ABB High Voltage Direct Current
Applications of a Well-proven System
HVDC History
Reliable power to millions, for decades

Near Future of HVDC in South America
An overview

Skagerrak Project
A challenging history

Maritime project
The first bipole HVDC Light solution

Conclusion
HVDC flexibility
HVDC history
A proven track record of innovation

1893
ABB starts providing power to the mining industry

1928
Dr Uno Lamm began developing HVDC in Ludvika, Sweden

1954
The world’s first commercial HVDC link at Gotland, Sweden

1960s
Mercury arc valves replaced with thyristor semiconductor valves

1997
The world’s first VSC HVDC installation

2010
The world’s first 800 kV UHVDC link at Xiangjiaba-Shanghai, China

2013
Hybrid HVDC Breaker, solving a 100-year old technology puzzle enabling the DC-grids of the future.

2014
Complete 1,100 kV UHVDC system developed.

2017
VSC HVDC highest performance ever – 3,000 MW, 640 kV, 2,000 km

The Future
DC support in AC grids DC grids

“The best way to predict the future is to create it”
- Abraham Lincoln
The Birth of HVDC

Gotland

First commercial HVDC transmission in 1954
(100 kV, 20 MW)

Cable length: 100 km

Gotland – Swedish mainland
Case study
Itaipu

One of the largest HVDC transmissions in the world - two major ABB HVDC links that supply Sao Paulo.

6,300 MW
600 kV
1,590 km

Key facts

- The largest and most powerful HVDC transmission in the world for 20 years from 1990-2010.
- A considerable step forward in HVDC technology compared to the HVDC stations of the 1970s.
Case study
Rio Madeira

Integrating remotely located renewables, transmitting clean electricity, reliably and efficiently across a massive distance with minimum losses, to millions of consumers.

3,150 MW + 2x 400MW (BtB)
600 kV
2,375 km

Key facts

- Essential for the integration of vast hydro electric power from the Amazon Basin.
- Highly challenging remote location in the Amazon jungle.
Case study
North East Agra – ultrahigh-voltage DC, multi-terminal solution

The world’s first ultrahigh-voltage multi-terminal HVDC link, a step towards a true DC grid.

6,000 MW
800 kV
1,775 km

Key facts
- Bulk 2-way transmission.
- Multi-terminal solution to integrate two generation locations.
- Minimum transmission corridor due to limited space.
Case study
Changji-Guquan – in execution

Due to set new world records on voltage level, transmission capacity and distance, supplying millions of people with reliable electricity.

12,000 MW
1,100 kV
3,000 km

Key facts

- ABB was the first to successfully develop and test the world record breaking, 1,100kV converter transformer technology.
- Key in integrating remote renewables on a large scale and transmitting power over greater distances.
HVDC Classic from ABB:
- Low losses
- High reliability
- High availability
- World’s largest greenfield project experience
- Extensive service and upgrade experience

HVDC Classic LCC
Cost effective, bulk transmission (up to 12 GW+)
Installed base
Over 120 projects and over 60 years experience

**America**
- CU Upgrade 2019
- Maritime Link 2017
- Quebec – New England Upgrade 2016
- Madawaska Upgrade 2016
- Celilo Upgrade 2016
- Railroad DC Tie 2016
- IPP Upgrade 2014
- Blackwater 2010

**Europe**
- North-sea Link 2021
- Nordlink 2021
- IFA2 2020
- Kriegers Flak Cgs 2019
- Johan Sverdrup 2019
- Gotland Upgrade 2018
- Caisnhirn – Moray 2018
- Krieks Upgrade 2016
- Troll 1 & 2, 3 & 4 2015
- Dolwin 1, 2 2015
- Åland 2015

**South America**
- Rio Madeira Back to back 2013
- Rio Madeira 2013
- Brazil – Argentina Interconnection I & II 1999
- Itaipu 1984

**Asia**
- Changji-Guquan 2019
- Raigarh-Pugaikur 2019
- North East Agra 2016
- Jinping-Sunan 2013
- Molünbeir – Liaoning 2010
- Lingbao II Extension 2010
- Xiangjiaba – Shanghai 2010
- Three Gorges – Shanghai 2006
- Vizag Li 2005
- Three Gorges – Guangdong 2004
- Three Gorges – Changzhou 2002
- Chapad 1999
- Rihand-Delhi 1990
- Gezhouba – Shanghai 1989
- Vindhyachal 1989
- Sakuma 1985

**Africa**
- Inga – Kolwezi Upgrade 2016
- Cahora Bassa, Songo 2015
- Capriei Link 2010
- Apollo Upgrade 2008
- Inga – Kolwezi 1982
- Cahora Bassa 1977

**Australia and Oceania**
- Broken Hill 2013
- Murraylink 2013
- Directlink 1999
- Leyte-Luzon 1998
- New Zealand 1 & 2 1984

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## HVDC Light: 20 year of success!

Harmonic and Loss Reduction – Eliminating the Need for Harmonic Filters

### Modulation principles

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997 – 2001</td>
<td>Two level converter</td>
</tr>
<tr>
<td>2002 – 2004</td>
<td>Three level converter</td>
</tr>
<tr>
<td>2005 – 2009</td>
<td>Two level converter, optimized switching</td>
</tr>
<tr>
<td>2010 – 2015</td>
<td>Cascade two level converter</td>
</tr>
<tr>
<td>2016 –</td>
<td>Modular multi-level converter</td>
</tr>
</tbody>
</table>

![Graph showing voltage over time for HVDC Light technologies]
Case study
Nordlink – in execution

Interconnecting grids using HVDC technology helping our customers reach their targets for a renewable energy mix.

1,400 MW
525 kV
623 km

Key facts
- VSC bipole HVDC
- Balances intermittent wind power in Germany with controllable hydropower in Norway.
- Most powerful HVDC Light® system in construction, joint with NordLink.
VSC HVDC Light®
Up to 640 kV and 3,500 MW

Your grid challenges, solved by HVDC Light:

Weak network?
- Black start power restoration
- Active/reactive power control (statcom functionality)
- AC voltage and frequency stabilization (increasing AC grid utilization)

Bi-directional power trade?
- Fast power reversal

Integration of renewables?
- Power, voltage and frequency control
VSC HVDC Light
ABB supplied 70% of all VSC links in the world

*VSC: Voltage sourced converter
Near Future of HVDC in South America
An overview
HVDC Installed Base and Future Projects
South America

SAM in 2029
**HVDC Future Projects**

**Brazil**

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**N/SE and NE/SE Transmission Expansion**
- **Transmission Line:** 2,100 km N/SE, 1,500 km NE/SE
- **Voltage:** ±800 kV DC
- **Power:** 8,000 MW for 2 bipoles
- **Expected Auction/Award:** 2021 BP B, 2023 BP A

**HPP Tapajós Transmission System**
- **Transmission Line:** 1,500 km BP1, 2,500 km BP2
- **Voltage:** ±800 kV DC
- **Power:** 8,000 MW for 2 bipoles
- **Expected Auction/Award:** 2025 BP1, 2027 BP2

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HVDC Future Projects
Chile

3000 MW / ±600kV DC
To be in operation up to 2028

Source: CEN – Coordinador Electrico Nacional
Skagerrak Project
A continuous evolution

General Information
- Connection between Kristiansand, Norway and Tjele, Denmark.
- The transmission system belongs to Statnett on the Norwegian side and to Energinet on the Danish side.
- Skagerrak 1 and 2 (SK 1 e SK 2) entered commercial operation in 1975/1976.
- Skagerrak 3 (SK 3) was commissioned in 1993.
- Skagerrak 4 (SK 4) is in operation since 2014.
- The distance between the substation is around 240 km.
- Hydroelectric power from Norway.
- Initially thermoelectric power form Denmark.
- Today Denmark has a considerable amount of windfarms.
Skagerrak Project
Connecting Norway and Denmark
Skagerrak 1 & 2
The first bipole

General Information
- Bipole with Line-Commuted Converters (LCC).
- Uses thyristor in the converters.
- Voltage of ± 250 kV DC (until Skagerrak 3).
- Current of 1000 A.
- Total power of 500 MW.
- 127 km submarine cables and 113 km overhead lines.
- Earth electrode on both sides.
- Revitalized in 2007.
Skagerrak 1 & 2
The first bipole
Skagerrak 3
The third pole. Changes were needed...

General Information
- Monopole with LCC converter.
- Voltage of 350 kV DC.
- Current of 1430 A.
- Power capacity of 500 MW.
- 127 km submarine cable and 113 km overhead line.
- Commissioned in 1993.

But...
- No metallic return dedicated cable was built.
- There is a limitation to the amount of time the earth return can be used.
- The rated voltage, current and power for SK3 is different from SK 1 and 2.

How to operate the new system with a new pole with different specs?
Skagerrak 3
Adaptations

Before SK3
- SK1 and SK2 are two monopoles that form a bipole.
- SK1 and SK2 have different DC voltage polarities.
- SK1 and SK2 have DC currents flowing in opposite directions.

After SK3
- SK1 and SK2 have their converters in parallel and form a monopole.
- SK1 and SK2 have the same DC voltage polarity.
- SK1 and SK2 have their DC currents flowing in the same direction.
Skagerrak 3
The addition of a new pole

With Skagerrak 3
- SK3 operates with a DC voltage polarity to SK1 and SK2.
- SK3 has its DC current flowing in the opposite direction to SK1 and SK2.
- SK1 and SK2 operate as a monopole and, together with SK3, form a new bipole.
From 1993 on....

- SK1 and SK2 operated with +250 kV DC e maximum current of 1000 A. The total power capability was 500 MW (250 MW per pole).
- SK3 operated with -350 kV DC and maximum current of 1430 A. The power capability was 700 MW.
- The new bipole has a total power capability of 1200 MW.
- Normally the power was distributed between the two poles so they had the same DC current in order to minimize the earth current.
- During the operation with full power, the current flowing to ground was 600 A.
Changes in the Danish System
Wind power: More changes were needed...

Norway
- The main energy source is hydroelectrical.

Denmark
- When SK1 and SK2 were commissioned, the Danish system had primarily thermal power sources.
- In the last decade, many windfarms have been built in the country.
Changes in the Danish System
Advantages of HVDC with renewable power

What was HVDC initially intended for?
- Initially the Skagerrak transmission system was designed for optimal economical energy dispatching among the two countries.
- Stabilization of the AC grids after contingencies.

What happened more recently?
- Wind generation in Denmark sometimes exceeds the consumption of the loads connected to it.
- The HVDC system compensates for swift variations in wind power and assures the balance between load and generation.
- Hydro power in Norway compensates for quick changes in windfarm output in Denmark.
- In some situations the active power in the HVDC link is inverted and Denmark exports energy to Norway.
Changes in the Danish System
The fourth pole

Why a forth pole?
- The need for an increase in the energy exchange capability between Norway and Denmark requires the construction of a new HVDC pole.

LCC or VSC?
- SK1, 2 and 3 are located electrically far away from big conventional generators.
- The LCC converters demand a minimum AC network short-circuit level to work properly.
- There are other two HVDC links (Norned and Konti-Skan) that are relatively close to Skagerrak and multi-infeed interactions might may appear.
- Voltage and electromechanical stability problems may occur and synchronous condensers were installed in Norway to increase the short-circuit level.
- A new HVDC pole using LCC technology would require the installation of a few synchronous condensers in both the Norwegian and Danish systems.
Advantages of a Voltage Source Converter

- No need of new synchronous condensers.
- The reactive power exchange between the converter and the AC network is controlled.
- The VSC converters can be used to control the AC voltage of both networks.
- Great increase in AC system stability.
- Black start capability.

Skagerrak 4
The VSC pole
**HVDC Light**

**System Configuration**

**Symmetric monopole**
- Positive: Low cost
- Positive: Low transmission losses
- Negative: Loss of 100% power at trip

**Asymmetric monopole**
- Positive: Only one high voltage cable
- Negative: Bipole enabled

**Bipole**
- Positive: High Availability for half power
- Negative: Temporary ground current (can be avoided at the expense of a metallic return conductor)

---
Skagerrak 4
Specifications

The new pole

- VSC converter – asymmetric monopole
- Rated DC voltage of +500 kV.
- DC current of 1400 A.
- Rated active power of 700 MW.
- 140 km submarine cable and 104 km overhead line.
- Commissioned in 2014.
Final Configuration
Two bipoles

Since 2014....
- SK1 and SK2 operate once again as two poles of a bipole.
- SK3 and SK4 operate now as an hybrid bipole, as the first one is a LCC monopole and the second one is an asymmetric monopole with VSC technology.
- Both bipoles use the same earth electrode.
- SK3 and SK4 have different power ratings and rated DC voltages, but their rated DC currents are very similar, which results in low currents to ground.
Final Configuration
Two bipoles
Final Configuration
How flexible and HVDC transmission can be...

<table>
<thead>
<tr>
<th></th>
<th>Poles 1 &amp; 2</th>
<th>Pole 3</th>
<th>Pole 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>MW</td>
<td>2 x 250</td>
<td>500</td>
</tr>
<tr>
<td>DC Voltage</td>
<td>kV</td>
<td>250</td>
<td>350</td>
</tr>
<tr>
<td>DC Current</td>
<td>A</td>
<td>1000</td>
<td>1430</td>
</tr>
<tr>
<td>Converter Technology</td>
<td>LCC</td>
<td>LCC</td>
<td>VSC</td>
</tr>
<tr>
<td>AC Voltage (Kristiansand, NO)</td>
<td>kV</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>AC Voltage (Tjele, DK)</td>
<td>kV</td>
<td>150</td>
<td>400</td>
</tr>
<tr>
<td>DC Submarine Cables</td>
<td>km</td>
<td>127</td>
<td>127</td>
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<tr>
<td>DC Overhead Lines</td>
<td>km</td>
<td>113</td>
<td>113</td>
</tr>
<tr>
<td>DC underground Cables</td>
<td>km</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Commissioning Year</td>
<td></td>
<td>1976 - 1977</td>
<td>1993</td>
</tr>
</tbody>
</table>
1. HVDC History
   Reliable power to millions, for decades

2. Near Future of HVDC in South America
   An overview

3. Skagerrak Project
   A challenging history

4. Maritime project
   The first bipole HVDC Light solution

5. Conclusion
   HVDC flexibility
## Maritime Link
### Canada

### Main data

<table>
<thead>
<tr>
<th>Customer needs</th>
<th>NSP Maritime Link (Emera)</th>
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</thead>
<tbody>
<tr>
<td>• Integrate renewable generation into the North American grid</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>ABB's response</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>• Bipole HVDC Light solution</td>
<td></td>
</tr>
<tr>
<td>• Two 500 MW HVDC Light stations</td>
<td></td>
</tr>
<tr>
<td>• Two AC substations at 230 kV</td>
<td></td>
</tr>
<tr>
<td>• One AC substation at 345 kV</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Customer benefits</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Improved grid stability</td>
<td></td>
</tr>
<tr>
<td>• Power sharing enabled</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• 2017</td>
<td></td>
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</tbody>
</table>
Maritime Link
Canada

Phase 1 – Muskrat Falls
Labrador-Island Transmission Link and Maritime Link

Muskat Falls Generation
- 824 MW hydroelectric facility; 4.9 TWh/yr
- Two dams, one powerhouse
- 60 km reservoir
- Construction start 2012; in-service 2017
- Construction cost $2.9 billion
- Ownership 100% Nalcor

Maritime Transmission Link
- 500 MW capacity
- Includes 180 km underwater link from Cape Ray, NL to Cape Breton, NS
- Construction start 2014; in-service late 2015
- Construction cost $1.2 billion
- Ownership 100% Emera for 35 years

Labrador-Island Transmission Link
- 900 MW capacity
- Muskat Falls to Soldiers Pond near Holyrood
- 1,106 km, including 30 km under Strait of Belle Isle
- Construction start 2013; in-service 2017
- Construction cost $2.1 billion
- Ownership 71% Nalcor, 29% Emera
Case study
Maritime

Enabling clean, renewable electricity generated in Newfoundland and Labrador to be transmitted to the North American grid in Nova Scotia.

500 MW
200 kV
360 km

Key facts
- World’s first VSC bipole HVDC interconnection overcoming unique control challenges.
- Demanding environment.
- Unique socio-economic and environmental requirements.
Case study
Nordlink – in execution

Interconnecting grids using HVDC technology helping our customers reach their targets for a renewable energy mix.

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525 kV
623 km

Key facts
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- Most powerful HVDC Light® system in construction, joint with NordLink.
Conclusion
HVDC flexibility
Conclusion

HVDC Flexibility

HVDC systems are ideal for connecting renewable generations as they compensate for power fluctuations that are typical to this kind of energy source.

HVDC converters can adapt to different needs from the transmission grid in different stages of its lifespan which is perfect for a power generation system that will change over time.