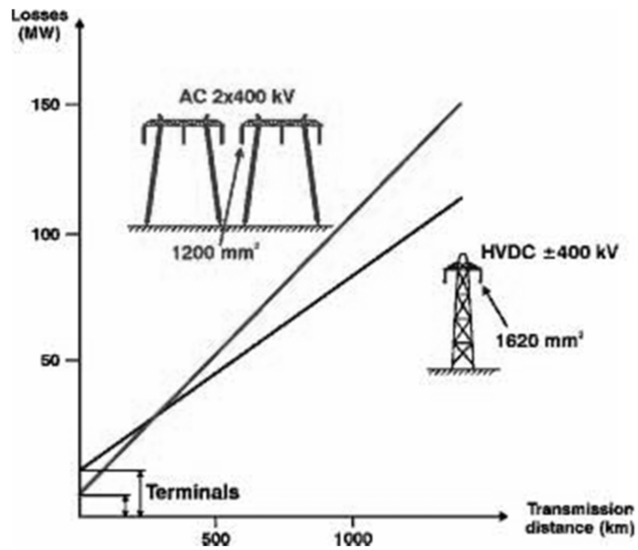
Typical tower structures and rights-of-way. Capacity: 2000 MW



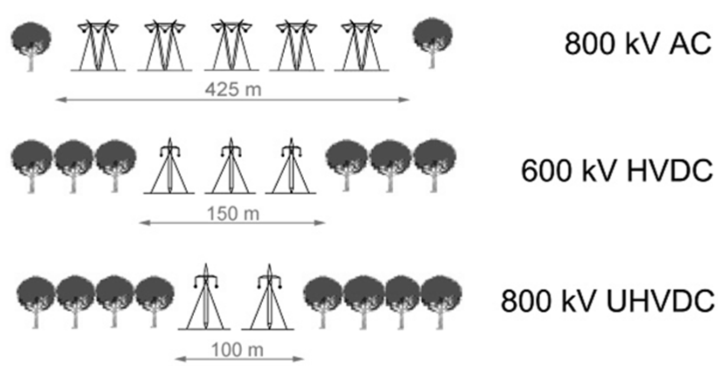
Cost comparison of AC and DC transmission



Example Losses on Optimized Systems for 1200 MW



Space required for 10 GW Power Transmission



(Quelle: ABB, erweitert)

AC Alternate Current
HVDC High Voltage Direct Current
UHVDC Ultra High Voltage Direct Current

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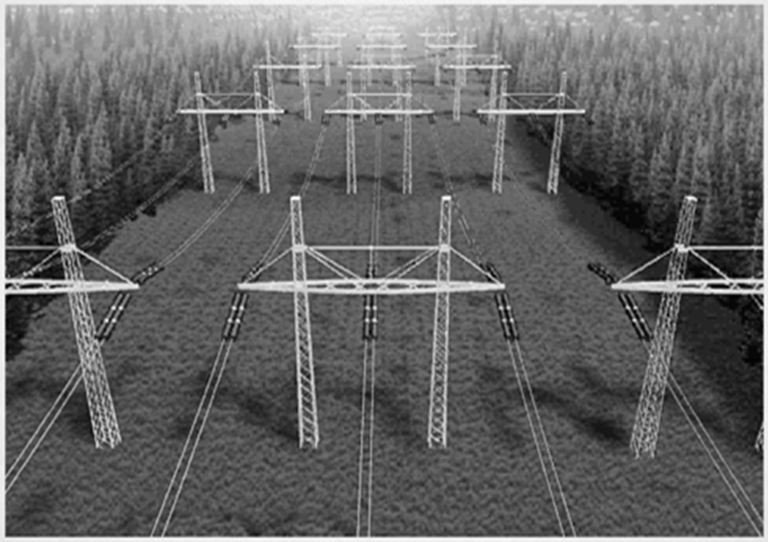
AC Transmission Line Corridor



DC Transmission Line Corridor

DC Transmission Line Corridor

Problems associated with HVDC

(a) Expensive converters
(b) Reactive power requirement
(c) Generation of harmonics
(d) Difficulty of circuit breaking
(e) Difficulty of voltage transformation
(f) Difficulty of high power generation
(g) Absence of overload capacity

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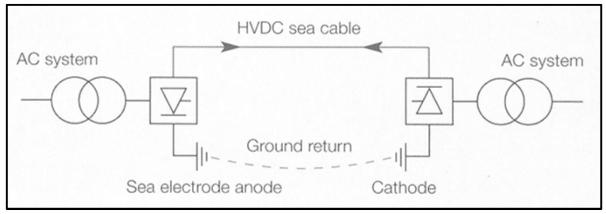
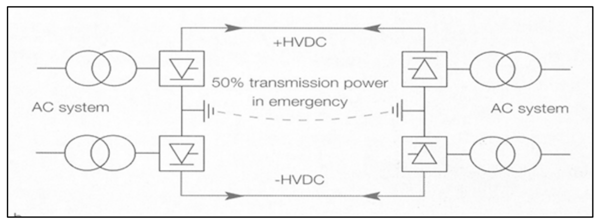
HVDC Configuration Alternatives

- Monopolar
- Bipolar
- Homopolar



Monopolar HVDC cable link with ground return



Bipolar HVDC cable transmission link

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The Cahora Bassa HVDC line between the Cahora Bassa Hydroelectric Generation Station at the Cahora Bassa Dam in Mozambique, and Johannesburg, South Africa.

The system comprises two parallel monopolar lines across a 1,400-km long route; 900 km is in Mozambican territory.

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Two HVDC lines cross near Wing, North Dakota. Square Butte uses +/- 250 kV DC and single conductors per pole and is the line of towers on the left in this picture. CU uses +/- 400 kV, two conductors per pole and is the line of towers on the right.

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Typical 40 m high suspension tower along ±400 kV line to Tibet. Height of towers determined by maximum permitted electro-magnetic field in populated areas.

HVDC Configuration Alternatives

- A Homo polar arrangement consist of two conductors of same polarity on the same tower.
- It is a mono polar system having two conductors /pole.
- The ground is used as a return path.
- Homo polar system is used for the overhead d.c. line feeding into the d.c. cable.

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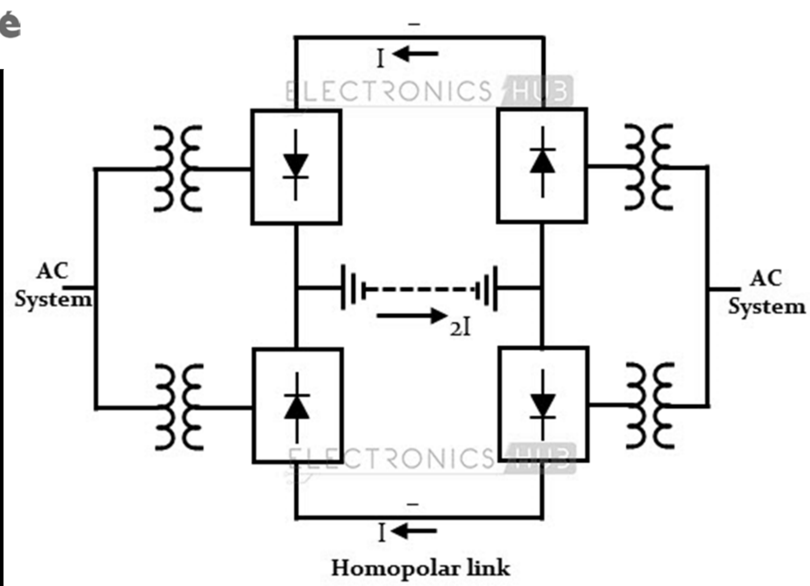

Homopolar HVDC cable transmission link

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Categories of HVDC Transmissions

- There are three different **categories of HVDC transmissions:**

1. Point to point transmissions
2. Back-to-back stations
3. Multi-terminal systems

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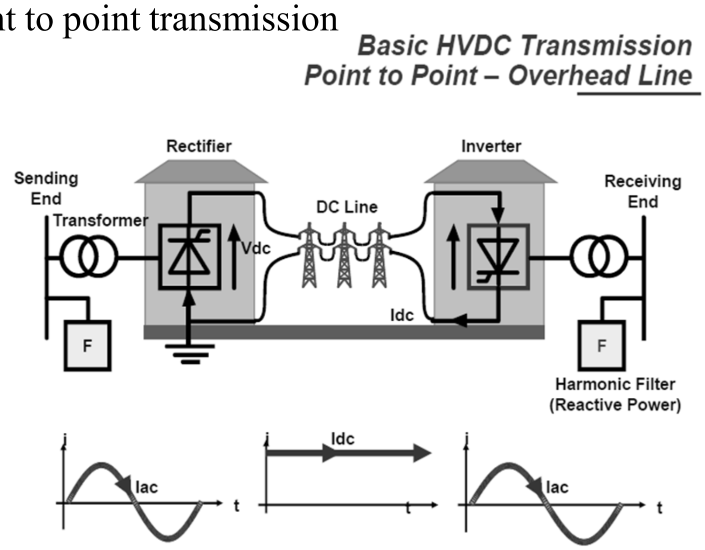
4- Categories of HVDC Transmissions

Point to point transmission



Point to point- TL

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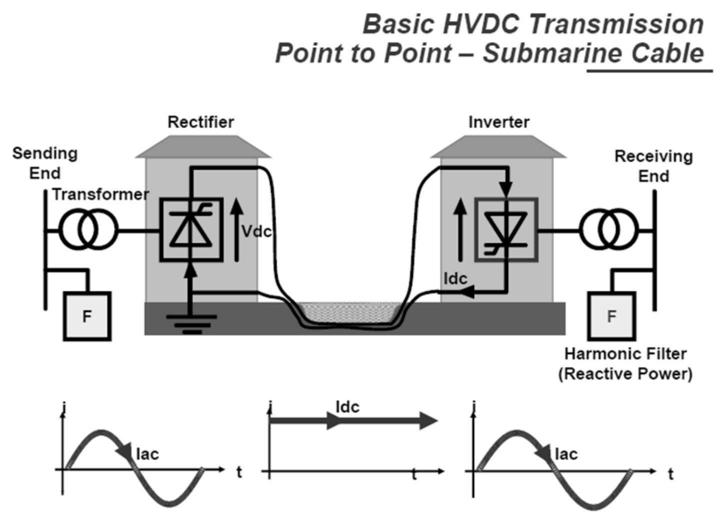
4- Categories of HVDC Transmissions



Point to point- submarine cable

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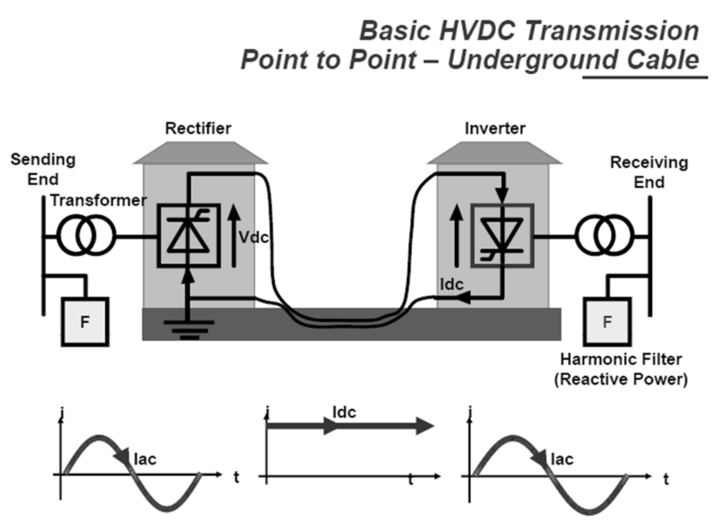
4- Categories of HVDC Transmissions



Point to point- underground cable

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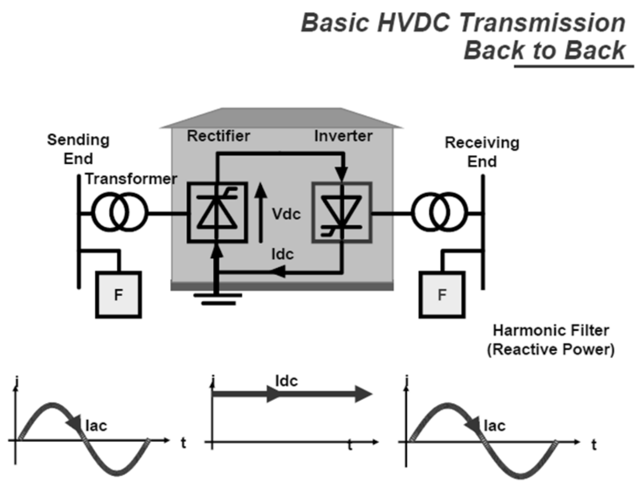
4- Categories of HVDC Transmissions



Back to Back

Categories of HVDC Transmissions

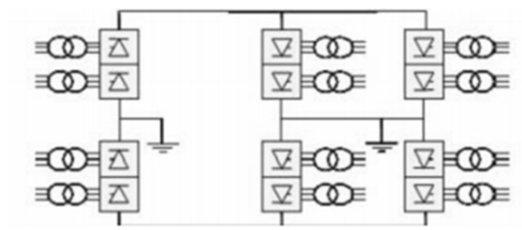
Back-to-back HVDC: for connection of asynchronous systems

- No transmission DC link
- Smoothing reactor on DC side
- Bipolar for long distance transmission
- Independence between pole operation to ensure power flow
- Pole design may allow 50% transient power flow on the pole

Categories of HVDC Transmissions

Multiterminal connection

- It is used to connect with more than two converter stations.
- This is considered a complex network.
- The reversal of power can be easily achieved.



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The world’s longest power transmission lines

Rio Madeira transmission link, Brazil

- The Rio Madeira transmission link in Brazil, with an overhead length of 2,385km, is the world's longest power transmission line.
- The 600kV HVDC bipolar line was brought into commercial operation in November 2013 and is capable of transmitting 7.1GW of power.

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The world's longest power transmission lines

Jinping-Sunan transmission line, China

- China's 2,090 km-long Jinping-Sunan transmission link, an 800 kV ultra high-voltage direct current (UHVDC) transmission line, is the world's second longest power transmission line.
- The 7.2GW transmission link is owned by State Grid Corporation of China (SGCC) and was put into operation in December 2012.

Xiangjiaba-Shanghai transmission line, China

- The Xiangjiaba-Shanghai transmission line, with an overhead length of 1,980 km, is the world's third longest transmission line.
- The 800kV, 7.2GW line, owned by SGCC, is the world's first ever UHVDC transmission line and started commercial operation in July 2010.

The world's longest power transmission lines

Inga-Kolwezi transmission line, Congo

- Congo's 1,700 km-long Inga-Kolwezi transmission line, formerly known as the Inga-Shaba link.
- It transmits power from Inga Falls on the Congo River to the copper mining district of Katanga in the Democratic Republic of Congo (DRC).
- The 500kV transmission line, with a rated capacity of 560MW, is owned and operated by Democratic Republic of Congo's (DRC) national electricity utility, Société Nationale d'Electricité (Snel).

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The world's longest power transmission lines

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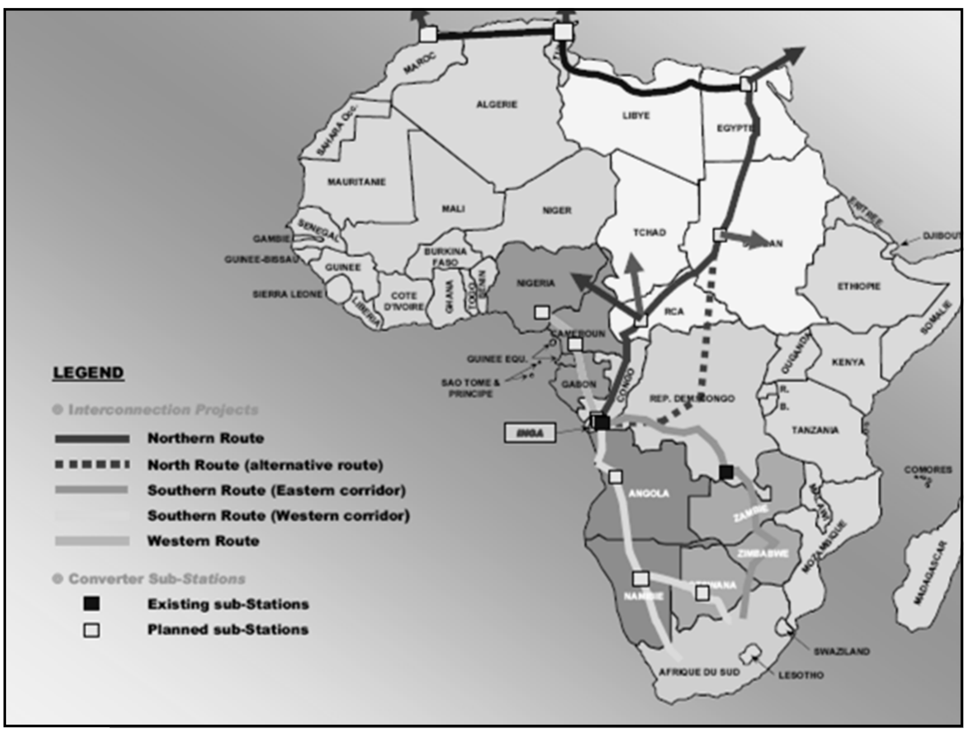
The world's longest power transmission lines

« Northern Highway »

NORTHERN HIGHWAY *(Inga – Boali – El Fasher - Cairo)*	
Voltage type	Direct current
Length	5.300 km
Power Demand	4.000 MW (ph.1)
Converter Stations	- Inga (DRC) - Cairo (Egypt)
Tapping Stations	- Boali (CAR) - El Fasher/Sudan
Investment Cost (by 2012)	5.753 Mio USD
Studies Completed	- Pre feasibility (1994) - feasibility (1997)



The world's longest power transmission lines

Talcher-kolar transmission link, India

- India's 1,450km-long Talcher-Kolar transmission link is the world's fifth longest transmission line.
- The 500kV HVDC transmission line, also known as the East-South transmission link, has a rated capacity of 2,500MW and is owned by Power Grid Corporation of India.
- It was the world's second longest transmission link at the time of commissioning in February 2003.

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Main Components of HVDC

1. Converter Transformer
2. Valve Hall
3. AC Harmonic Filters
4. Shunt Capacitors
5. DC Harmonic Filters
6. Smoothing Reactors
7. DC Current / Voltage measuring devices
8. Valve Cooling / Ventilation System

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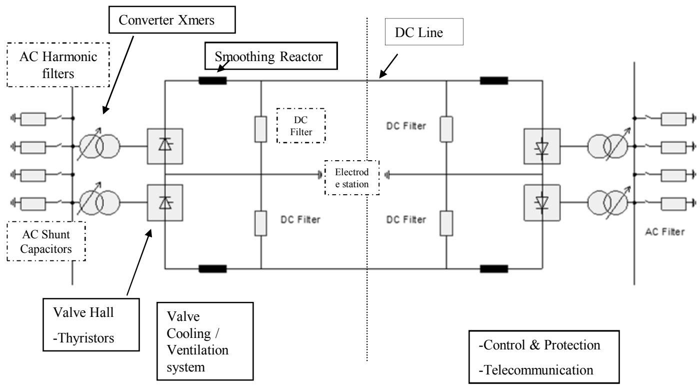
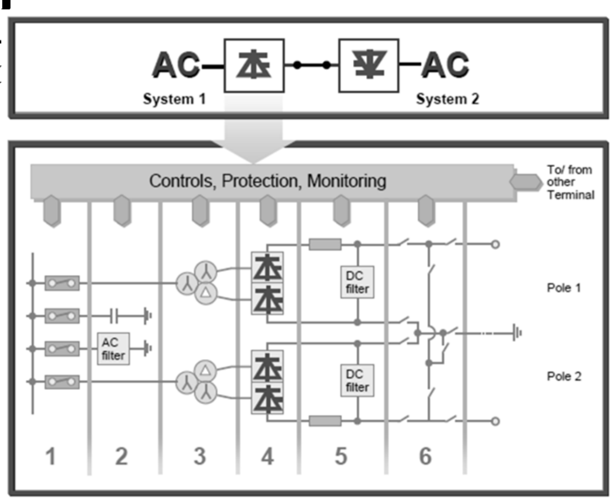
Basic Components of HVDC Terminal



Bipolar HVDC Station



1 AC Switchyard
2 AC Filters, Capacitor Banks
3 Converter Transformers
4 Thyristor Valves
5 Smoothing Reactors and DC Filters
6 DC Switchyard

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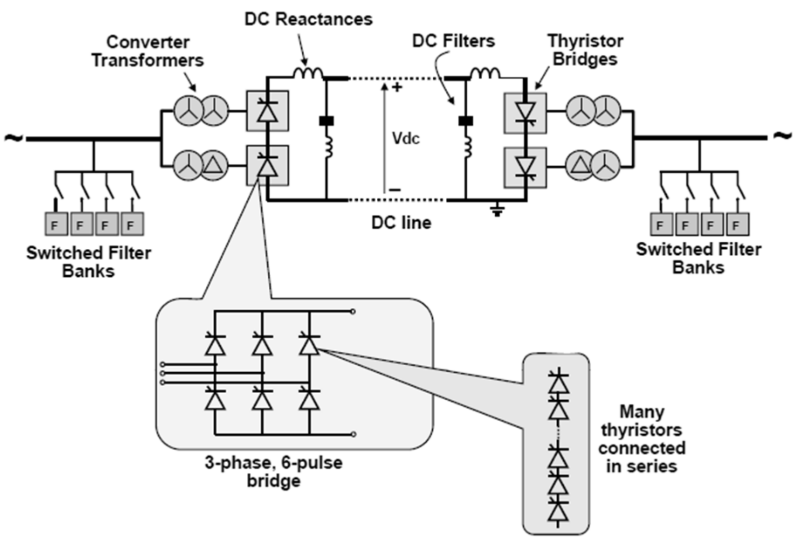
Classical 12-pulse HVDC Scheme Main Equipment



AC/DC Conversion

- Mercury arc rectifiers (at the beginning and still in operation).

Early mercury-arc valve for HVDC transmission

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❖1970: Thyristors switched on by a trigger and off at zero cross point.

❖Gate: turn-off thyristor can be switched on and off at high frequency.

❖New IGBT (Insulated Gate Bipolar Transistor):
❖It can offer on and off of the circuit at high frequency (2 kHz).

❖It gives less harmonics.

❖Can be used in cascade (series and parallel) connection to give HV and high current ratings.

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Main Technologies of DC conversion

Power converters can be classified in two major categories:

- Line Commutated Converter (LCC) or (CSC) and Voltage Sourced Converter (VSC).
- Both technologies have the same ultimate function and both can provide all benefits related to HVDC transmission.
- They perform in a different way because of the intrinsic differences of power electronic components and therefore have some distinct features.

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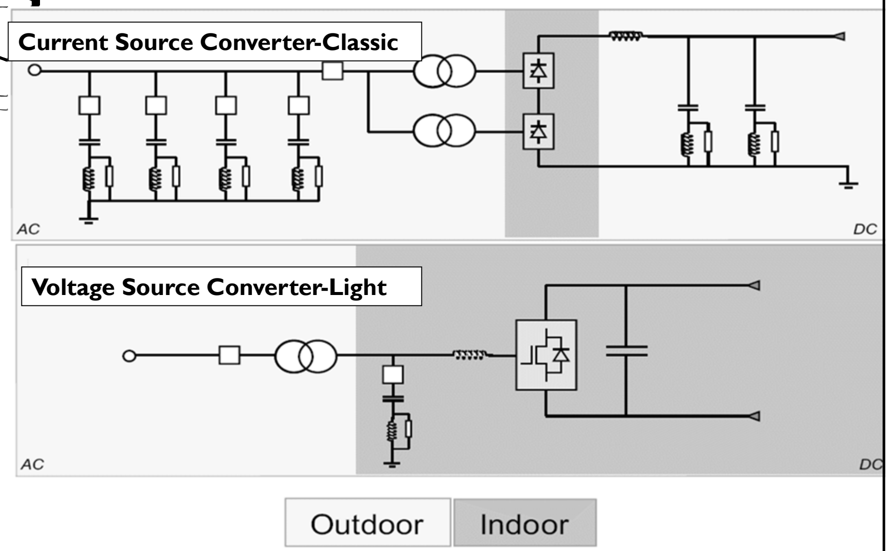
Converter Stations between AC and DC Networks



HVDC Light has fewer components and most equipment indoors

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Converter Stations between AC and DC Networks

- **Current Source Converters (CSC)** are traditional method of connecting networks – requires strong AC network [HVDC – Classic]
- **Voltage Source Converters (VSC)**. [HVDC – Light]

Weak electric grid:

- low short circuit capacity
- low x/r ratio for the feeders
- distribution networks with low voltage are weak grid

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Voltage Source Converters (VSC)

- VSC can perform independent control of active/reactive power at both ends.
- This ability of VSC makes it suitable for connection to weak AC networks, i.e. without local voltage sources.
- For power reversal, the DC voltage polarity remains the same for VSC based transmission system and the power transfer depends only on the direction of the DC current.

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Current Source Converter (CSC)

- In a CSC the DC current is kept constant with a small ripple using a large inductor, thus forming a current source on the DC side.
- The direction of power flow through a CSC is determined by the polarity of the DC voltage while the direction of current flow remains the same.

Self-commutated VSC are more flexible than the more conventional CSC since they allow controlling active and reactive power independently.

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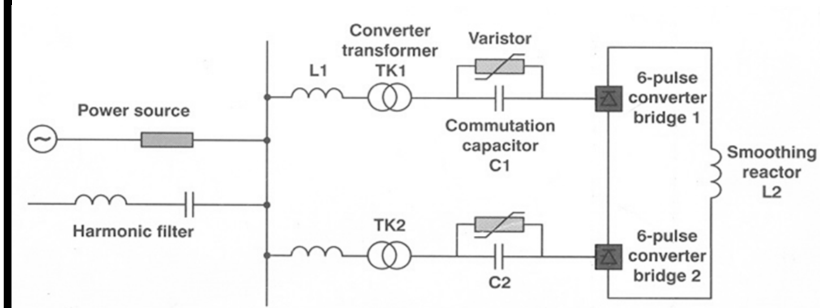
Capacitor-Commutated Converters (CCC)

- A strong alternative to classic converters for HVDC transmission is the rather recent CCC (Capacitor Commutated Converters).
- It uses series connected commutation capacitors inserted between the converter transformers and the thyristor valve bridge



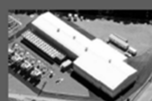
The CCC uses series connected commutation capacitors inserted between the converter transformers and the thyristor valve bridge.

HVDC Technologies

- HVDC Light is a high voltage, direct current transmission technology and is well suited to meet the demands of competitive power market for transmission up to 330MW and for DC voltage in the ± 150kV range-Transistor IGBT controlled.
- Traditional HVDC, or HVDC Classic, is designed for high voltage, direct current transmission above 300MW and for DC voltage up to ± 600kV- Thyristor controlled.
- IGBT: Insulated Gate Bipolar Transistor.

HVDC Technologies

120 x 200 m, height 22 m



50 x 120 m, height 11 m

HVDC Classic 300 – 3000 (6000) MW

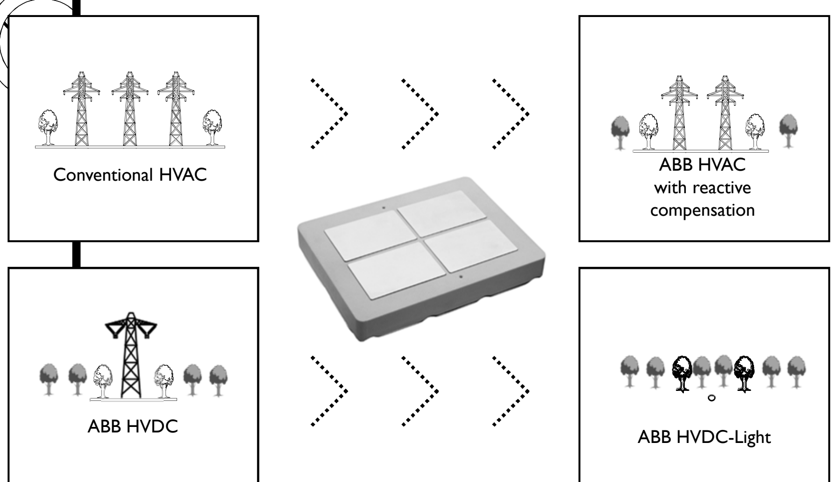
- Thyristor controlled
- Switched Reactive Power Control
- Typical design valve building plus switchyard
- Mass impregnated cables

HVDC Light 50 -1200 MW

- Transistor (IGBT) controlled
- Continuous Voltage and Reactive Power Control
- Typical design with all equipment (excluding transformers) in compact building
- Extruded cables

Invisible power transmission

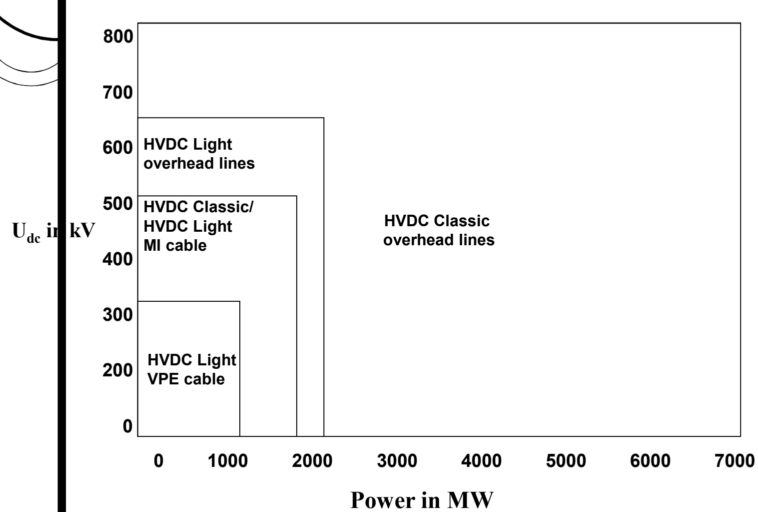
IGBT power electronics, the enabling technology



Comparison between HVDC Classic and HVDC Light

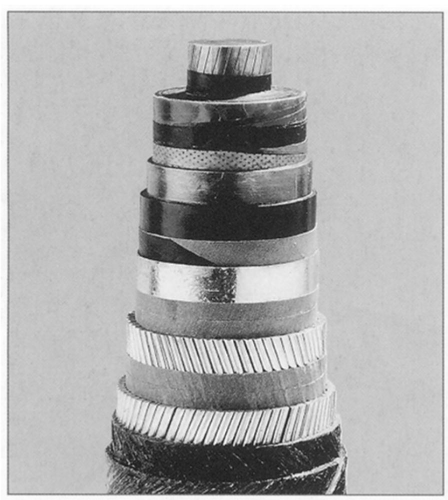
HVDC Classic	HVDC Light
• Requires strong AC networks at connection points to control reactive power issues.	• Does not require strong AC connection
• Difficult to connect to weak Island /offshore generation grids.	• Relatively easy to connect to weak Island /offshore generation grids.
• Most suited to single node links	• Ideal for Multi-mode connection
• Much experience of operation	• Less operational experience
• Higher power transmission compared to HVDC (Light) experimentation with higher voltages ~ 800 kV.	• Power transmission restricted to around 1000 MW per cable pair @ 300 kV.

HVDC projects and technology
HVDC Classic vs. Light



HVDC Cable Options

- MI: Insulated with special Paper, impregnated with High-Viscosity Compound up to 600 kV &2000MW.
- SCFF: Insulated with special Paper, impregnated with Low-Viscosity Oil up to 600 kV & 2400 MW.
- Extruded: Insulated with extruded Polyethylene-Based Compound up to 320 kV & 1150 MW.



Submarine cable for the 600- MW Baltic Cable HVDC link between Germany and Sweden.

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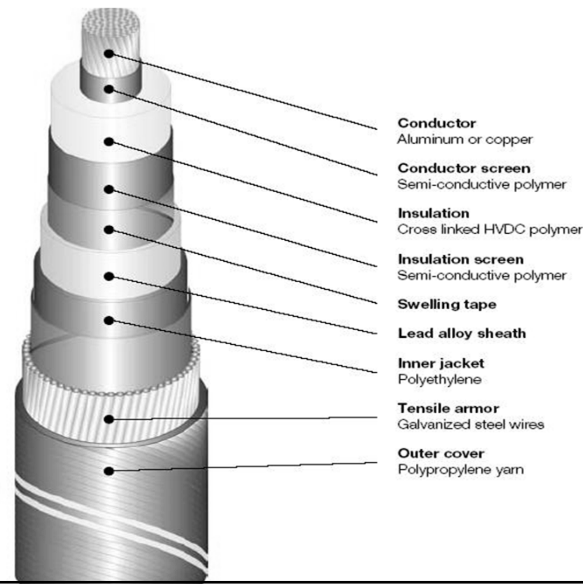
HVDC Cables



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- HVDC Light® cables are buried underground and underwater so there is no visual impact from the power cables.
- They do not emit fluctuating electric and magnetic fields (EMFs) so there are no human health related issues.
- HVDC Light® cables are made using a strong polymeric insulation material, and contain no oil.
- Overall, the cables provide a minimal impact alternative for large-scale electrical power transmission.
- The converter stations use state-of-the-art semiconductor technology to deliver highly flexible, reliable and maintainable electrical power transmission.
- Virtually all components with the exception of transformers and heat exchangers are enclosed in a building that can be designed to be visually compatible with the local environment.

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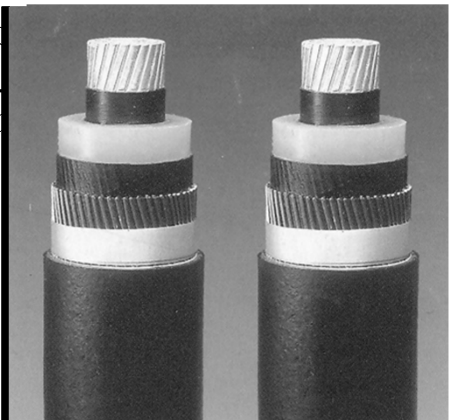

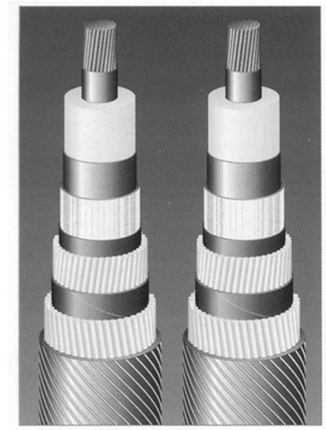

Extruded HVDC Light land cables

HVDC Light extruded submarine cable, with double armoring (80 kV rating)

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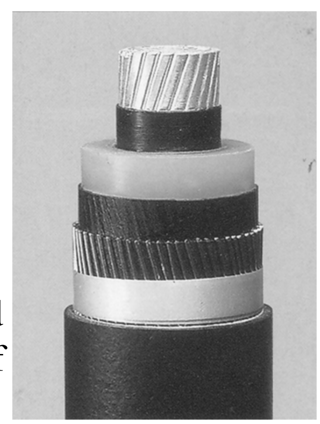
Work at higher electrical stress ⟶ thin insulation.

- AC cables are dimensioned for skin effect losses, proximity effect losses, induced losses in screens and sheath, armouring.

- HVDC light cable is dimensioned only for ohmic conductor losses if there is armouring.



HVDC Light land cable

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- The 580 kilometer-long Double-core FMI (Flat Mass impregnated) cable is the longest submarine high-voltage cable in the world.
- This cable design comprises two independent cable cores each representing a complete electric system.
- The FMI cable comprises two independent cable cores each rated 450 kV dc put side by side into a common steel wire armouring.

Submarine FMI cable
The Norned HVDC Cable Link bet. Norway and Netherlands

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Advantages of HVDC cables

- HVDC light cables are installed close in bipolar pairs with anti parallel currents and thus eliminating the magnetic fields
- They have no technical limitation for distance as in ac cables
- Its strength and flexibility makes it well suited for several installation conditions

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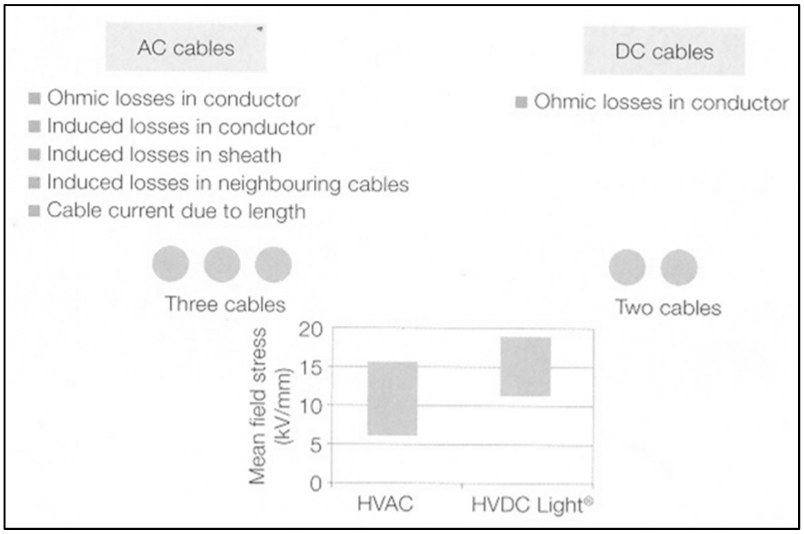
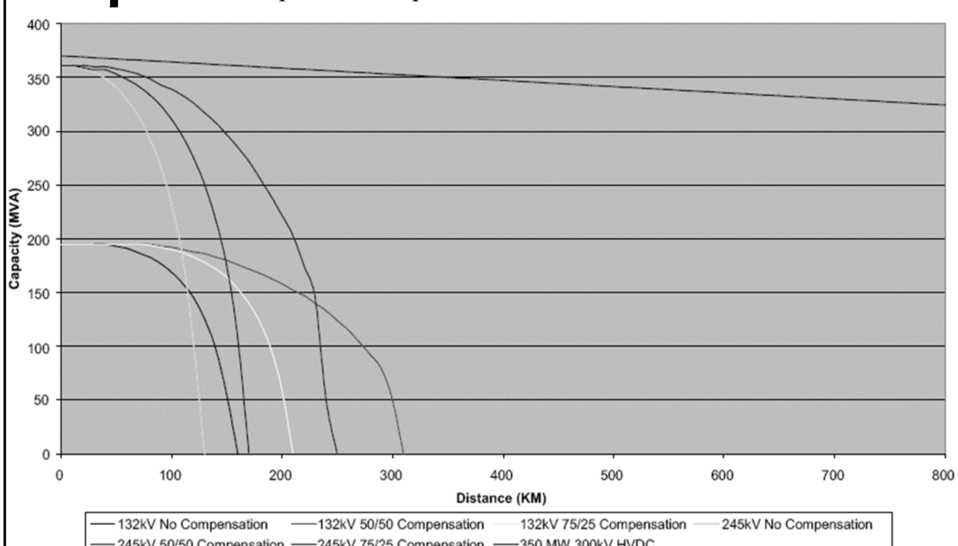


Comparison between HVAC and HVDC Light cables

AC - DC transmission of electricity

- DC transmission is purely resistive and decreases slowly with distance
- AC transmission is inductive and resistive and power falls off rapidly even when compensation is provided



AC and DC electromagnetic fields

- Conductor surface field is less for DC systems.
- Radio interference (RI) is less for DC.
- Electric and magnetic field for DC systems are less effective than AC systems.
- Limits for human exposure are less for DC systems, table 2.

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Table 2: Limits of Electromagnetic Fields

Limits for low-frequency electric and magnetic fields			
Frequency	HZ	50	$16\frac{2}{3}$
Electric field	kV/m	5	10
Magnetic field	μT	100	300
Limits for DC electromagnetic fields (rms values)			
Electric field	kV/m	20	
Magnetic field	μT	21200	

- Effect of heat generation near submarine cable.
- Magnetic fields generation effect on founa and vessels compass.
- Electric field & earthing electrodes.

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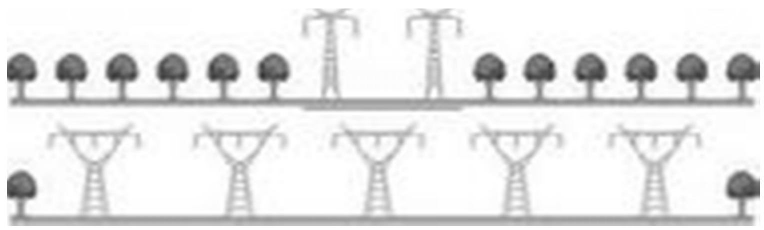
Environmental benefits of HVDC

- Many HVDC transmissions have been built to interconnect different power systems by overhead lines or cables.
- By means of these links the existing generating plants in the networks are used more effectively so that the **building of new power stations can be deferred**.
- This makes **economic sense**, but it is also good for the environment.

Environmental benefits of HVDC

- The **greatest environmental benefit** is obtained by **linking a system**, which has much **hydro generation to a system with predominantly thermal generation**.
- This has the benefit of **saving thermal generation** by hydro generation.
  - Also the thermal generation can be **run more efficiently at constant output** and does not have to follow the **load variations**.
  - This can be done easily with the hydro generation.

A DC line can carry more power than an AC line of the same size.



- The figure above compares two 3,000 MW HVDC lines (for the Three Gorges - Shanghai transmission, China) to five 500 kV AC lines that would have been used if AC transmission had been selected

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Special Applications of HVDC

- HVDC is particularly suited to undersea transmission, where the losses from AC are large.
  - First commercial HVDC link (Gotland 1 Sweden, in 1954) was an undersea one.
- Back-to-back converters are used to connect two AC systems with different frequencies – as in Japan – or two regions where AC is not synchronized – as in the US.

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Special Applications of HVDC

- HVDC links can stabilize AC system frequencies and voltages, and help with unplanned outages.
  - A DC link is asynchronous, and the conversion stations include frequency control functions.
  - Changing DC power flow rapidly and independently of AC flows can help control reactive power.
  - HVDC links designed to carry a maximum load cannot be overloaded by outage of parallel AC lines.

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Renewable Energy and HVDC

- HVDC seems particularly suited to many renewable energy sources:
  - Sources of supply (hydro, geothermal, wind, tidal) are often distant from demand centers.
  - Wind turbines operating at variable speed generate power at different frequencies, requiring conversions to and from DC.
  - Large hydro projects, for example, also often supply multiple transmission systems.

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HVDC and Solar Power

- HVDC would appear to be particularly relevant for developing *large scale* solar electrical power.
- Major sources are low latitude, and high altitude deserts, and these tend to be remote from major demand centers.
- Photovoltaic cells also produce electricity as DC, eliminating the need to convert at source.

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HVDC and Wind Power

- BorWin1, offshore wind in Germany
- The world's largest offshore wind park in operation
- 125 km subsea and 75 km underground power connection 400 MW HVDC Light system
- Environmentally friendly power transport
- Reduce CO_2emissions by 1.5 million tons per year by replacing fossil-fuels
- Supports German wind power development

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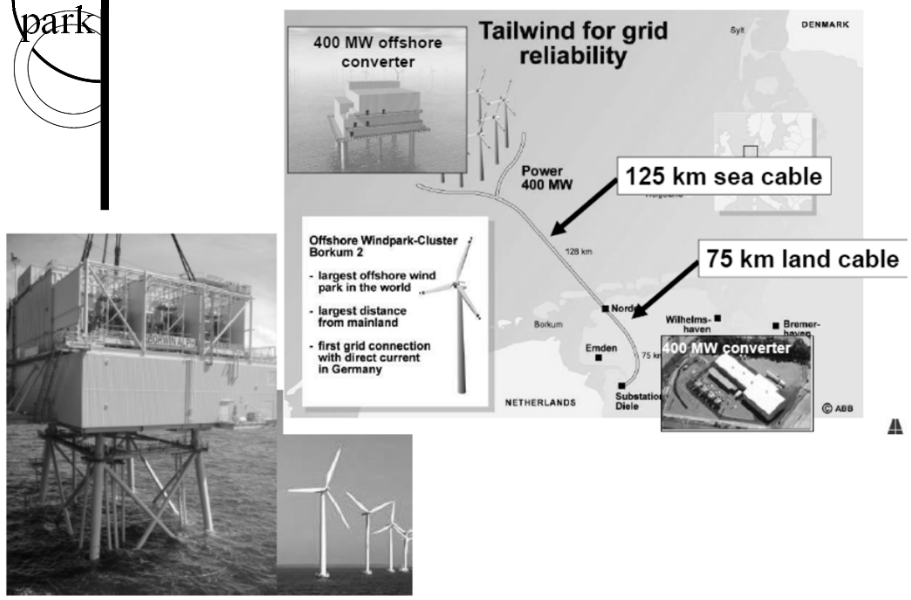
BorWin1, the world's most remote offshore wind park



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HVDC and Wind Power

- DolWin1 Offshore Wind Power Connector 800 MW, ±320 kV DC
- One of the two converter stations is built on a platform in the sea.
- Voltage Sourced Converters are used.
- 165 km long subsea and underground power connection to offshore wind farm
- Robust grid connection
- Turnkey 800 MW HVDC Light system
- First ± 320 kV extruded cable delivery
- Low losses and high reliability
- Reduce CO_2 emissions by 3 million tons per year replacing fossil-fuel generation
- Supports German wind power

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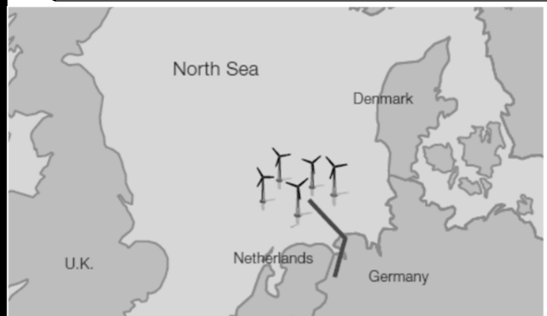
DolWin1 HVDC Light® wind farm link



Transcontinental Energy Bridges

- Siberia has large coal and gas reserves and could produce 450-600 billion kWh of hydroelectricity annually, 45% of Japanese output in 1995.
  - A 1,800 km 11,000MW HVDC link would enable electricity to be exported from Siberia to Japan.
  - Siberia could also be linked to Alaska via HVDC.
- Zaire could produce 250–500 billion kWh of hydroelectricity annually to send to Europe (5-6,000 km) on a 30-60,000 MW link.
- Hydroelectric projects on a similar scale have been proposed for Canada, China and Brazil.

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New Technologies Needed

- For transfers of 5,000 MW over 4,000 km, the optimum voltage rises to 1,000–1,100 kV.
  - ✓Technological developments in converter stations would be required to handle these voltages.
  - ✓Lower line losses would reduce the optimum voltage.
- However, environmentalist opposition and unstable international relations may be the biggest obstacle to such grandiose schemes.

THANK YOU