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Role of HVDC & FACTS in Transmission Expansion Planning for Large Scale Renewable Integration

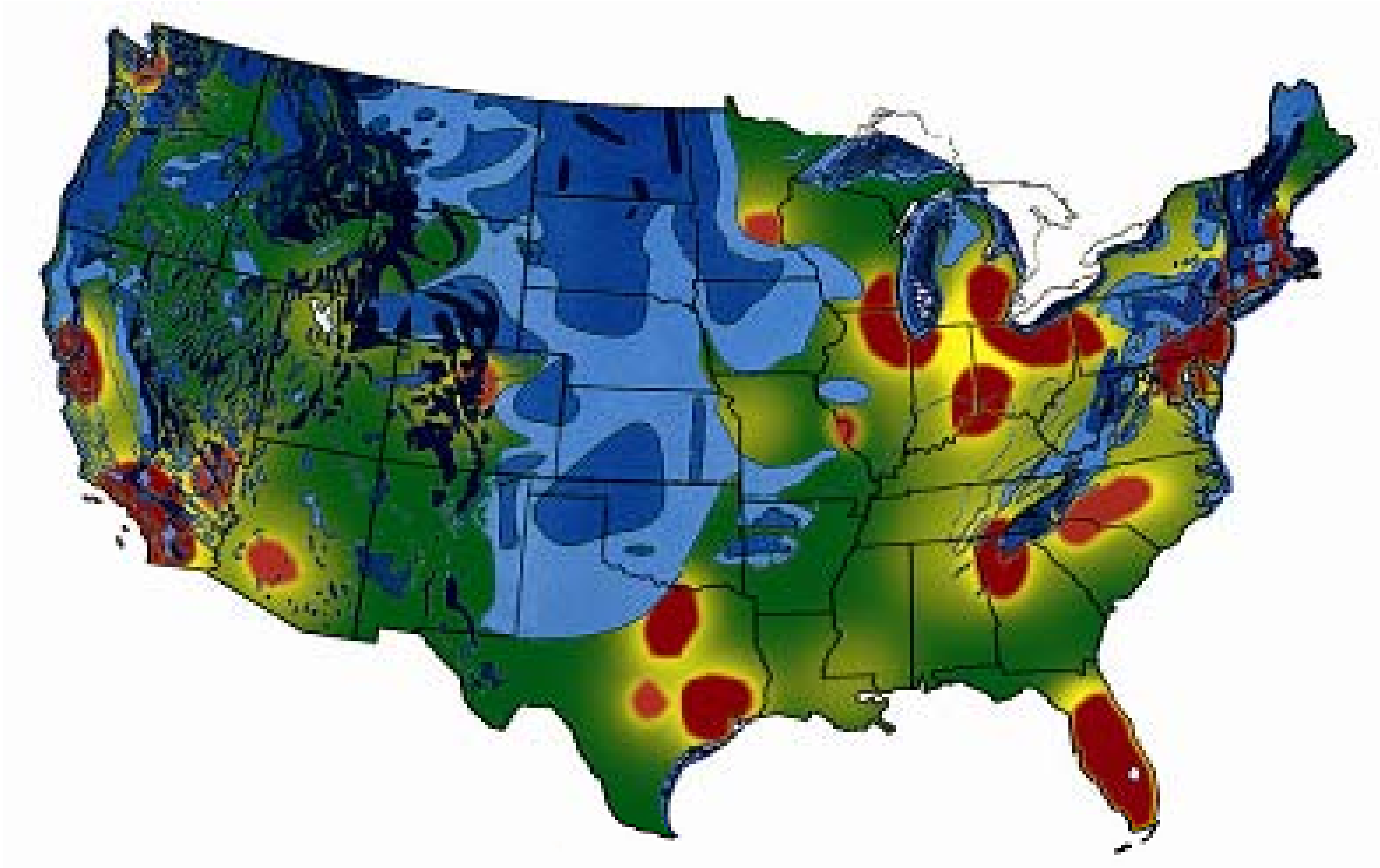
Dr. Ram Adapa, EPRI
radapa@epri.com

IEEE PES T&D Panel Session on

Transmission Planning in the Perspective of Renewable Integration: Education and Research Initiatives

April 15, 2014

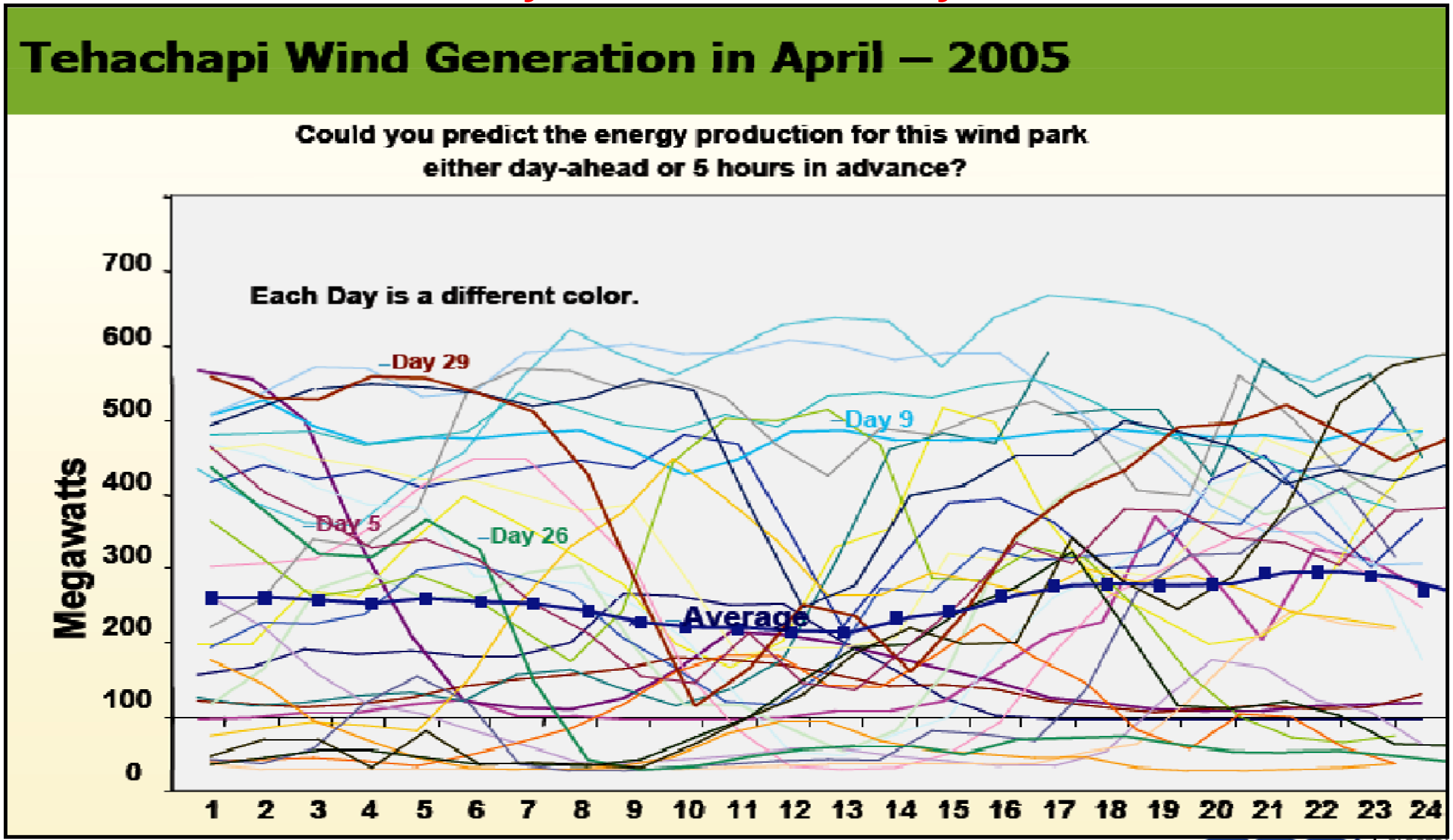
Transmission: Provides Highway between Renewables & Population Density



Wind Variability and Predictability: A Challenge to Integrate into Grid

California Energy Policy Targets for Renewable Energy Penetration:

20% by 2010 & 33% by 2020



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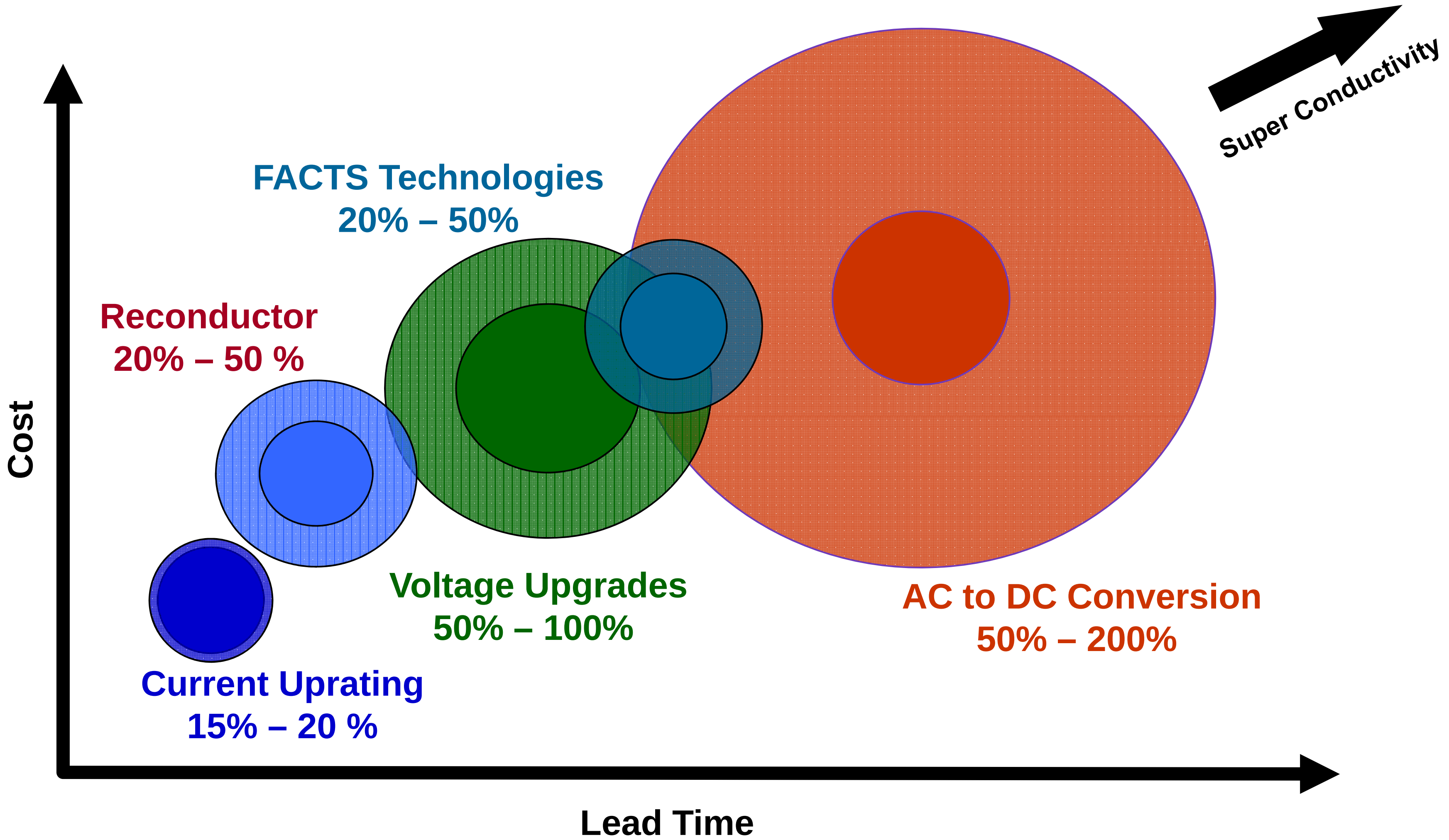
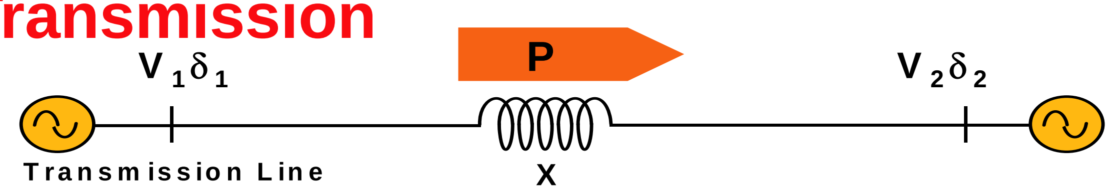
Increased Renewables require Increased Transmission Capacity – Options & Tradeoffs



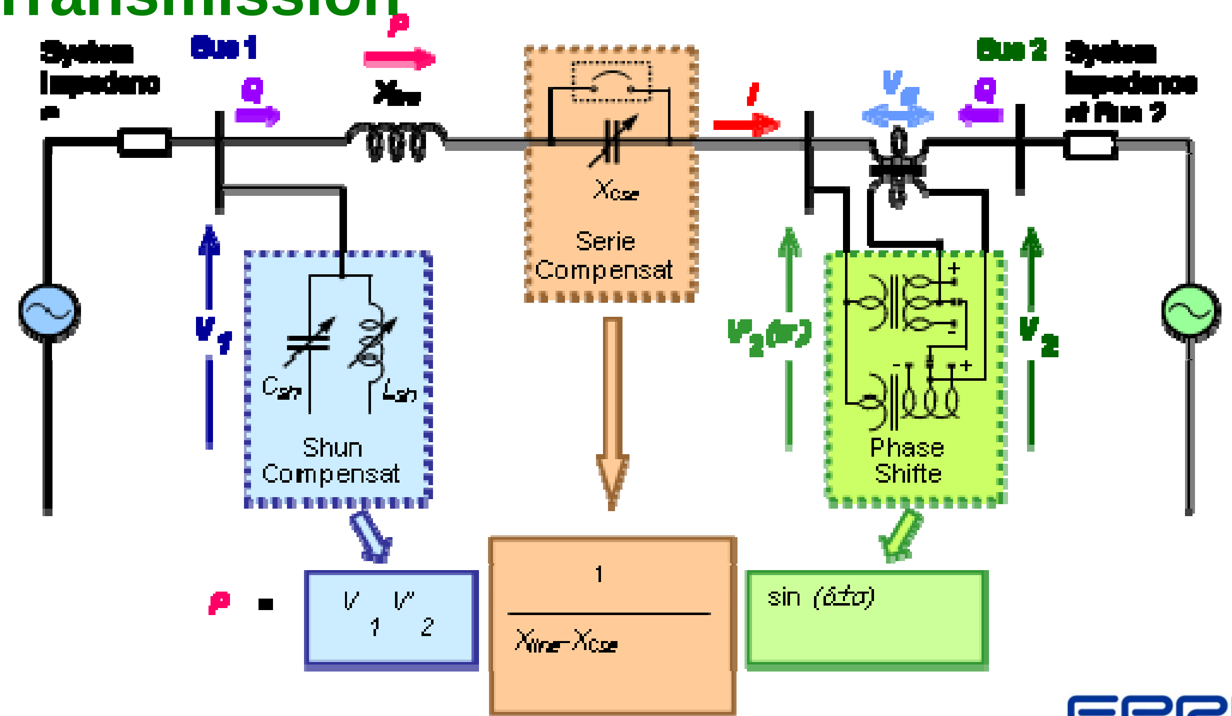
FACTS (Flexible AC Transmission Systems) – Expanding Laws of Physics

Passive Transmission



$$P = V_1 V_2 \frac{1}{X} \sin(\delta_1 - \delta_2)$$

Active Transmission



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FACTS Hardware

Traditional Technologies

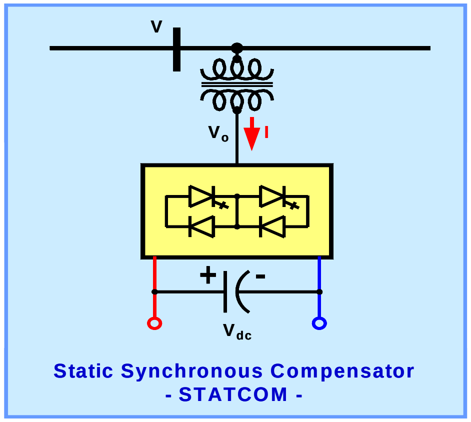
- Thyristor controlled reactors
- Thyristor switched reactors
- Thyristor switched capacitors
- Static Var Compensators (SVC)

"New" Technologies

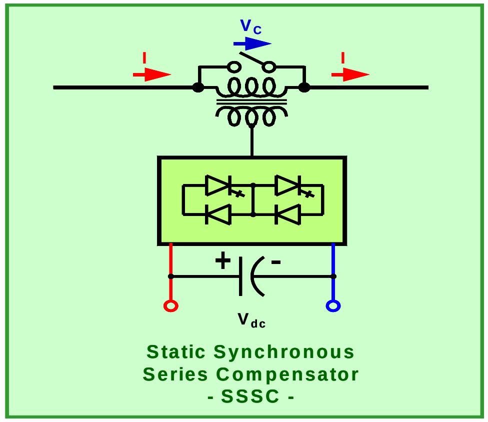
- Thyristor Controlled Series Compensation (TCSC)
- STATic synchronous COMpensator (STATCOM)
- Static Synchronous Series Compensator (SSSC)
- Unified Power Flow Controller (UPFC)
- Interphase Power Flow Controller (IPFC)

NanoMarkets Survey – Global FACTS installations from U.S. $330M in 2011 to $775 M in 2017

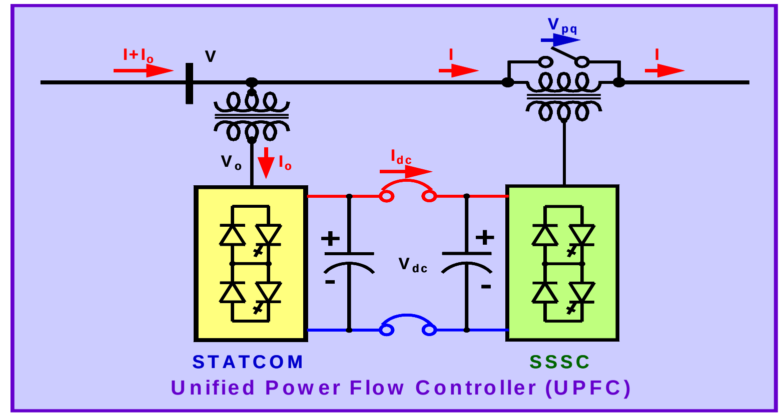
Transmission Applications of VSC-Voltage Source Converter



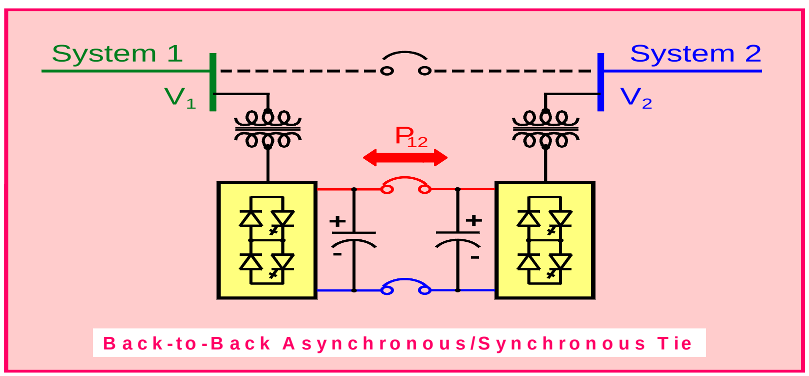
STATCOM
Voltage Control



SSSC
Line Impedance Control

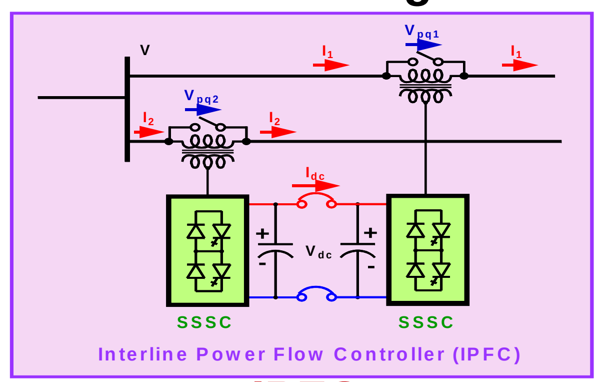


UPFC
Voltage, Line Impedance & Phase Angle Control



Back-to-Back
Voltage & Power Transfer Control

L. Gyugyi



IPFC
Interline Power Exchange

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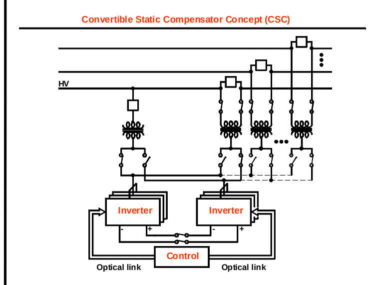
EPRI Sponsored FACTS Installations

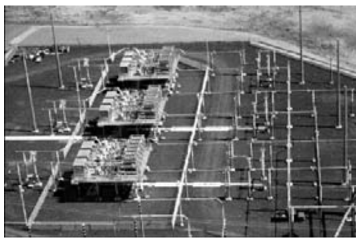
Unified Power Flow Controller (UPFC):
"All Transmission Parameters Controller"
± 160 MVA Shunt and ± 160 MVA Series at Inez Substation (AEP) 1998

UPFC



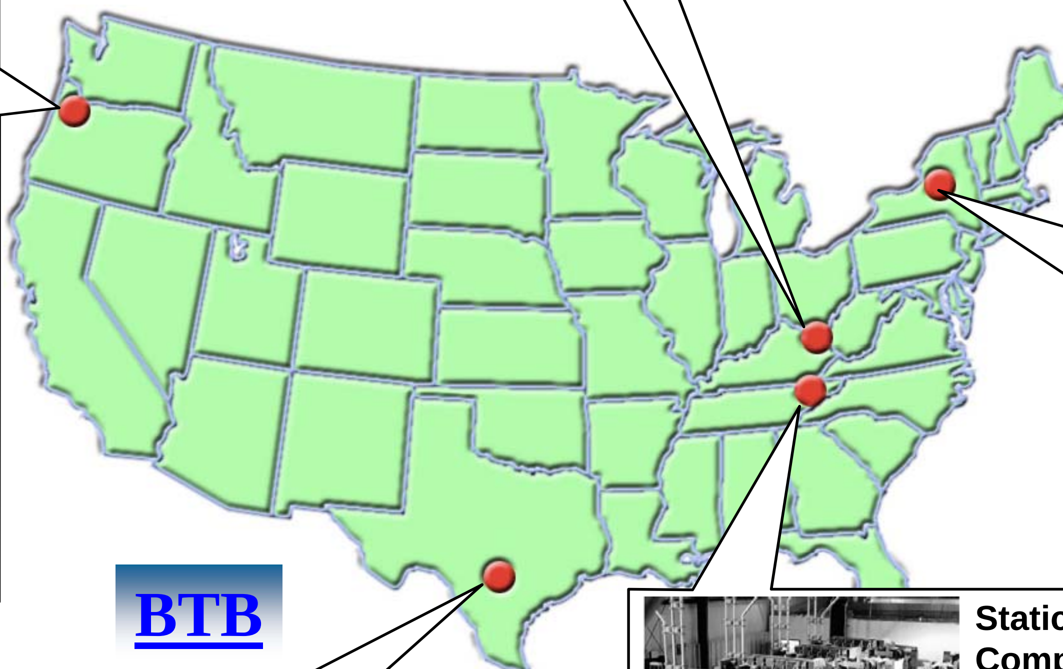
Convertible Static Compensator (CSC):
"Flexible Multi-functional Compensator"
± 200 MVA at Marcy Substation (NYPA)
2000 & 2002

CSC



Thyristor Controlled Series Capacitor (TCSC):
"Line Impedance Controller"
208 Mvar TCSC at Slatt Substation (BPA) 1993

TCSC



BTB

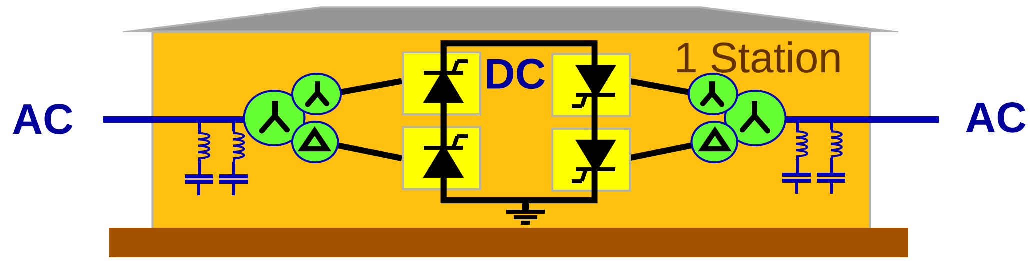
FACTS Controller
"Back-To-Back HVDC Tie"
36 MW at Eagle Pass (CSW)
2000

Static Synchronous Compensator (STATCOM) :
"Voltage Controller"
± 100 Mvar STATCOM at Sullivan Substation (TVA)
1995

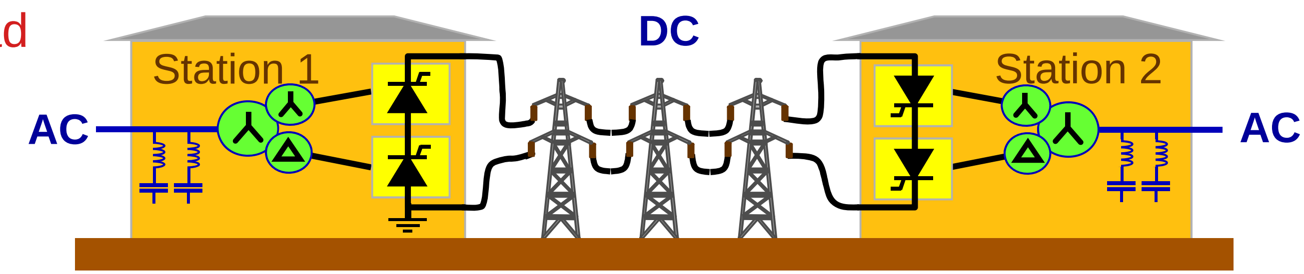
STATCOM

HVDC Scheme Types

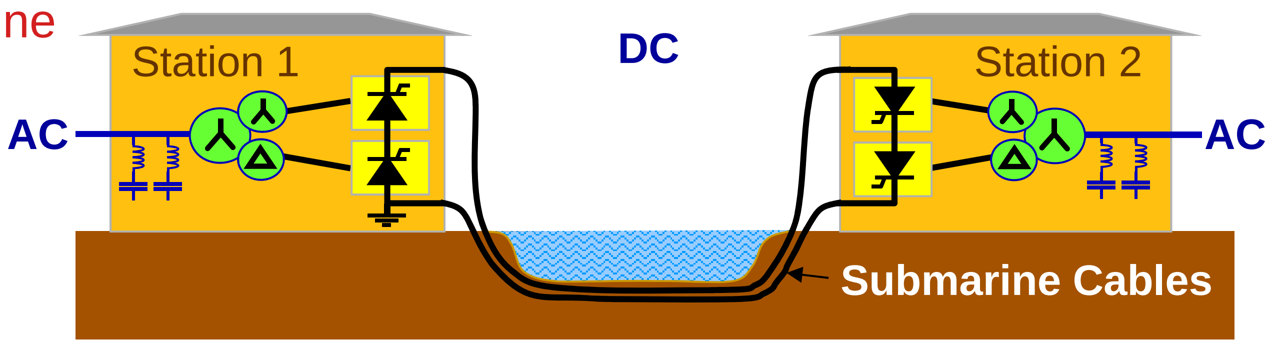
- Back-to-Back
  - frequency changing
  - asynchronous connection



- Point-to-Point Overhead Line
  - bulk transmission
  - overland

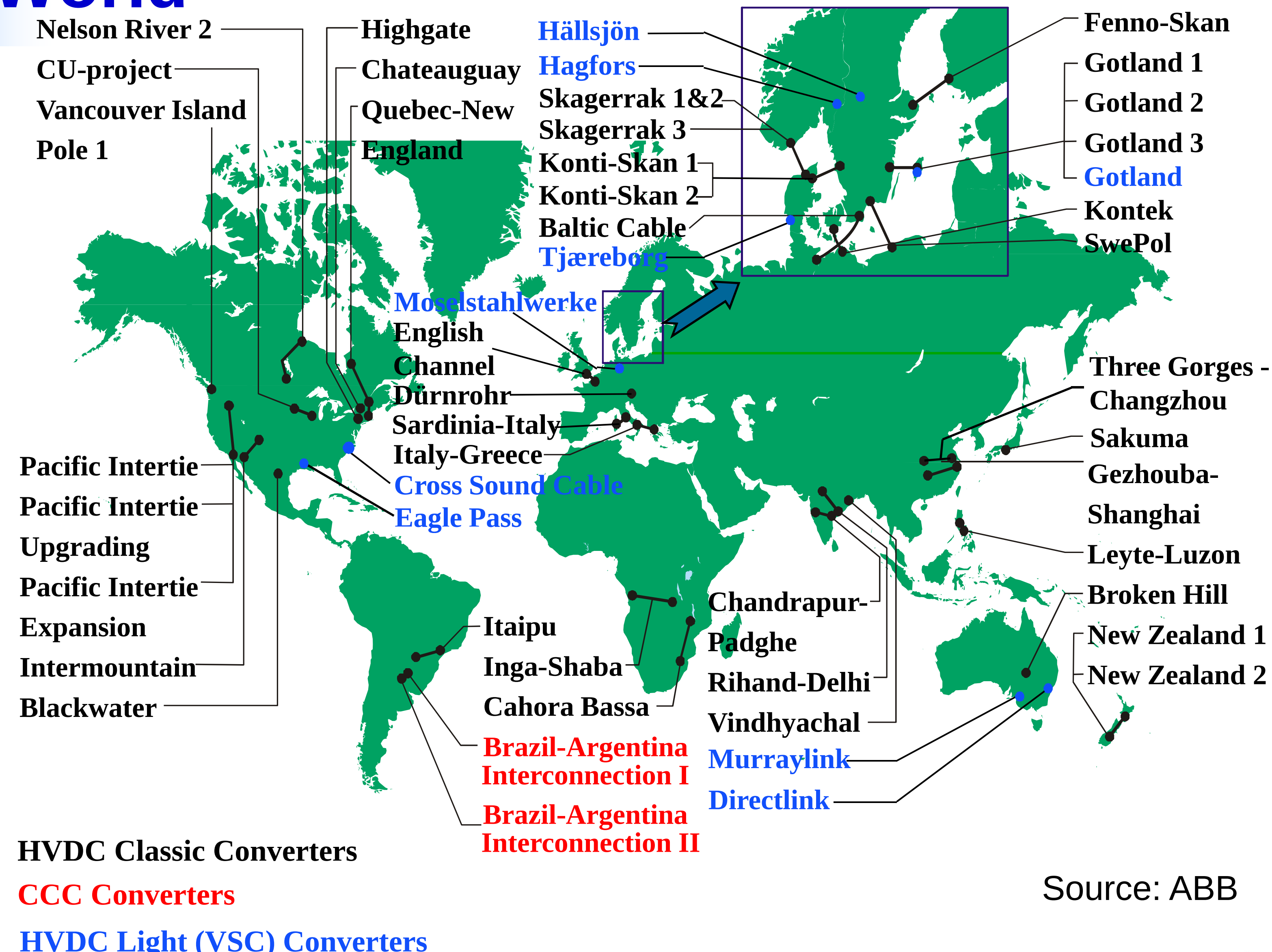


- Point-to-Point Submarine Cable
  - bulk transmission
  - underwater or underground



North American HVDC Stations

Examples of HVDC Projects Around the World



Source: ABB

HVDC Converter Technology: LCC Versus VSC

Line Commutated Converter

(or Current Source Converter)

• Thyristor based

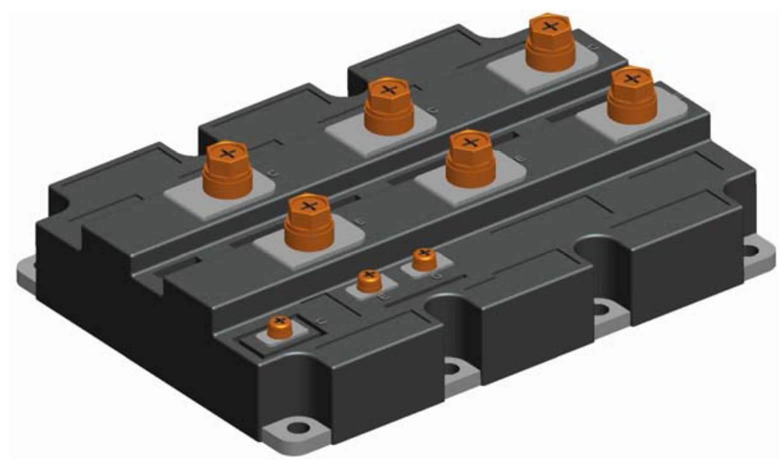
• Switches on-off one time per cycle

Voltage Source Converter

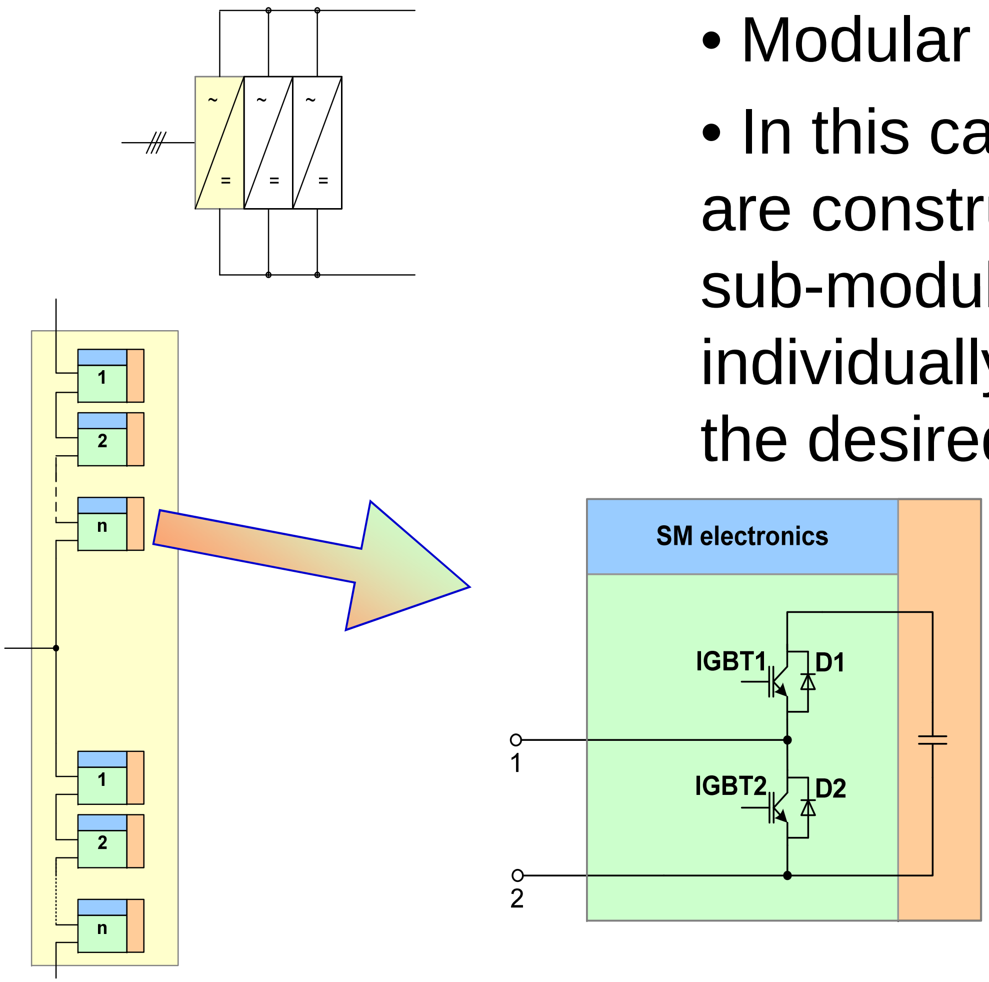
• IGBT Based

(Insulated Gate Bipolar Transistor)

• Switches on-off many times per cycle



VSC : Recent new Topology (MMC)



- Modular Multilevel Converter
- In this case the converter arms are constructed from identical sub-modules that are individually controlled to obtain the desired ac voltage.

Half-Chain Links shown here.

Full-Chain Links can be used to reduce fault currents on DC side

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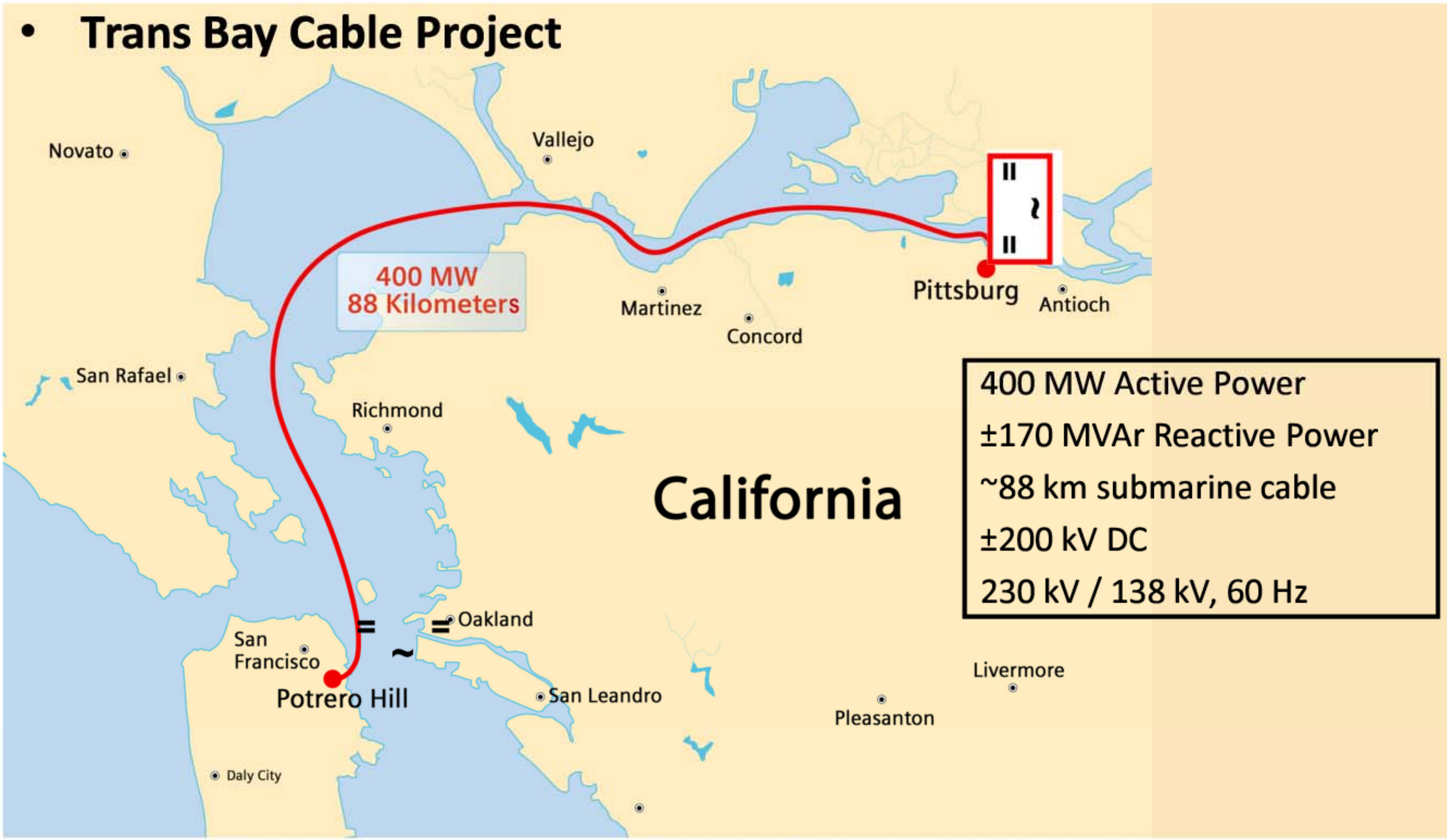
HVDC Converter Technology: LCC vs. VSC

Function	LCC	VSC
DC transmission voltage	Up to +/- 800 kV bipolar operation. 1000 kV under consideration in China	Up to +/- 320 kV currently limited by HVDC cable if extruded XLPE cable is used. Up to +/- 350 kV with Overhead line, can go higher
DC power	Currently in the range of 6000 MW per bipolar system	Currently in the range of 600 to 1000 MW per pole
Off shore wind farms	Can be applied with some dynamic voltage control	Straight forward application
Filtering	Requires large filter banks	Requires moderate size filter banks or no filters at all.

Trans Bay VSC DC Cable

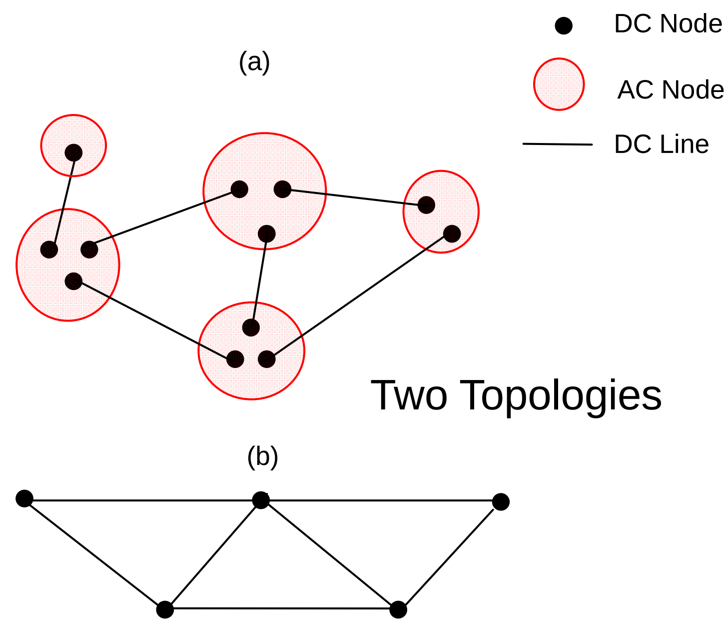


Representative HVDC Submarine Cable Links with Extruded Dielectric

Name of Link	Date	Voltage (kV)	Power (MW)	Length (cable-km)	Max. Water Depth (m)	Type
Cross Sound (CT-NY)	2002	150	330	2 x 42	40	XLPE
Estonia-Finland (Estlink 1)	2006	150	350	2 x 74	100	XLPE
Germany (BorWin1)	2009	150	400	2 x 125	100	XLPE
TransBay (San Fran Bay)	2010	200	400	2 x 88	30	XLPE
Ireland-Wales (Eirgrid)	2012	200	500	2 x 186	120	XLPE
Honshu-Hokkaido 2	2012	250	350	2 x 42	260	XLPE
Germany (DolWin 1)	2013	320	800	2 x 75	100	XLPE
Germany (BorWin2)	2013	300	800	2 x 125	100	XLPE
Germany (HelWin1)	2013	250	576	2 x 85	100	XLPE
Germany (DolWin 2)	2015	320	900	2 x 135	100	XLPE
Sweden - Lithuania	2015	300	700	2 x 453	?	XLPE

DC Grids – The Future of DC Transmission

- DC Grids for Offshore Wind
- Considered more in Europe than in other countries
- Need to resolve many issues
  - Power & Voltage control
  - DC circuit breakers
  - Standard DC voltages
  - Communication needs
- CIGRE WGs



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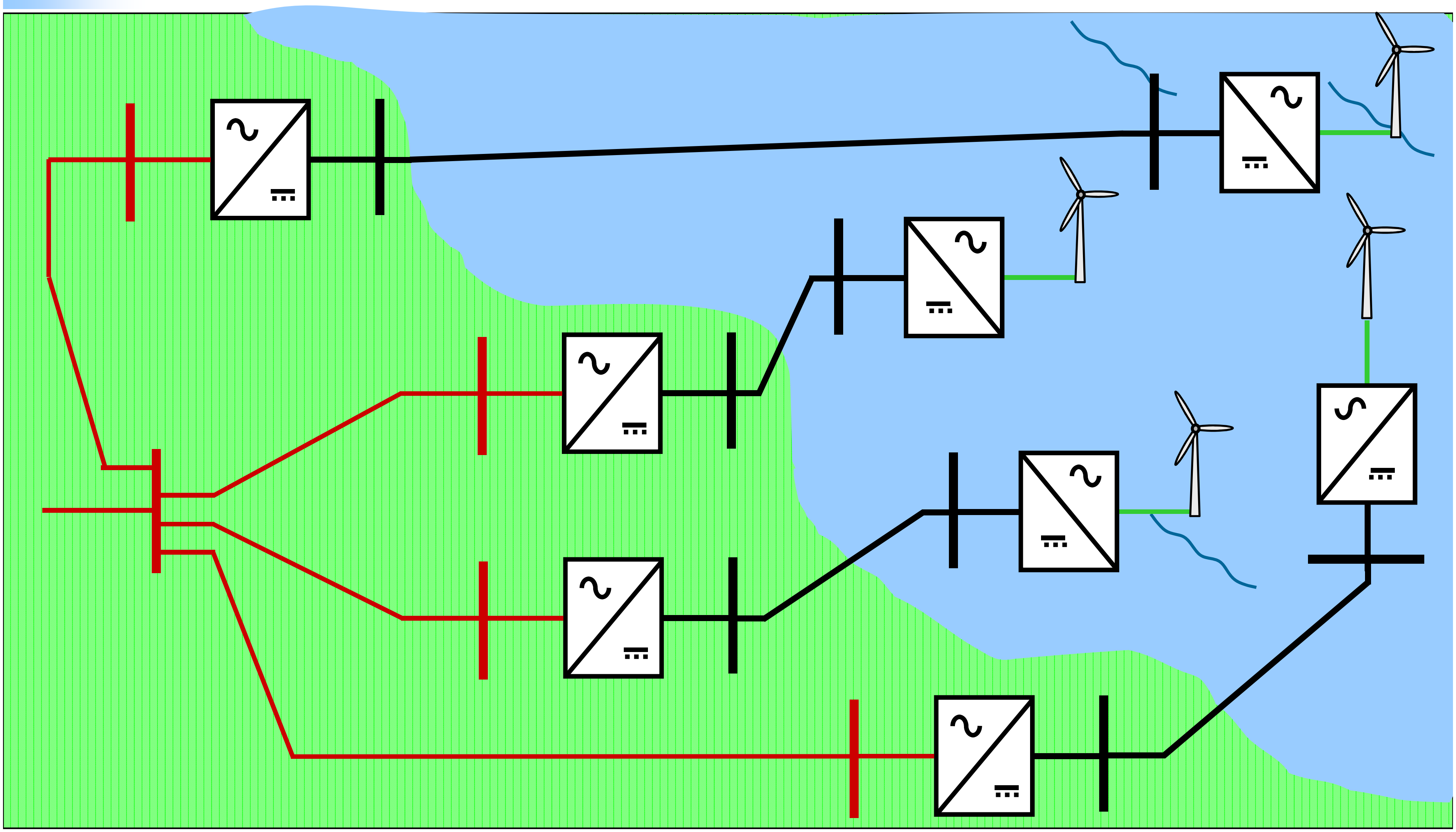
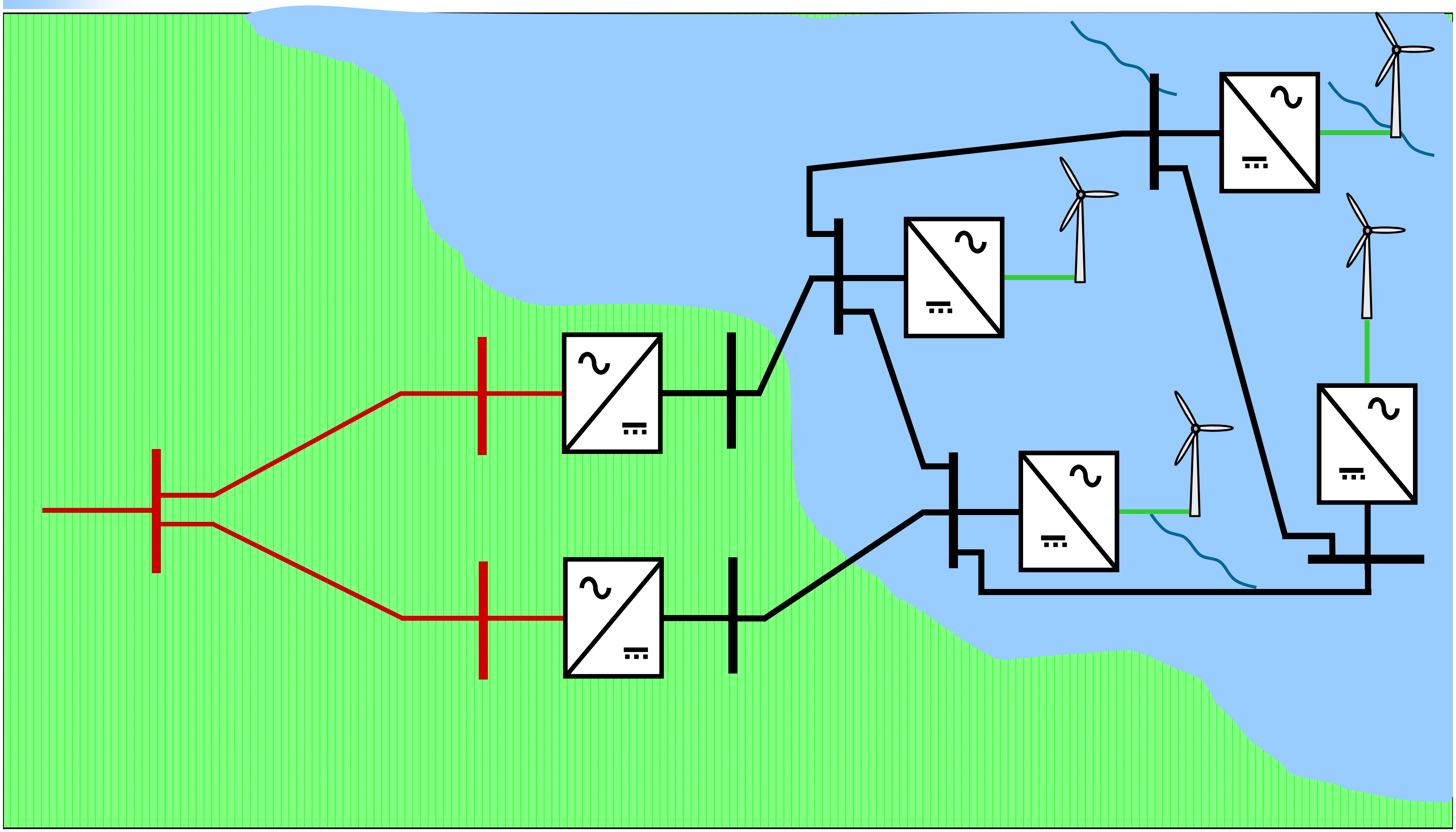
DC Grid Configurations: Offshore Development – Point to Point System



Source: ALSTOM

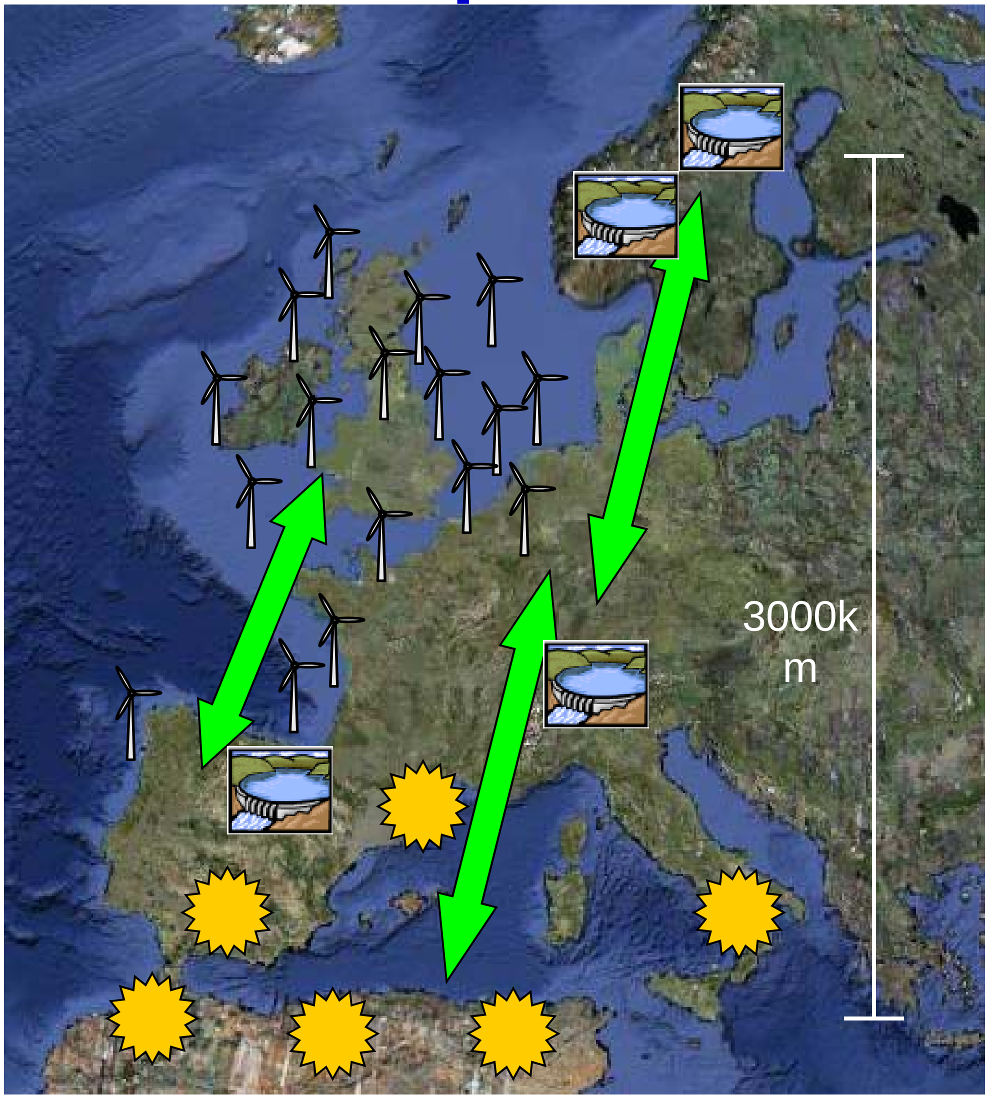
DC Grid Configurations: Offshore Grid System



Source: ALSTOM

Overlay DC Grid Gives Access to Renewable Sources within Europe

- Interconnection of remote renewable energy sources
- Overcoming “bottlenecks” in the existing AC grids
- Low loss (HVDC) transmission systems
- Controllable power flows over a wide area
- Avoidance of synchronisation over a wide area
- Less environmental impact than AC reinforcement



Cigrè B4-52: HVDC Grid Feasibility Study

1 Introduction
2 HVDC grids – concepts and lessons learned from history
3 Available Converter Technologies, VSC and LCC Comparison
4 Motivation of an HVDC grid
5 HVDC grid Configurations
6 Fault Performance
7 Protection Requirements
8 New components in HVDC grid – Including Questionnaires to manufacturers
9 Power Flow Control in DC Grids
10 The Requirements on an HVDC grid – Security and Reliability
11 Needed Standardization
12 New working groups within the HVDC grid area

DC Grid Standardisation Activities

- Cigrè have started five further DC grid working groups;
  - B4-56: Guidelines for the preparation of “connection agreements” or “Grid Codes” for HVDC grids
  - B4-57: Guide for the development of models for HVDC converters in a HVDC grid
  - B4-58: Devices for load flow control and methodologies for direct voltage control in a meshed HVDC Grid
  - B4-59: Protection of Multi-terminal HVDC Grids
  - B4-60: Designing HVDC Grids for Optimal Reliability and Availability performance

A Sample of European Proposals

G. Asplund, B. Jacobson, B. Berggren, K. Lindén "Continental Overlay HVDC-Grid", Cigré conference, B4-109, Paris, 2010

Atlantic Wind Connection

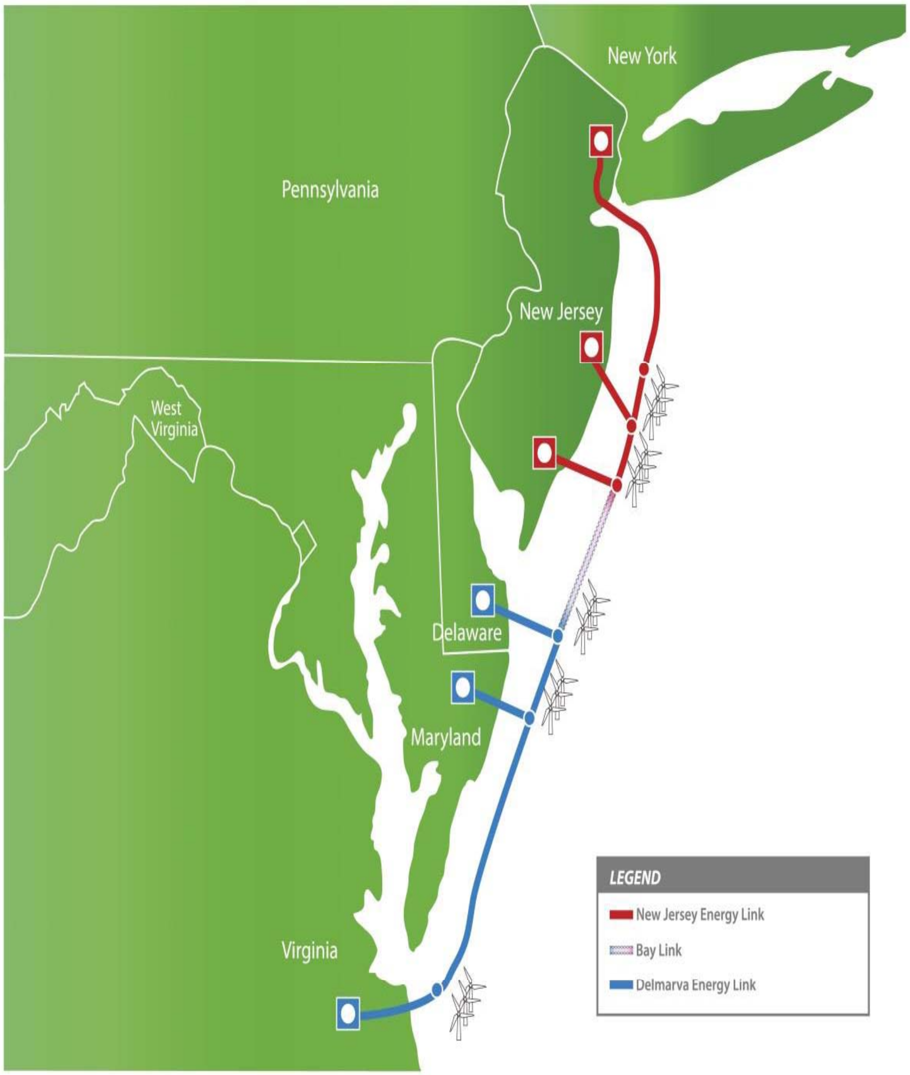
(see: www.atlanticwindconnection.com/ferc/2010-12-filing/Petition_for_Declaratory_Order.pdf)

What
- A sub-sea HVDC backbone transmission system

Where
- Extending from northern New Jersey to southern Virginia.

Who
- Google
- Marubeni
- Good Earth
- Elia

Why
- Serve as an efficient collector of ac power from offshore wind farms
- Relieve transmission congestion on the eastern ac grid
- Improve regional system reliability.



2010 PS36A

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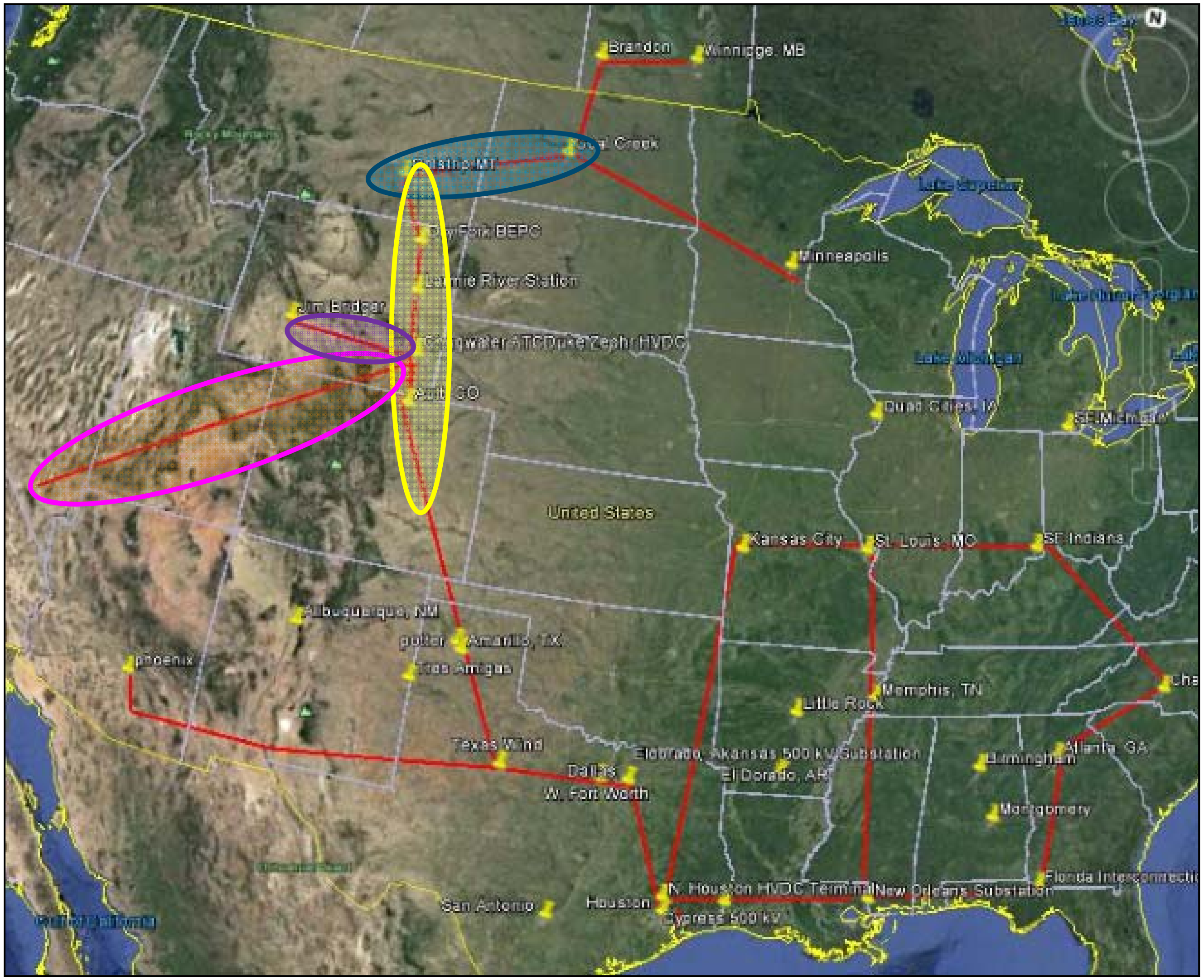
MISO View of a Potential Future HVDC Overlay on North American Grid



Source: Dale Osborn, MISO

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Comparison of AC and DC parameters

AC PARAMETER	DC PARAMETER
Frequency (ω)	Target DC Voltage (Vdc)
Voltage Change $(V \cdot \sin(\delta))$	Voltage Change (ΔV)
Impedance of Connection (X)	Resistance of Connection (R)
Real Power $\dfrac{V \cdot V \cdot \sin(\delta)}{X}$	Real Power $\dfrac{V \cdot \Delta V}{R}$

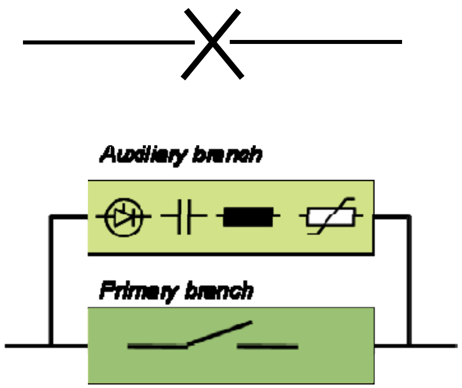
DC Breakers

When closed the DC breaker must have very low losses

- optimum solution mechanical switch

AC

DC



Main switch

Unlike an AC breaker the DC current never experiences a current zero. Hence, to interrupt the DC current the DC breaker must drive the load current to zero.

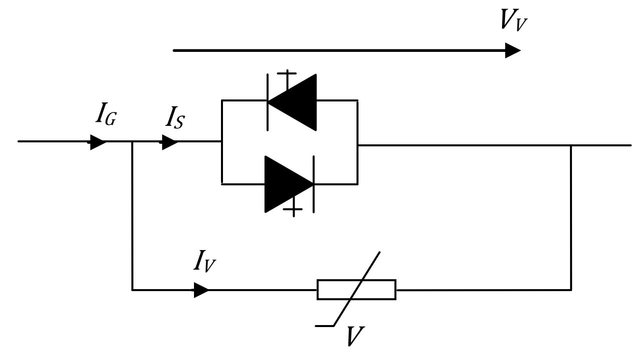
Modular hybrid solution to drive current to zero

- critical component is the mechanical switch as it has to operate **VERY** fast to minimise the peak current to be interrupted by the auxiliary branch

HVDC Circuit Breaker Developments

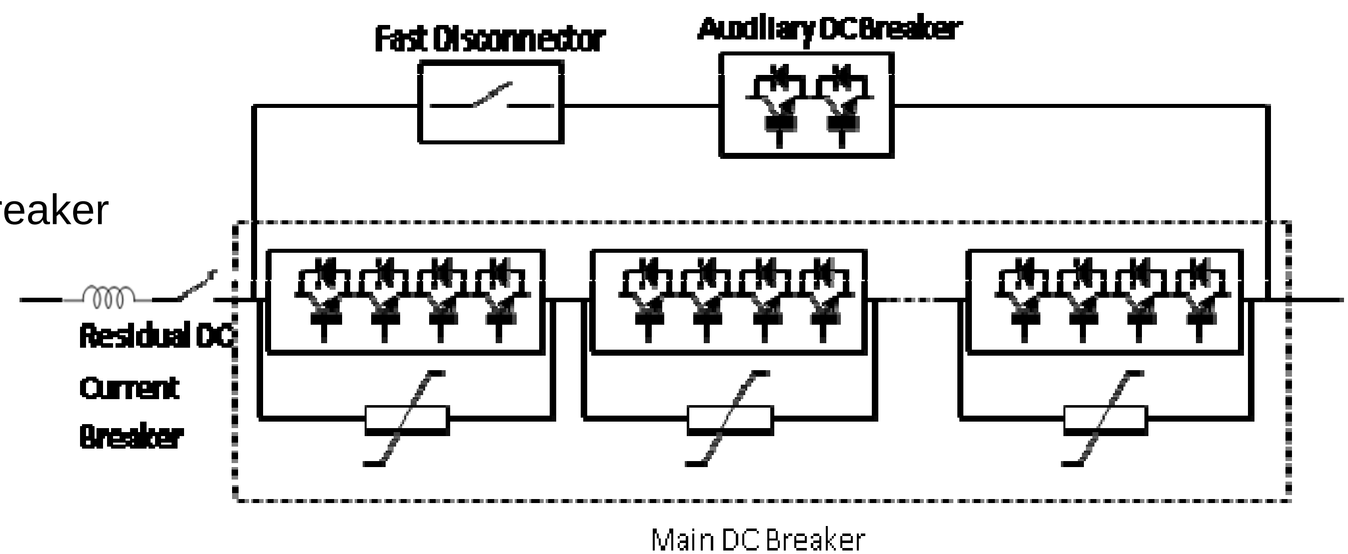
- Many ideas are explored
- Fast growing area
- Numerous R&D projects
- Minimize size, cost, & interruption time

Solid State Circuit Breaker



New Hybrid Circuit Breaker

Source: ABB



Current State of HVDC versus HVAC

- Many Existing HVDC systems are old (30 - 50 years old)
  - Life extension is taking place
- Highest DC Voltage is UHVDC at +/- 800 kV in China & India
  - South Africa & Brazil are also considering
  - For long distances over 3000 km
  - For Bulk Power Transfer (3000 to 6000 MW)
- UHVDC of +/- 1000 to 1100 kV is planned in Asia for up to 8000 MW - China & India
- VSC HVDC is increasing (+/- 320 kV up to 1000 MW)

- Max AC Voltage in North America is 765 kV (EHVAC)
- UHVAC (1000 kV to 1200 kV) is considered in China (highest in the world)

Future Trends in HVDC

- For transfers of above 6,000 MW over 4,000 km, the optimum voltage rises to 1,000–1,200 kV.
  - Technological developments in LCC converter stations seem to be ready to handle these voltages.
- HVDC and HVAC overlays for regional interconnections
- Segmenting AC grids with DC back-to-backs for improved reliability
- Growth of VSC DC applications – more dc cable projects
- DC Grids for renewable integration

Materials for HVDC and FACTS Devices Silicon - SiC - GaN

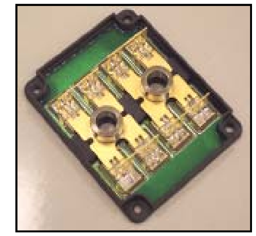
- Silicon - presently used

- Future Candidates - Wide Bandgap Materials
  - Silicon Carbide (SiC)
  - Gallium Nitride (GaN)

- DOE is funding SiC & GaN work
  - ARPA-E with CREE Inc for 15 to 20 kV SiC Modules

- EPRI is participating in NSF Industry / University Research Center – GRAPES (GRid-connected Advanced Power Electronic Systems)

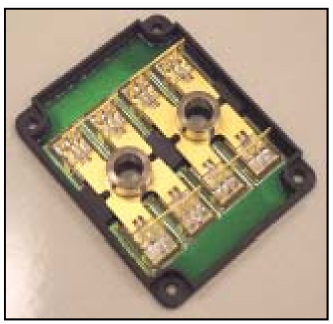
Advanced Power Electronics



Addresses fundamental research required for advances in PE materials

Silicon

- Widely available
- Low cost



Super GTO Switch
2007 R&D 100 Award

Silicon Carbide

- High operating temperature
- Lower switching losses

Silicon Carbide + Gallium Nitride

- Higher Temperature
- Higher Voltage
- Optical switching

New power electronics materials enable newer applications and benefits

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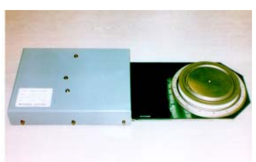
Technical Innovations – *Power Electronics*

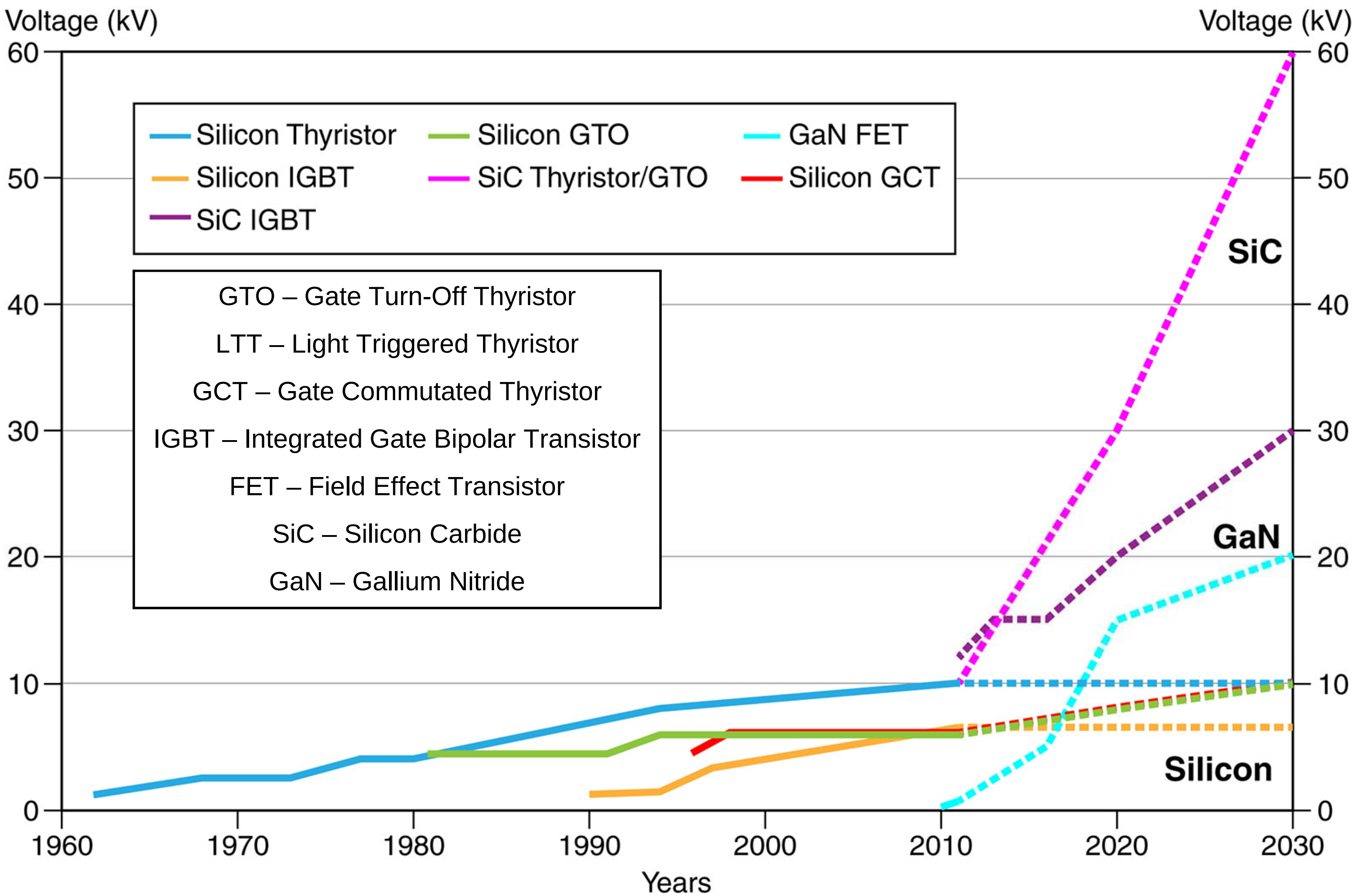

Thyristor


GTO


LTT


GCT


IGBT



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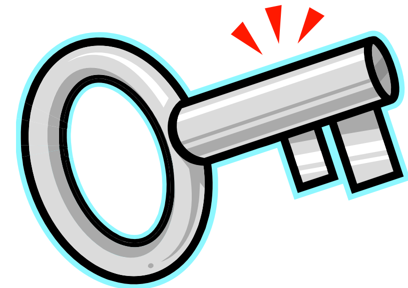
In Conclusion



HVDC & FACTS are key technologies for:

- Integration of renewables such as wind and solar with interconnections to the main grid
- Future SMART Electric Grid
- Reducing system losses and increasing efficiency
- Reducing carbon footprint
- Enhancing quality of life

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Together…Shaping the Future of Electricity