HVDC LEARN

Modules for Maturing HVDC Electric Transmission Knowledge

Funded by the US Department of Energy (DOE)
within the Office of Energy Efficiency & Renewable Energy (EERE)

HVDC-Learn Short Course

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Module 7a: Point to Point HVDC Systems

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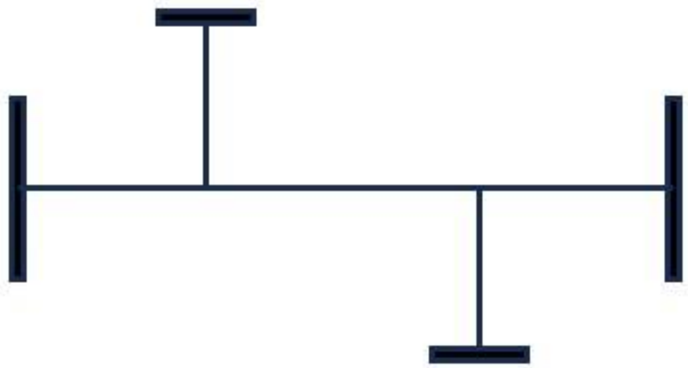
Overview

1. **Introduction**
2. **Point-to-point (PTP) design features**
   - Converter types
   - Electrical configurations
   - Components for LCC PTP systems
   - Components for VSC PTP systems
3. **PTP applications:**
   - Overhead
   - Asynchronous interconnections
   - Underground & submarine
   - Atlantic offshore design
   - Macrogrid design
4. **Summary of main learning points**

1. Introduction

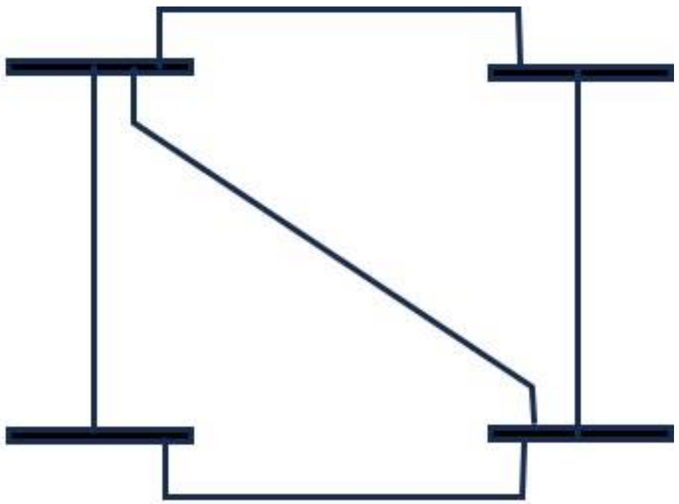
(a) PTP Line

A PTP HVDC line, also referred to as two-terminal HVDC system, is an HVDC transmission system consisting of two HVDC transmission substations (also referred to as converter stations) and the HVDC transmission line(s) between them.



(b) Multiterminal Line

A multiterminal HVDC system as one that consists of more than two separated HVDC converter stations together with the interconnecting HVDC transmission lines. A multiterminal line is, then, when the additional converter stations are arranged along a single HVDC line; i.e., a multiterminal line is not meshed.



(c) DC Grid

A DC grid is a meshed multiterminal HVDC system, i.e., a multiterminal system for which the topology contains one or more loops

<u>Objective</u>: characterize PTP HVDC designs.

1. Introduction

WIKIPEDIA
The Free Encyclopedia

Search Wikipedia

https://en.wikipedia.org/wiki/List_of_HVDC_projects

List of HVDC projects

Legend [edit]

Converter technology:

- Thury = Series-connected generators as designed by René Thury
- Merc = Mercury-arc valve rectifier and inverter
- Thyr = Thyristor rectifier and inverter
- IGBT = Insulated gate bipolar transistor
- BIGT = Bi-mode insulated gate transistor[1]
- IEGT = Injection enhanced gate transistor[1]

Line status:

- Existing
- Under construction
- Planned
- Decommissioned

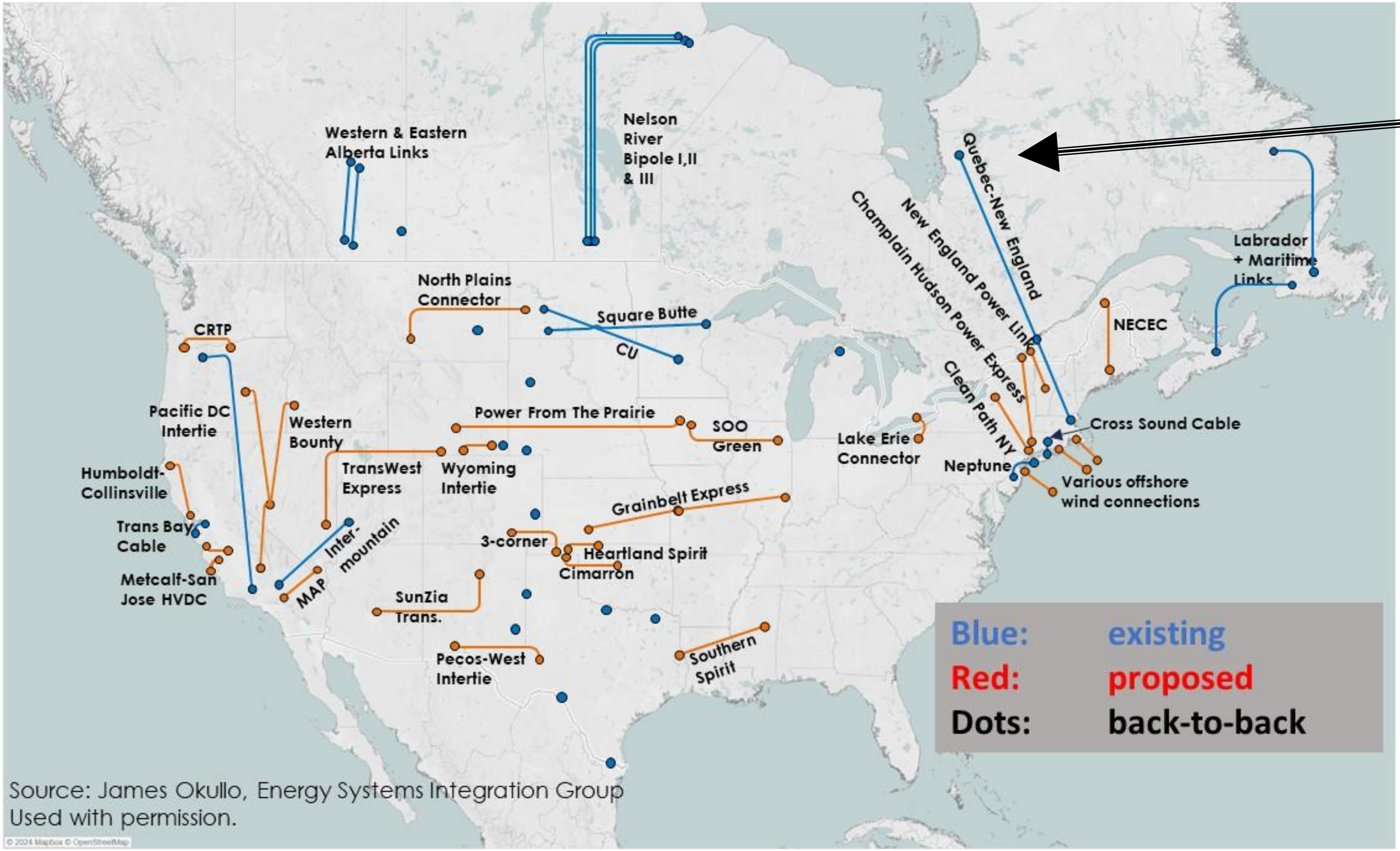
Africa [edit]

Name	Converter station 1	Converter station 2	Total Length (Cable/Pole) (km)	Nominal Voltage (kV)	Power (MW)	Year	Type	Remarks

- Originally developed by IEEE HVDC/FACTS subcommittee
- 233 projects listed (8/1/24)
  - 226 are PTP
  - 6 are multiterminal
  - 1 is DC grid (China)
  - DC grid, 4 multiterminal built post-2013

➔ Although multiterminal & grids are increasing, almost all HVDC systems today are PTP

1. Introduction: N. American HVDC Existing & Planned Projects



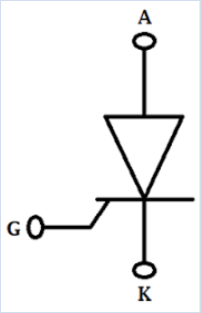
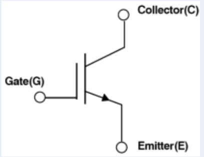
- This one is multi-terminal
- All others are PTP

1. Introduction: DC Grids & protection

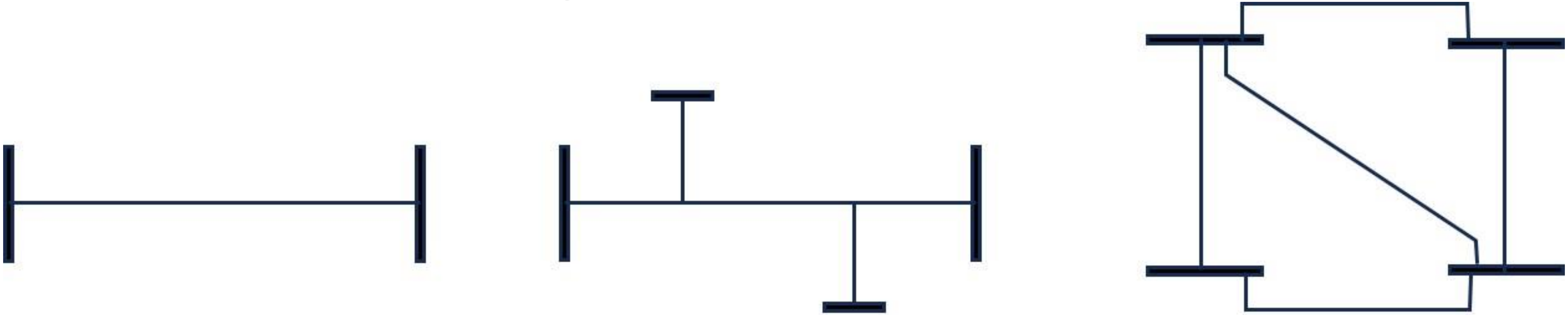
- From MISO 2024 Cost Estimation Guide,
  - AC CBs are cheap, \$400k (230 kV), \$500k (345 kV), \$1.5M (765 kV)
- DC CBs are expensive (\$25M each?)
- AC CB opens on current 0 whereas DC CB breaks full fault current.
- If HVDC system is single protection zone (entire DC system in or out), then isolation is performed entirely on AC side with “cheap” AC CBs.
- This is:
  - Acceptable for PTP systems
  - ~OK for multiterminal systems.
  - Not OK for DC grids (can be thinkable if fault occurrence very rare)

➔One reason for predominance of PTP systems in HVDC

2. PTP design features: converter type

Name 1	Name 2	Technology	Circuit symbol	Commu-tation	High-capacity bipole system	Reactive power
Current source converter (CSC)	Line compensated converter (LCC)	Thyristor		Line	6400 MW at ±800 kV	Absorbs only
Voltage source converter (VSC)		Insulated gate bipolar transistor (IGBT)		Self	2000 MW at ±320 kV	Absorbs & supplies

2. PTP design features: converter type



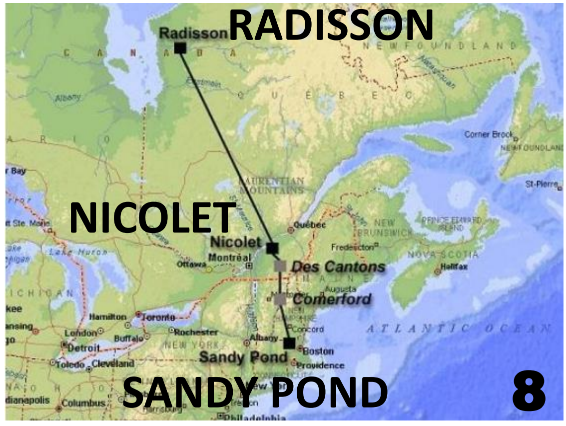
(a) PTP Line (b) Multiterminal Line (c) DC Grid

PTP can be either LCC (thyristors) or VSC (with IGBTs).

- Thyristors are unidirectional current devices.
- LCC-based systems must do polarity reversal to reverse power flow.
- Aside: Almost all multiterminal lines & all DC grids use VSC; otherwise, one polarity reversal changes flow direction on more than one line.
- The exception is the LCC Radison-Sandy Pond/Nicolet multiterminal line, but two terminals are fixed polarity:

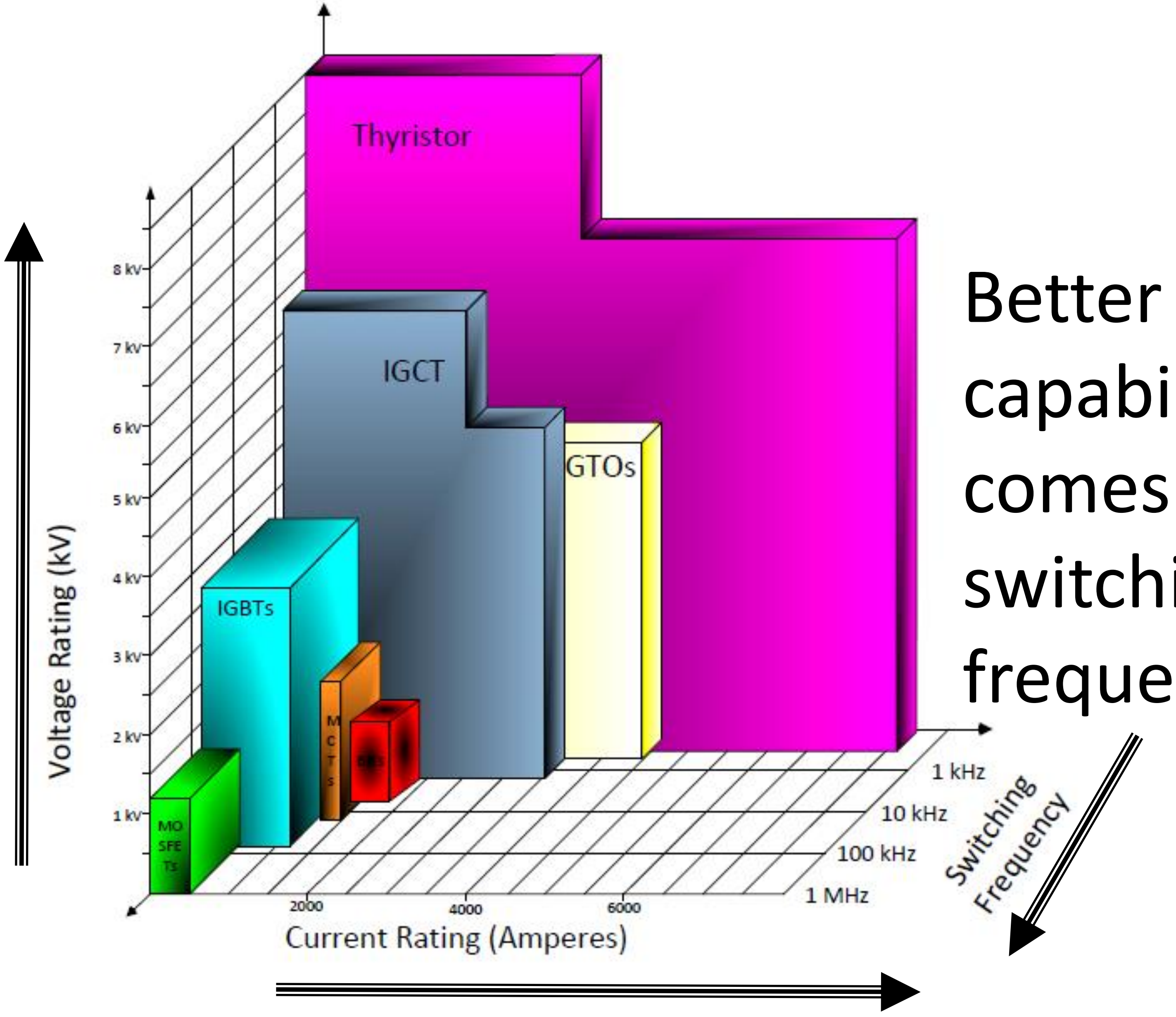
➔Radisson is rectifier, SandyPond is inverter; Nicolet changes polarity.

IEEE Transactions on Power Delivery, Vol. 5, No. 4, November 1990
Report of a panel discussion at the 1988 PES Winter Meeting, New York
sponsored by the Working Group on Multiterminal
DC Systems of the IEEE/PES DC Transmission Subcommittee



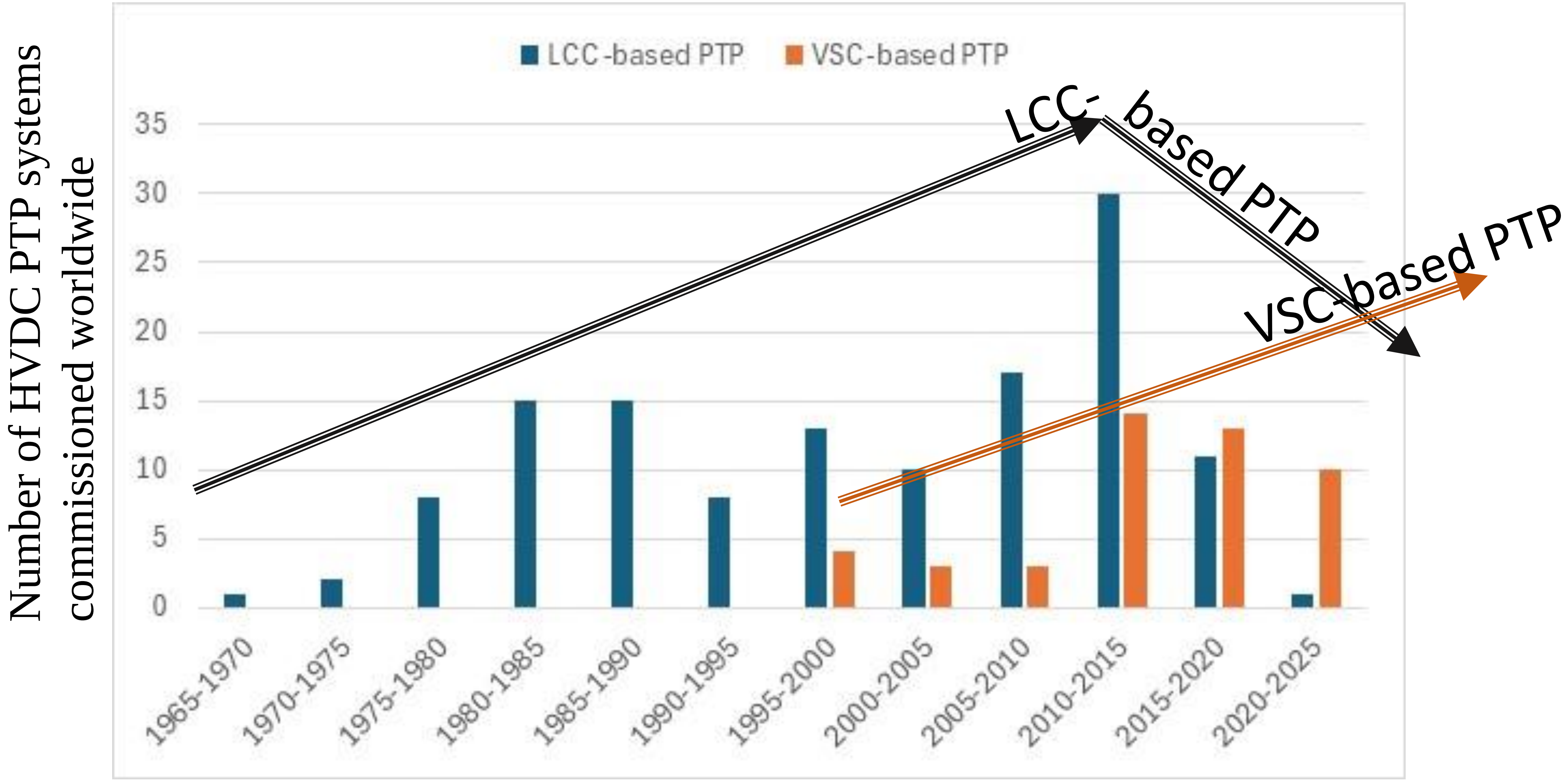
2. PTP Design features: converter type

Power handling capabilities proportional to height (V_{RATED}) & width (I_{RATED})

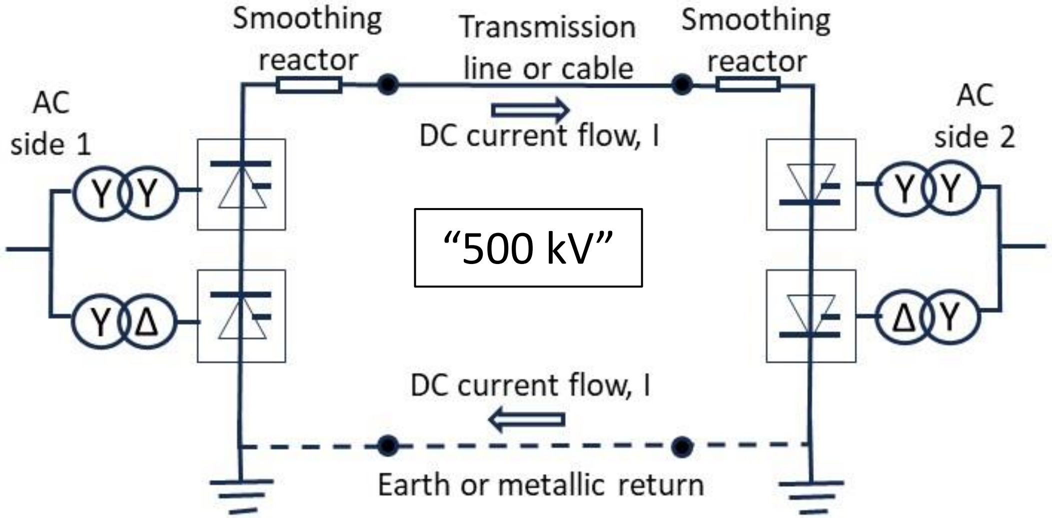


Better control capability comes w/higher switching frequency

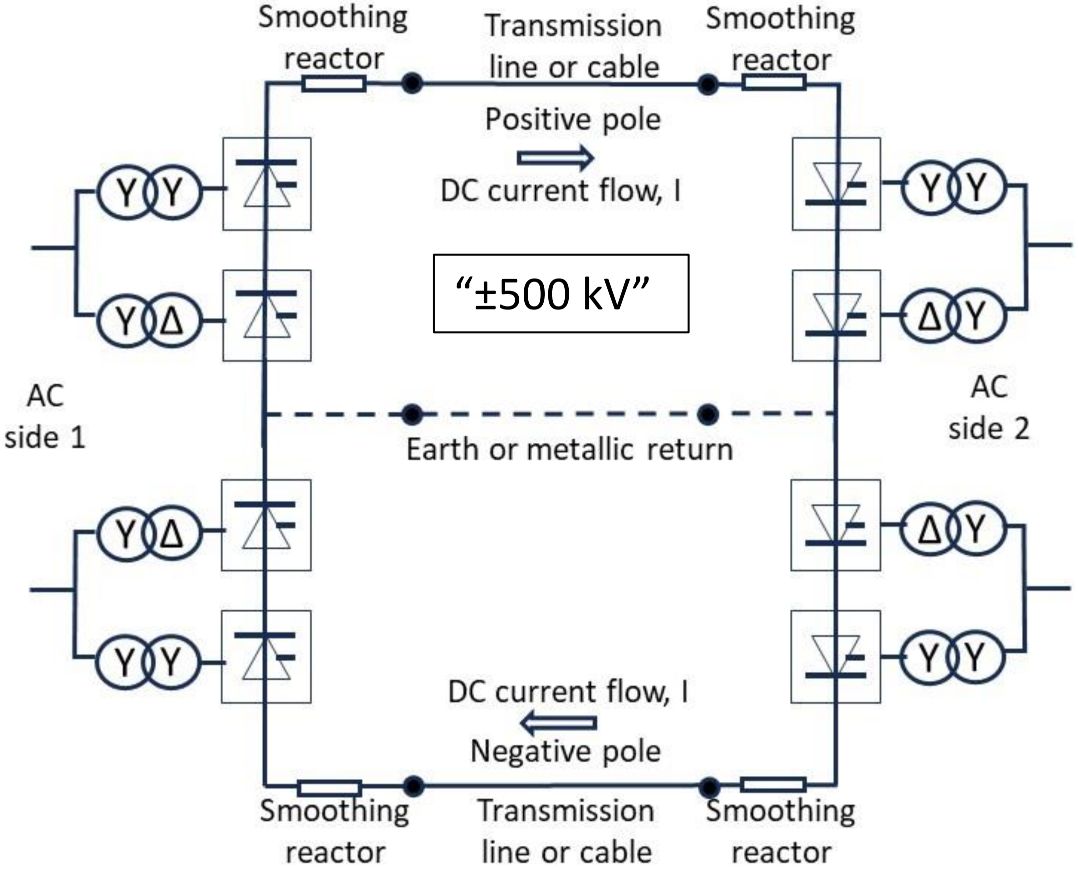
2. PTP Design features: converter type



2. PTP Design features: electrical configuration – LCC systems



(a) Asymmetric monopolar configuration



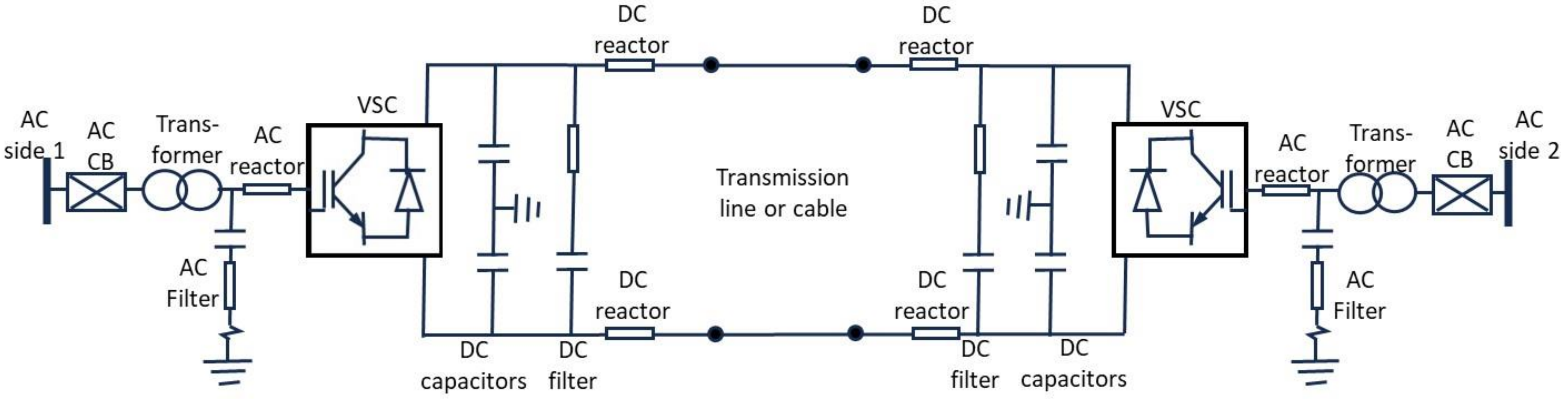
(b) Bipolar configuration

- **Monopole: 1 converter; Transfer capacity=$V_{RATED}I_{RATED}$**
- **Asymmetrical: 1 path at transmission voltage; other at ground.**

- **Bipole: 2 converters; Transfer capacity=$2 \times V_{RATED}I_{RATED}$**
- **Operates as asymmetrical monopole under pole fault, but NEC limits use of earth return to maintenance conditions to avoid risk of step & touch potential.**

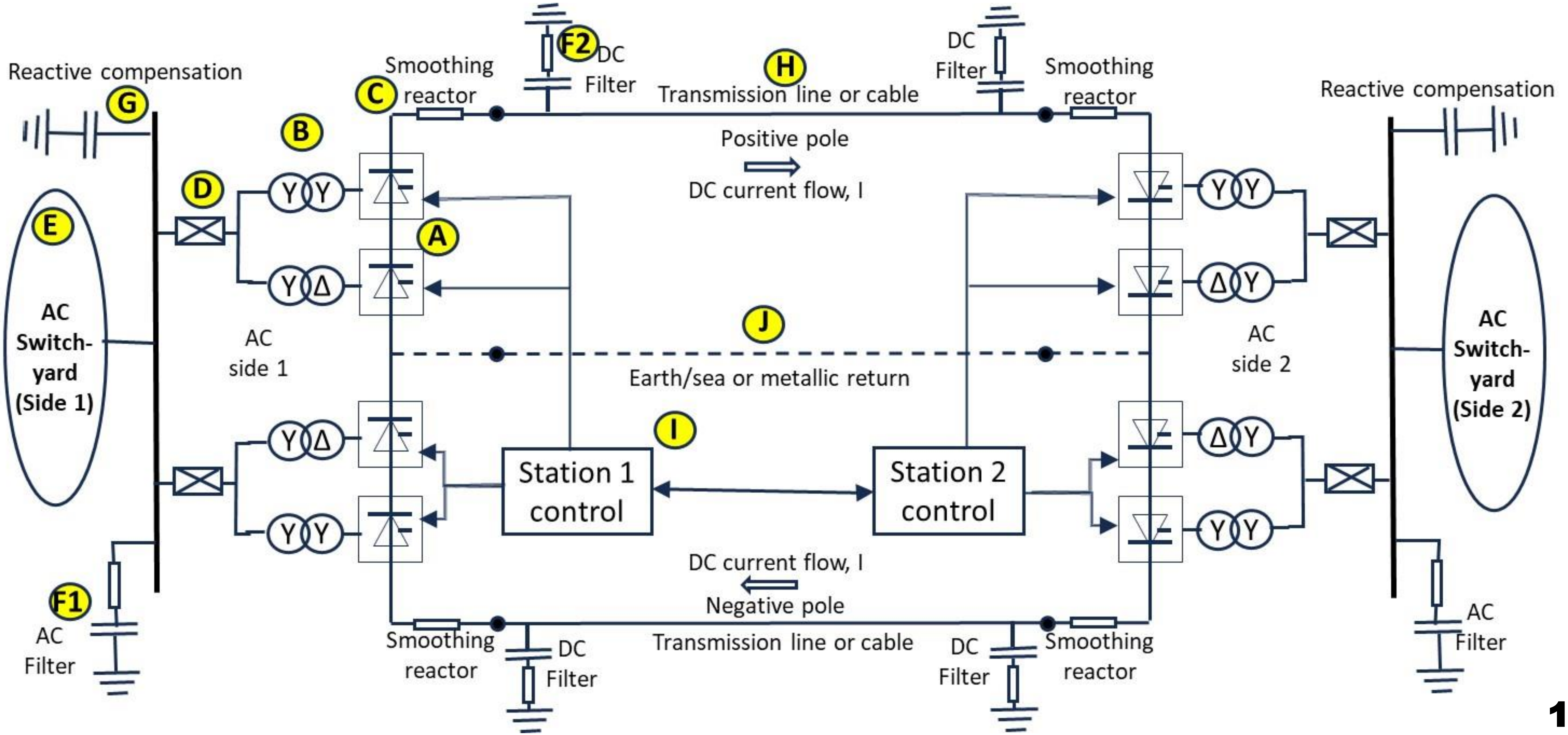
2. PTP Design features: electrical configuration – VSC systems

VSC systems can be used in asymmetric monopole and bipole configurations, but their lower capacity fits lower capacity undergrnd/undersea apps, requiring cables limited to 320 kV. A symmetric monopole design obtains 640 kV pole-to-pole voltage to double power transfer without violating cable rating, but unlike bipolar configuration, which uses 2 converter systems, it trades reliability for cost by using only 1 converter system operating as a single unit.

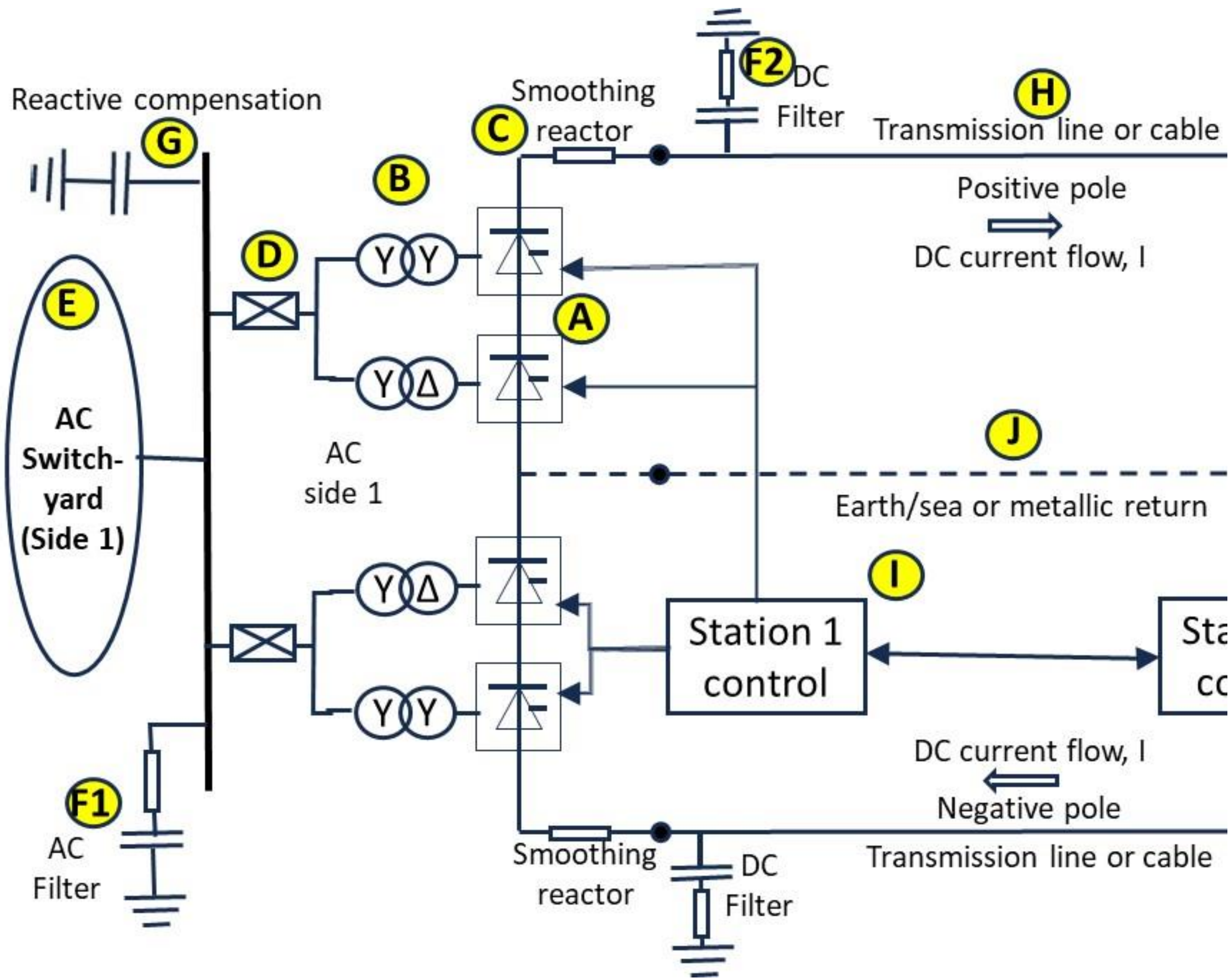


Symmetric monopolar configuration

2. PTP Design features: components for LCC PTP systems, Two-terminal view



2. PTP Design features: components for LCC PTP systems, One-terminal view with component identifications



<u>COMPONENT IDENTIFICATIONS</u>:

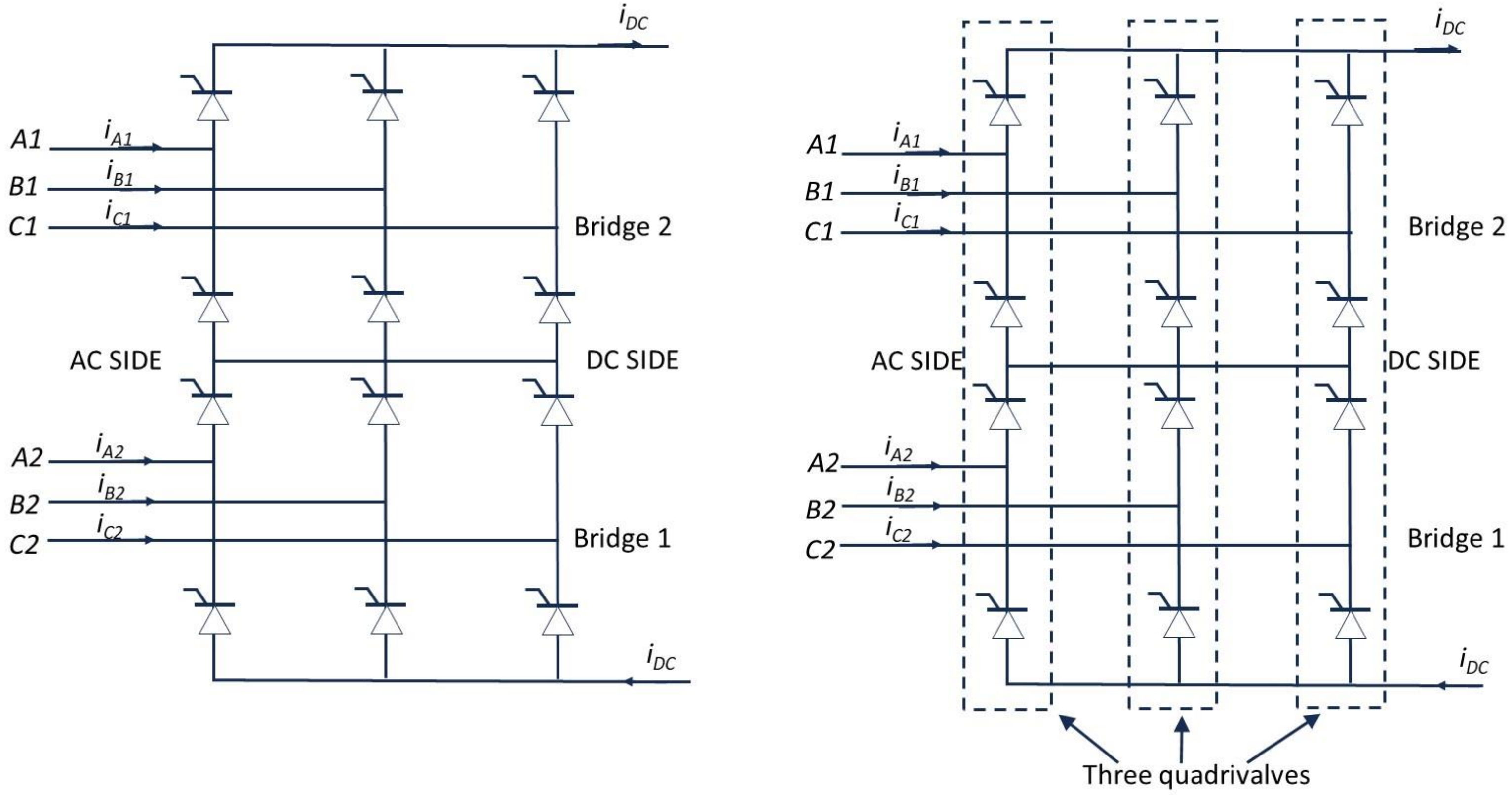
A. Converter unit
B. Converter transformer
C. Smoothing reactors
D. Circuit breakers & switching
E. AC switchyard
F. AC and DC Filters
G. Reactive power compensation
H. Conductor system
I. Control & communication sys
J. Electrodes&Earth/sea metallic return

2. PTP Design features: components for LCC PTP systems

A. Converter Units

Thyristor/IGBT: basic element in a converter unit;
Valve: package of elements (may be single element);
Converter: arrangement of valves together w/control scheme to provide conversion between AC & DC.

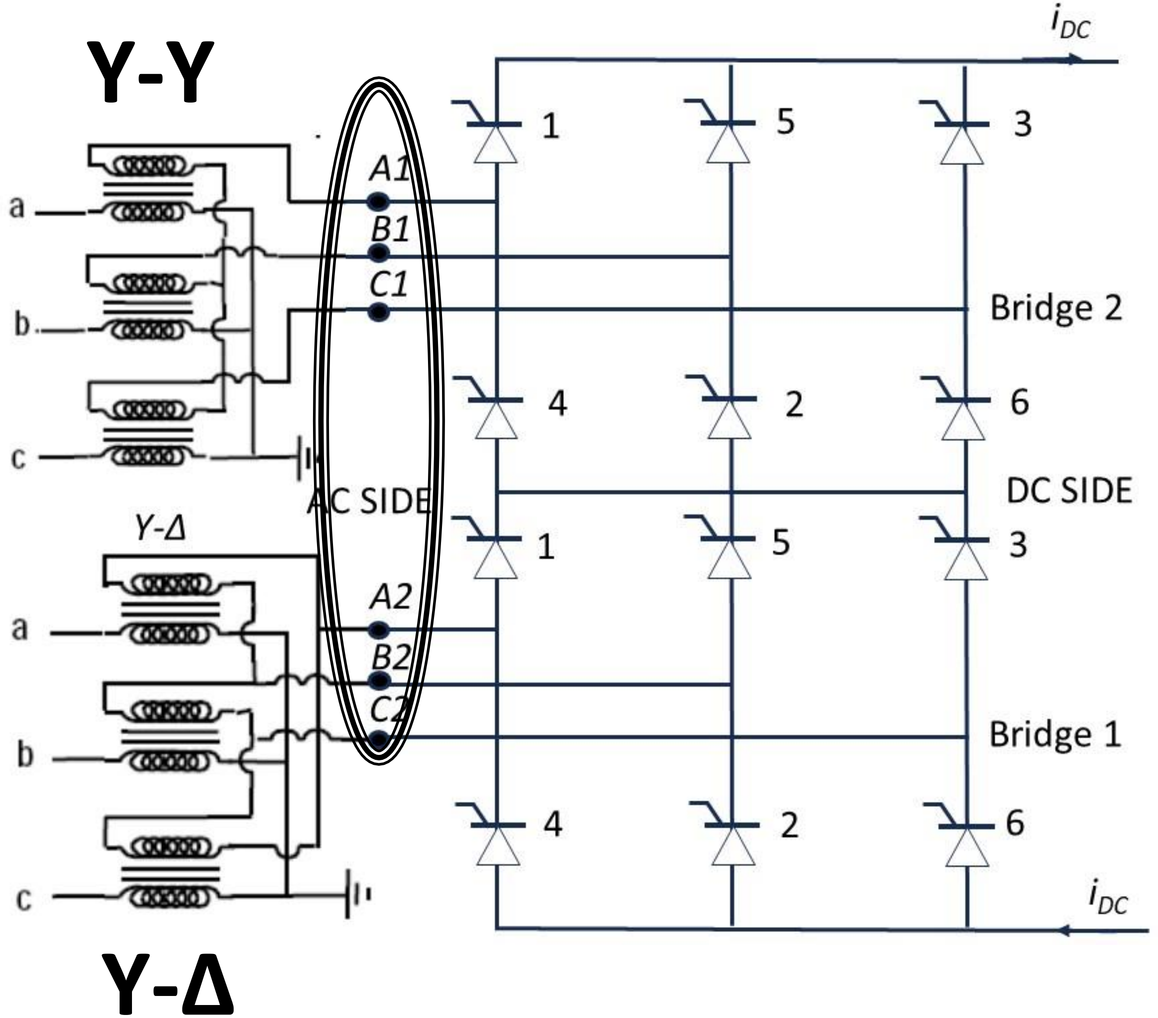
12-pulse converter using single device package (left) and quadrivalves (right)



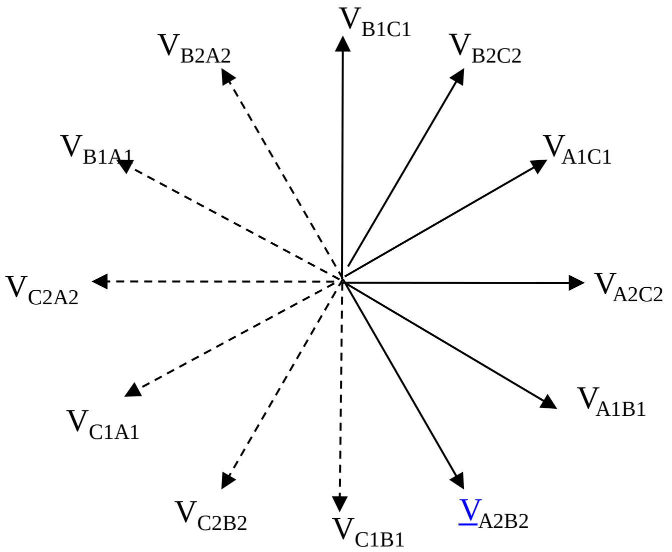
2. PTP Design features: components for LCC PTP systems

B. Converter transformer

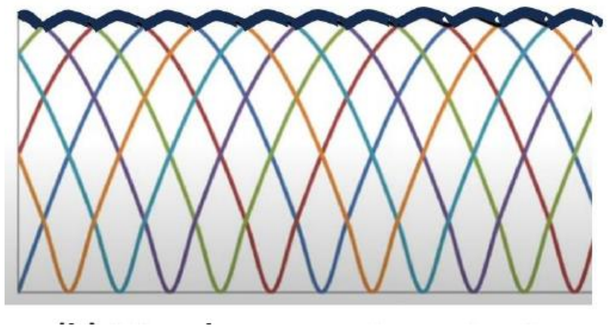
Secondary line-to-line voltages of bottom xfmr lag secondary line-to-line voltages of top xfmr by 30º



Gives voltage phasor sequence (CCW rot) seen at bridge input.



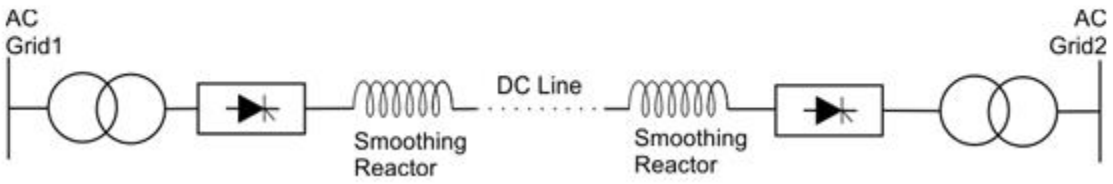
Firing sequence {5,6},{6,1},{1,2},{2,3},{3,4},{4,5} results in desired DC output.



2. PTP Design features: components for LCC PTP systems
C. Smoothing reactor (DC reactors)

Inductors w/large *L* ➔ DC-side tends towards constant current source (and thus the name CSC), since large *L* makes small $di(t)/dt$ [$di(t)/dt=(1/L)\,v(t)$].

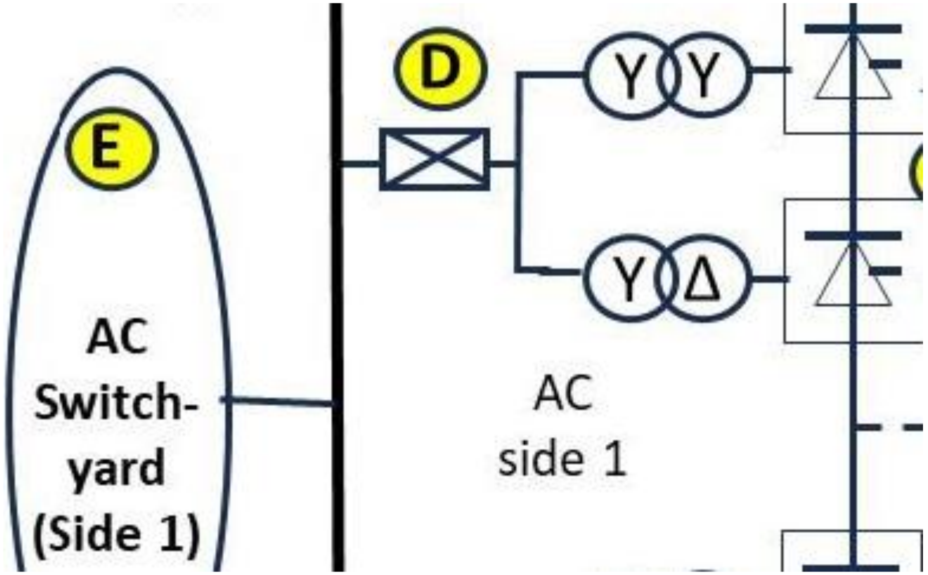
This limits rate of DC current rise under DC- or AC-side fault conditions,
and reduces DC-side harmonics.



2. PTP Design features: components for LCC PTP systems
D, E. Circuit breakers and switching

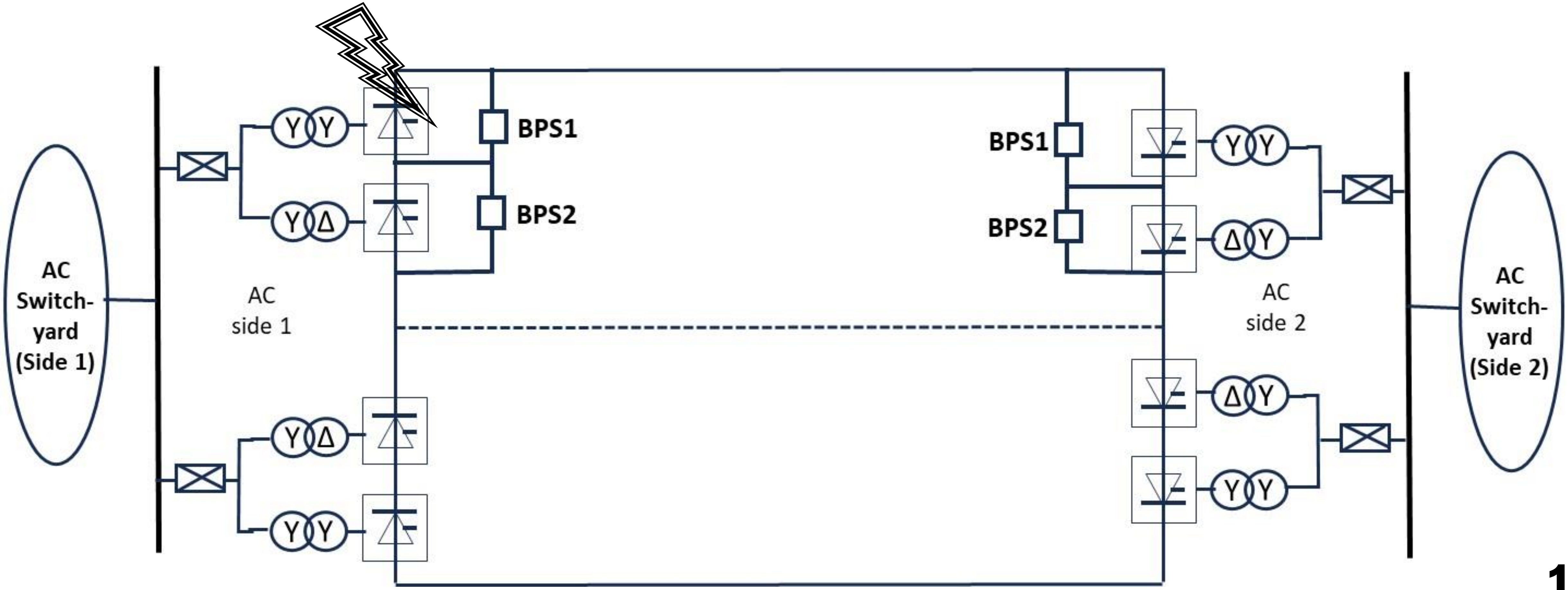
For PTP systems:

1. AC-side (item E)
   - AC switchyard CBs: standard AC CBs for faults in AC grid.
   - Converter pole CBs (CPCBs, item D): for isolating HVDC system for any faults on converter side of CB.
2. Reconfiguration switches (not labeled in our HVDC figure): They operate following fault isolation by CPCBs to enable continued use of HVDC system.



2. PTP Design features: components for LCC PTP systems
D, E. Reconfiguration switches

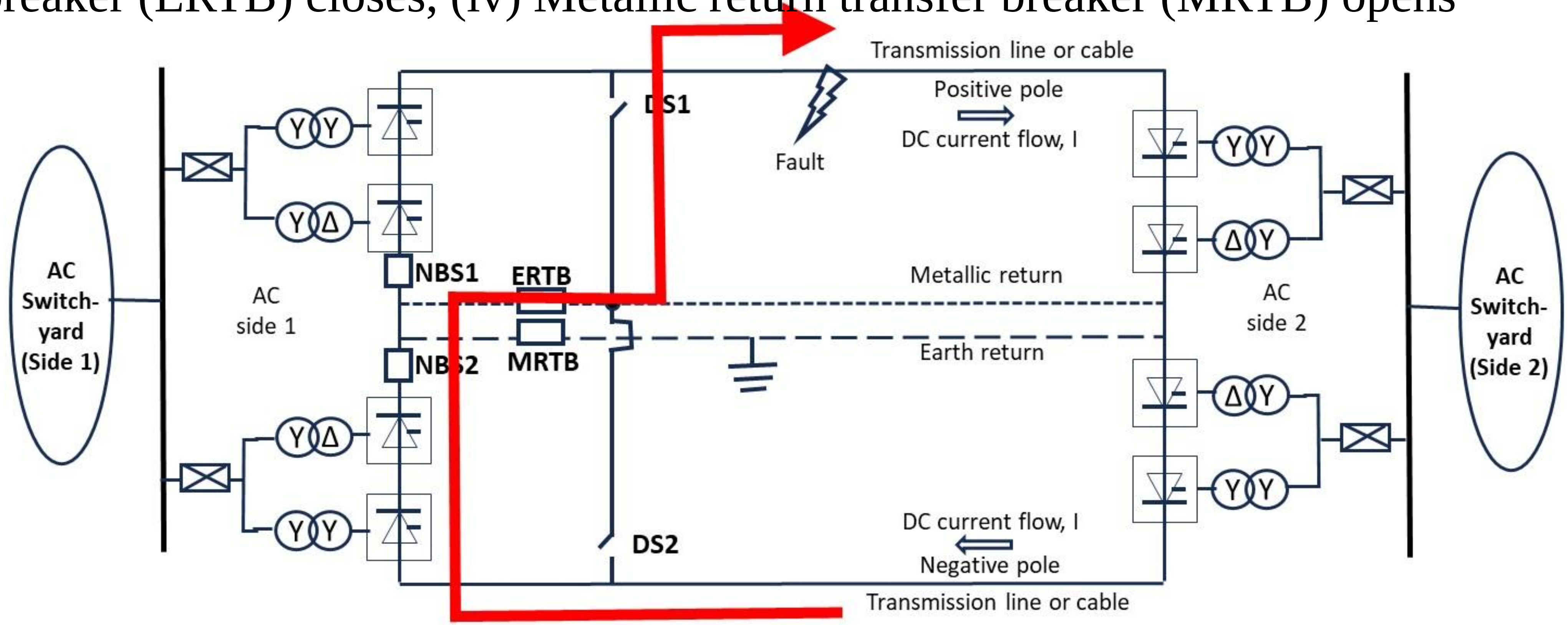
(a) Bridge faults: For fault on bridge k, close normally open bypass switch BPSk. Converter then operates as 6-pulse.



2. PTP Design features: components for LCC PTP systems
D, E. Reconfiguration switches

(b) Pole faults: Use the (lower-impedance) faulted pole as a grounded return, and operate as an asymmetric monopole.

(i) Neutral bus switch (NBS)1 opens, (ii) Disconnect switch (DS)1 closes, (iii) Earth return transfer breaker (ERTB) closes, (iv) Metallic return transfer breaker (MRTB) opens



2. PTP Design features: components for LCC PTP systems

D, E. Reconfiguration switches

4112 IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 10 October 1982

A NEW DC BREAKER USED AS METALLIC RETURN TRANSFER BREAKER

A. L. Courts J. J. Vithayathil
Bonneville Power Administration
Portland, Oregon

N. G. Hingorani J. W. Porter
Electric Power Research Institute
Palo Alto, California

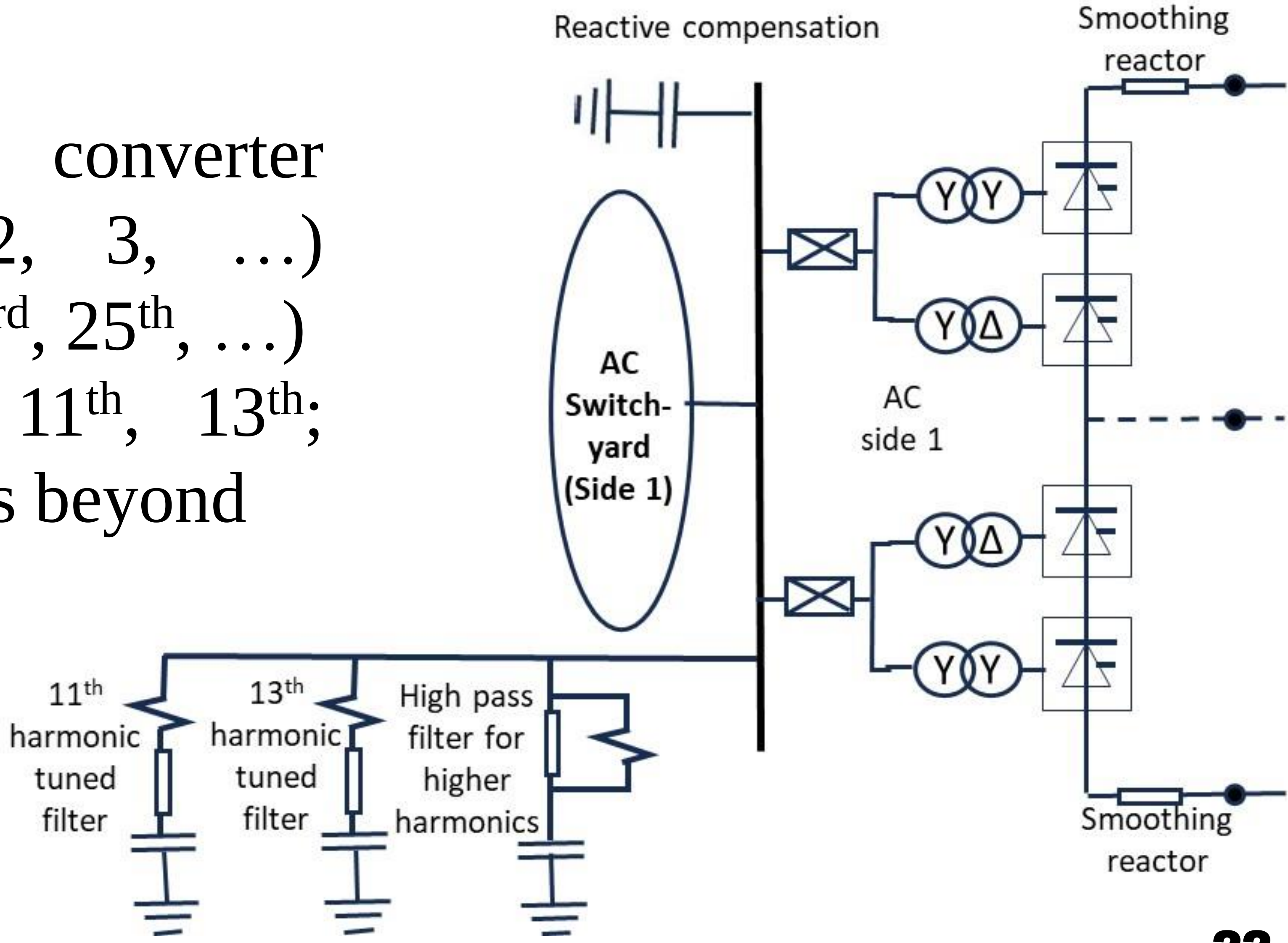
J. G. Gorman C. W. Kimblin
Westinghouse R&D Center
Pittsburgh, Pennsylvania

"When a bipolar HVDC transmission system is operating monopolar using the earth as a return path, it is often desired to divert the return current from the earth to the line from the unused pole. To do so requires either that the system be shut down temporarily or that a dc circuit breaker be used. This paper describes the development of such a new dc circuit breaker, and its application on the Pacific Intertie as a Metallic Return Transfer Breaker (MRTB)."

2. PTP Design features: components for LCC PTP systems

F1. AC filters

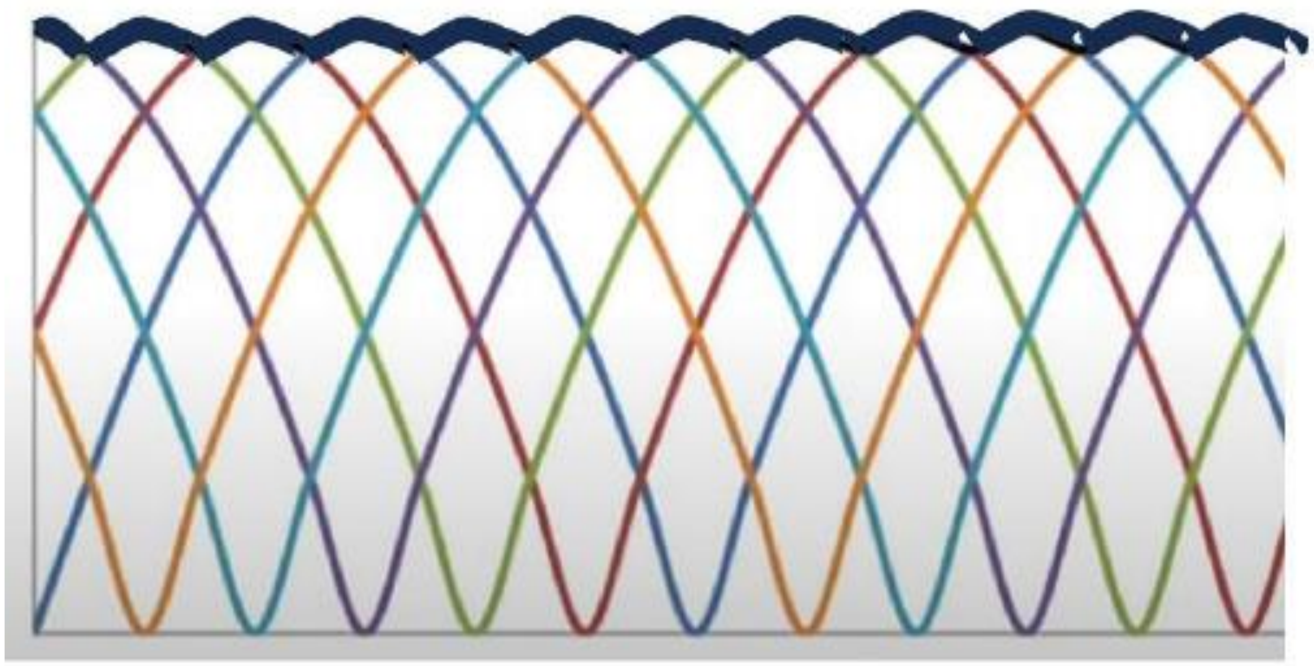
- Y-Y/Y-Δ 12-pulse converter generates 12k±1 (k=2, 3, …) harmonics (11th, 13th, 23rd, 25th, …)
- Tuned filters address 11th, 13th; high-pass filter addresses beyond

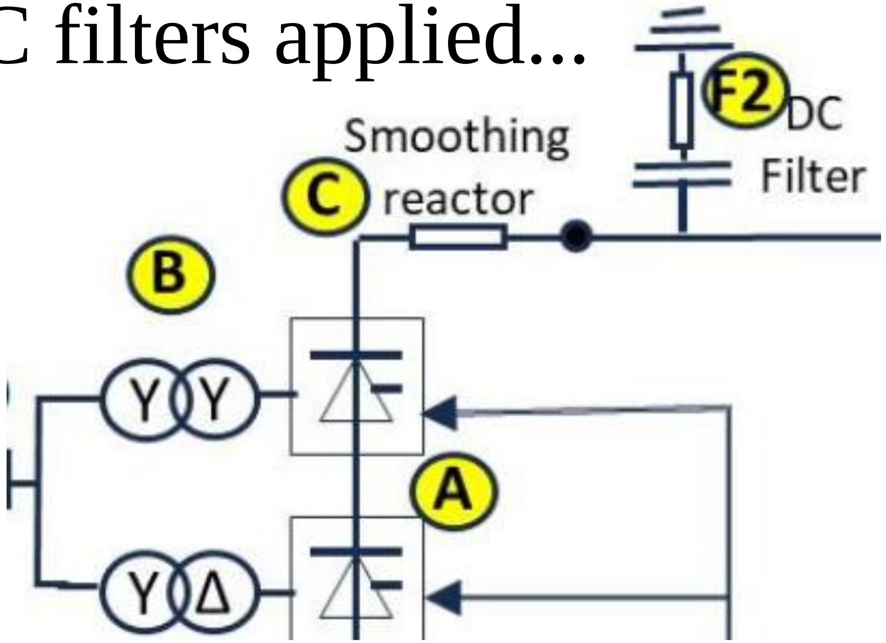


2. PTP Design features: components for LCC PTP systems

F2. DC filters

- DC waveform from 12-pulse converter clearly has harmonics
- Those harmonics create time-varying magnetic fields that interfere with wireline communications
- So DC filters applied...





2. PTP Design features: components for LCC PTP systems
G. Reactive power compensation

LCC is line commutated, i.e., thyristor control only turns it “on” but it is turned off by the circuit (or the “line”).

➔Current initiation in each thyristor can only be delayed with respect to the zero crossing of voltage,

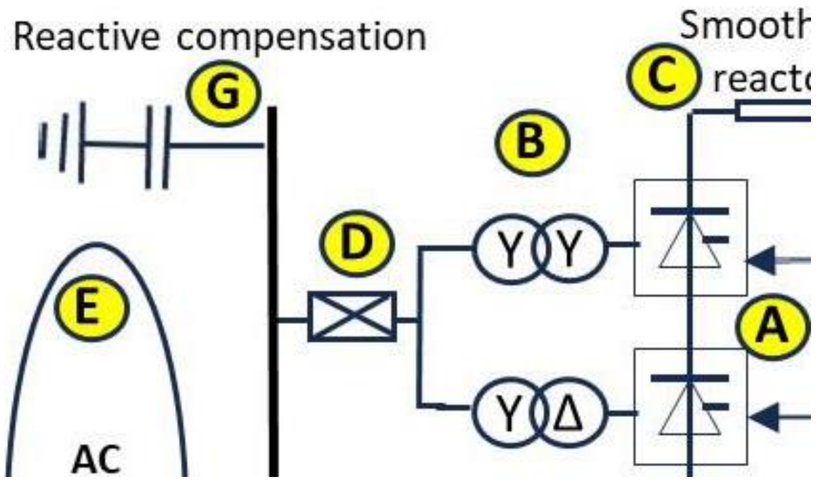
➔Current must lag corresponding voltage,

➔Lagging power factor for rectifier & inverter,

➔Rectifier & inverter are reactive sinks,

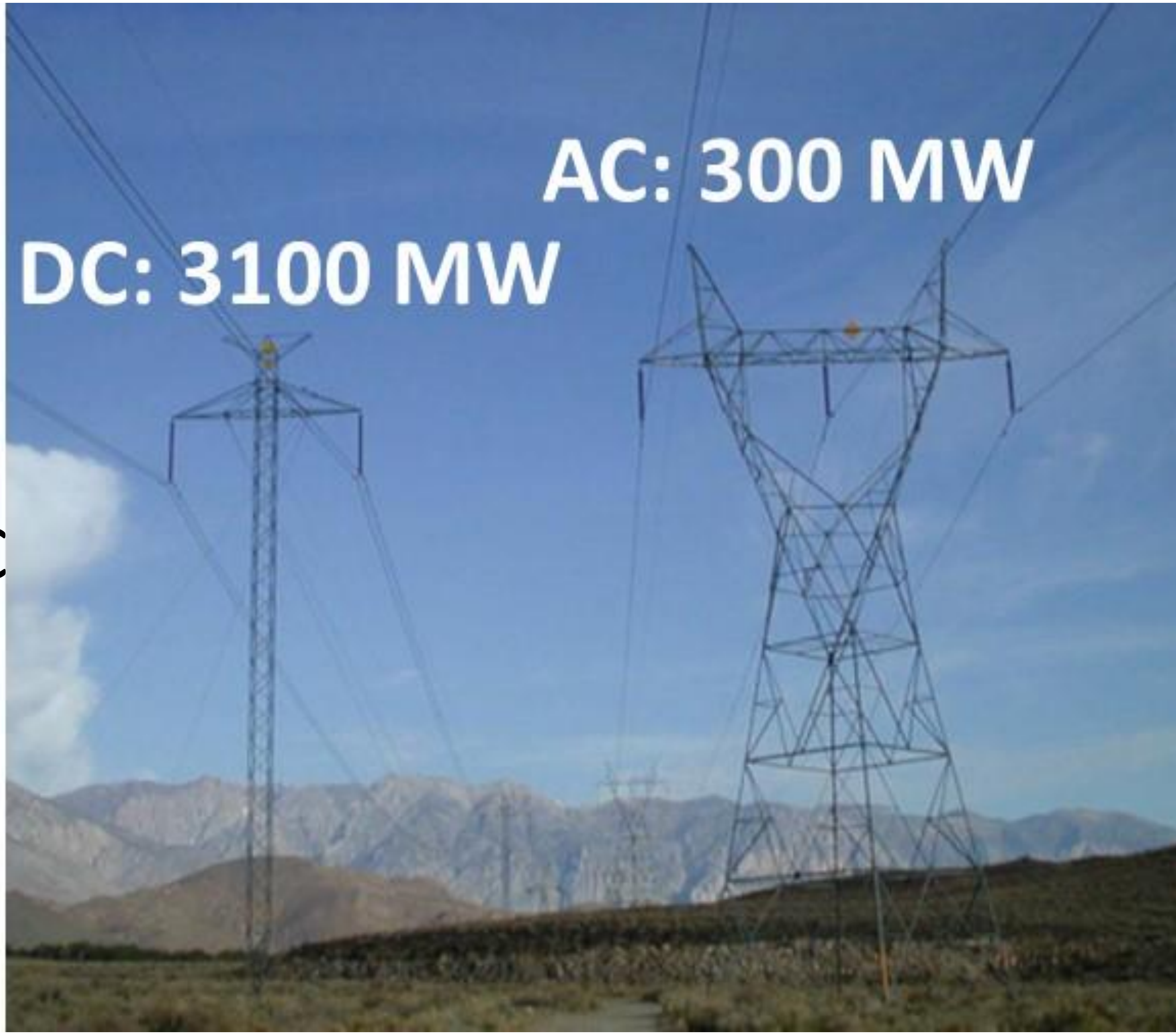
➔Rectifier & inverter require compensation.

➔PTP systems have at least 1 cap bank dedicated to var compensation.



2. PTP Design features: components for LCC PTP systems
H. Conductor systems: overhead

- Uses AAC or ACSR
- 2-conductor bundle doubles MW rating & decreases corona
- Ten times transfer capability of 345 kV line but less ROW!
- For same pwr xfer & voltage, HVAC losses≈2.2×HVDC losses,
  - ✓ # of phases vs # of poles
  - ✓ Current density $I_{RMS,AC}=1.15\times I_{DC}$
  - ✓ Skin effect: $R_{AC}=1.1\times R_{DC}$



2. PTP Design features: components for LCC PTP systems
H. Conductor systems: underground cables

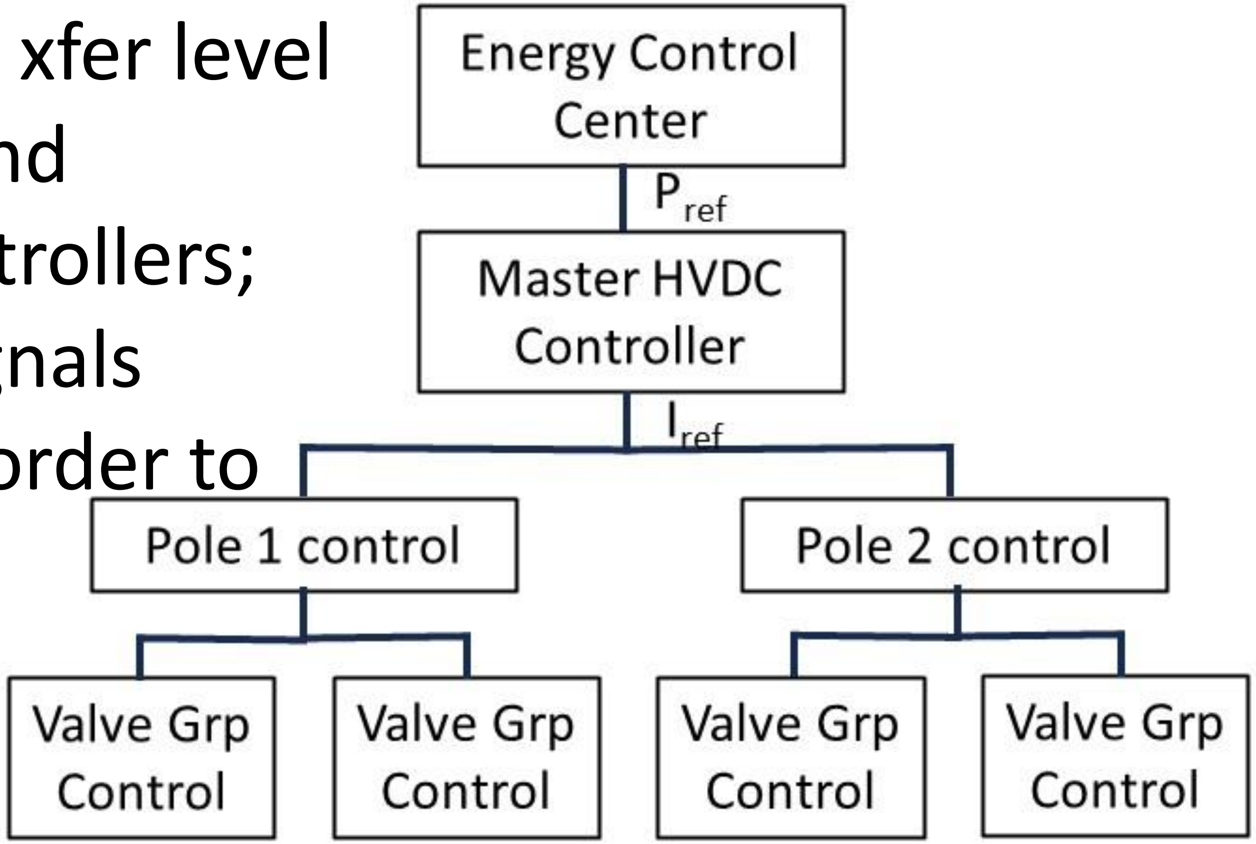
Two types of cables:

- XLPE (extruded), but cannot withstand polarity reversal required for bi-directional LCC systems due to space-charge accumulation that heavily increases E-field, resulting in insulation failure
- So most common for LCC is mass impregnated (MI)

2. PTP Design features: components for LCC PTP systems

I. Control & communication system

- ECC provides directionality & MW xfer level
- Master controller computes I_{REF} and communicates it to poles 1, 2 controllers; may also provide other control signals
- Pole controllers send firing angle order to valve group controllers



- Valve group (converter) controllers oversee firing logic applied to each valve group

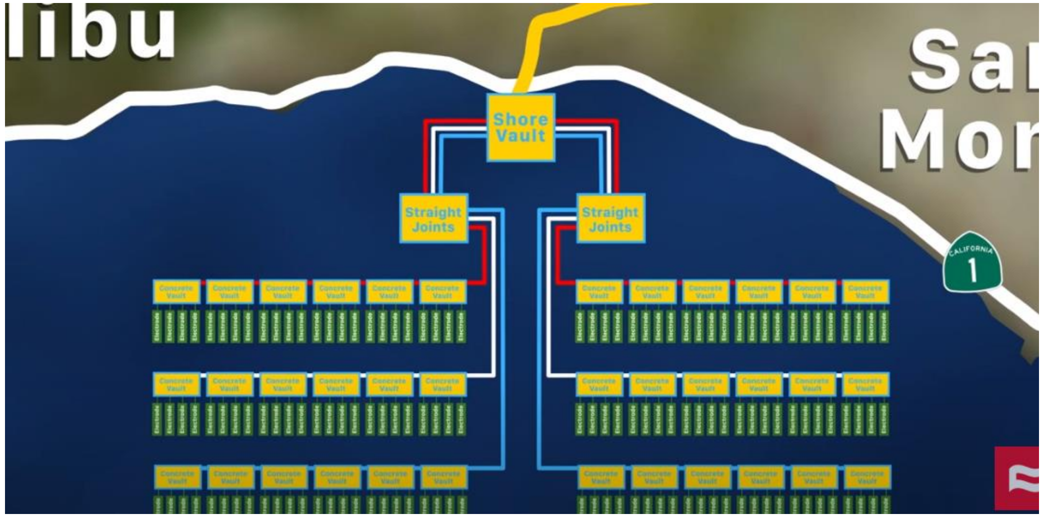
2. PTP Design features: components for LCC PTP systems
J. Electrodes and earth/sea/metallic return

If an HVDC system uses an Earth or a Sea return, then they must have electrodes.

- Earth electrodes: 100-meter depths to obtain hi path conductivity and avoid: (i) step + touch potentials; (ii) corrosion to UG facilities; (iii) AC system xfmr saturation via parallel flows on AC system.
- Sea returns: benefit from highly conductive sea water, but terminal to electrode must be cabled, see next slide…

2. PTP Design features: components for LCC PTP systems
J. Electrodes and earth/sea/metallic return

www.youtube.com/watch?v=9Ddi6sbSMwY



The Sylmar Ground Return System (SGRS), completed in 2018, is comprised of two primary cables that are tied into the PDCI at the Los Angeles Department of Water and Power Sylmar converting station facility. It provides a ground return by sea for the PDCI. These cables run from the Sylmar converter station about 28 miles on overhead lines and then an additional 9 miles underground. The system then extends 2 miles offshore into Santa Monica Bay. At that point, the primary power cables tie into a large area electrode array that consists of 144 electrodes distributed through 36 large concrete vaults. The design of the array is such that it distributes the electrical discharge over a large area making it safe for marine life, divers, and the nearby infrastructures.

2. PTP Design features: components for VSC PTP systems

<u>Compared to LCC</u>:

A. Converter unit: Increased control capability; higher cost per unit of converter capacity; VSC apps are almost entirely UG or undersea as they cannot handle DC fault currents. modular multilevel converters (MMC) provide that VSC losses and LCC losses are close.

B. Converter transformer: LCCs require tap-changing for voltage regulation; VSCs do not.

C. Smoothing reactors: VSCs produce less harmonics so smoothing reactors are less critical.

D. Circuit breakers & switching: Same as for LCCs.

E. AC switchyard: Same as for LCCs.

F1. AC filters: harmonic filters at higher freq➔are smaller in size/cost and incur less losses

F2. DC filters: MMC-based VSC provides smoother DC voltages and requires less DC filtering.

G. Reactive power compensation: None needed for VSC; they can be located anywhere.

H. Conductor system: Power reversal in LCC must reverse voltage polarity and so cannot use XLPE cables. VSC-based HVDC utilizes current reversal and therefore can use simpler, less costly XLPE cables.

I. Control & communication sys: Similar structure but control is more extensive.

J. Electrodes&Earth/sea metallic return: Same as for LCCs.

3. Other PTP Applications: asynchronous interconnections

Bridging grids for which grids' steady-state frequencies differ.

North American asynchronous interconnections

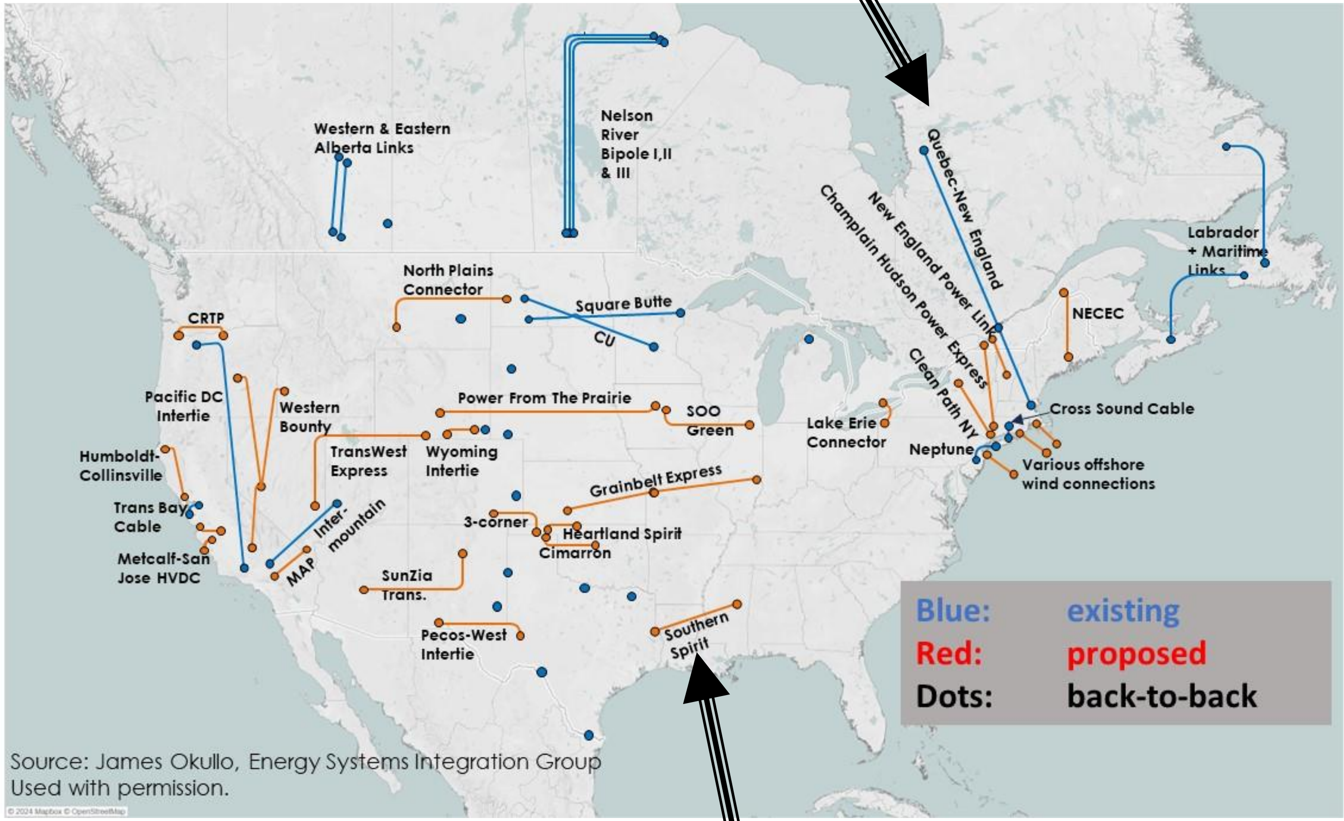
Name	Location	Grids connected	kV	Rating (MW)	Year
David A Hamel	Stegall, NE	Eastern & Western Intrcnnctns	50	100	1977
Eddy County	Artesia, NM	Eastern & Western Intrcnnctns	82	200	1983
Miles City	Miles City, MT	Eastern & Western Intrcnnctns	82	200	1985
Virginia Smith	Sidney, NE	Eastern & Western Intrcnnctns	50	200	1988
McNeill	McNeill, AB	Eastern & Western Intrcnnctns	42	150	1989
Rapid City	Rapid City, SD	Eastern & Western Intrcnnctns	13	200	2003
Lamar	Lamar, CO	Eastern & Western Intrcnnctns	63.6	210	2005
Châteauguay	Châteauguay, Canada	Quebec & Eastern Intrcnnctn	140	1500	1984
North (DC_N)	Oklaunion, OK	ERCOT & Eastern Intrcnnctn	82	220	1984[6]
East (DC_E)	Monticello, TX	ERCOT & Eastern Intrcnnctn	162	600	1998
Blackwater	Clovis, NM	ERCOT & Western Intrcnnctn	57	200	1984
Eagle Pass	Eagle Pass, TX	ERCOT & Mexico	15.9	36	2000
Railroad (Sharyland 1)	McAllen/Mission, TX	ERCOT & Mexico	21	150	2007
Railroad (Sharyland 2)	McAllen/Mission, TX	ERCOT & Mexico	21	150	2014

All are back-to-back. All are LCC except Eagle Pass.

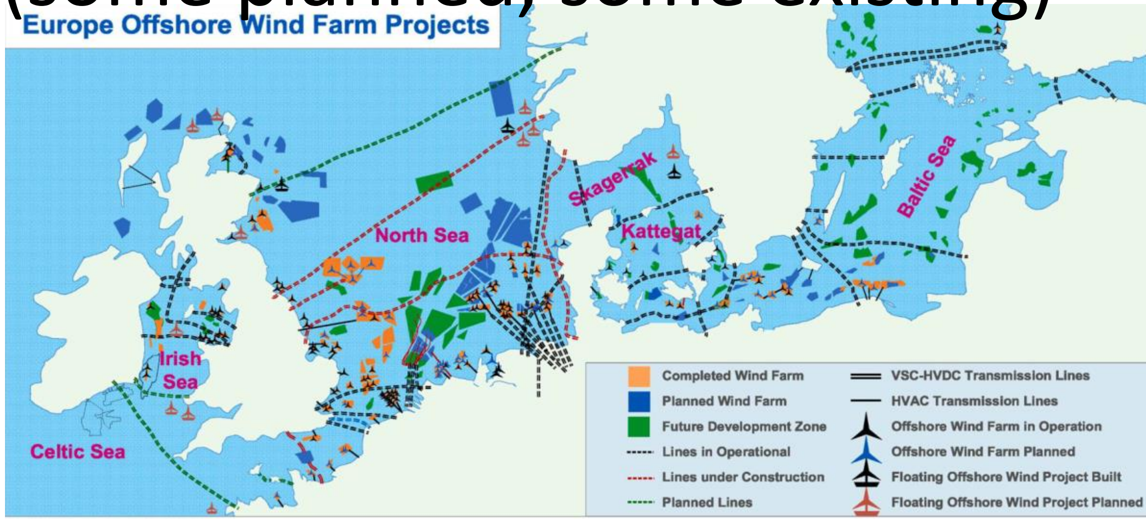
3. Other PTP Applications: asynchronous interconnections

Asynchronous connections may also involve HVDC lines/cables.

Quebec-New England Interconnection (existing)

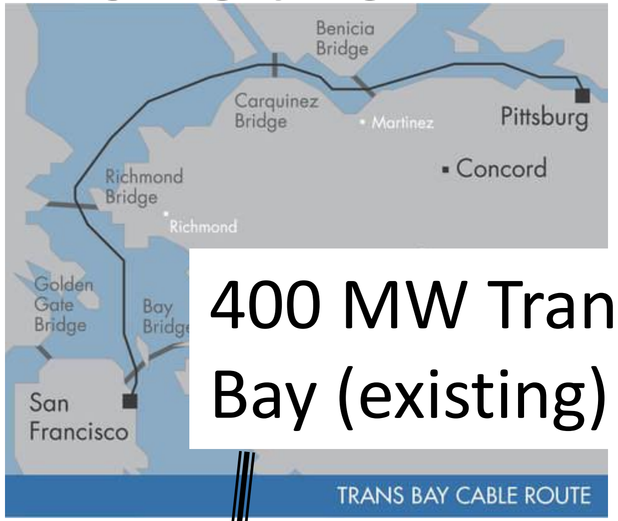


International connections in North, Baltic, Celtic, & Irish Seas (some planned, some existing)

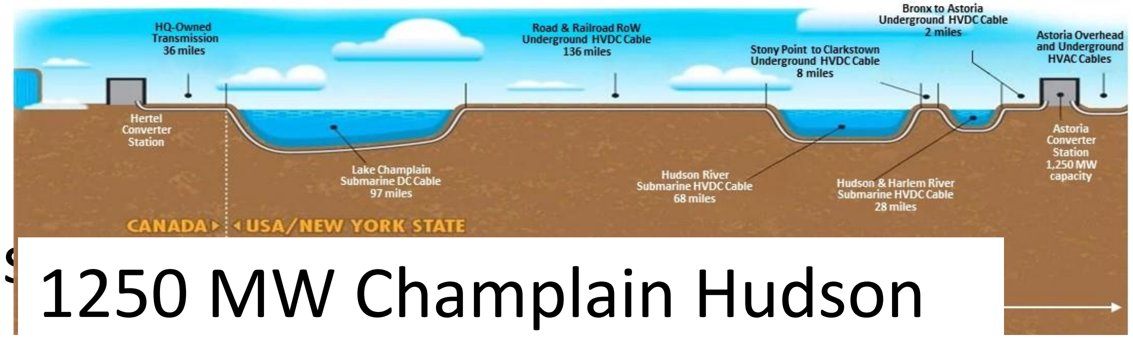


Southern Spirit Transmission project (planned)

3. Other PTP Applications: underground and/or undersea

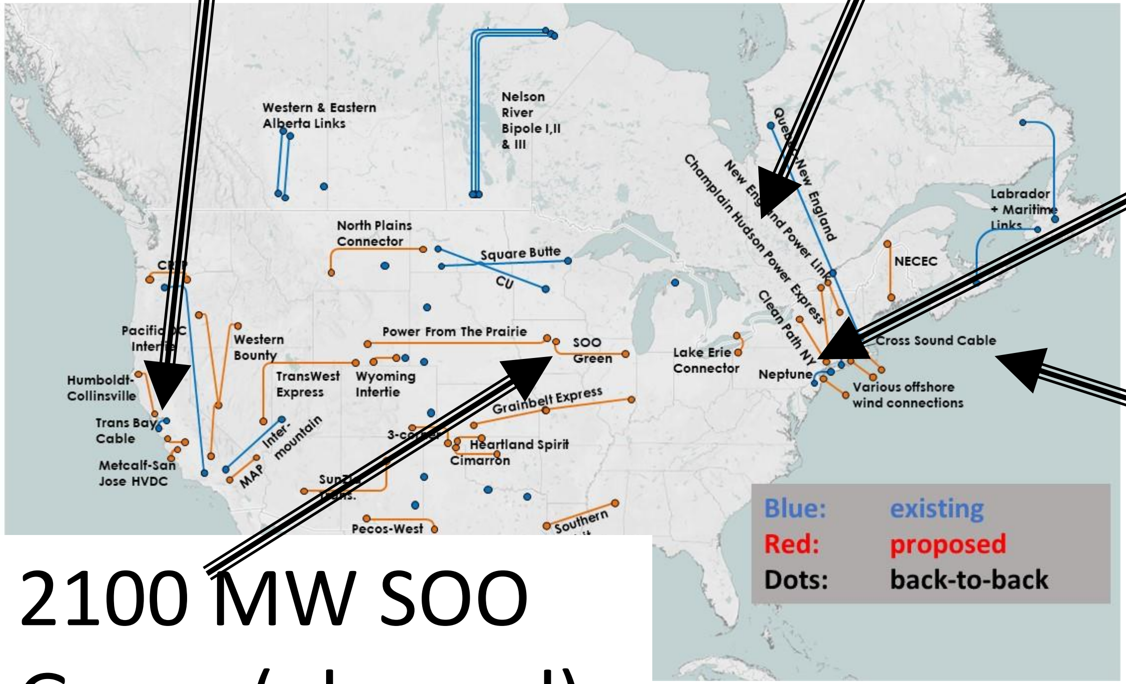


400 MW Trans Bay (existing)



1250 MW Champlain Hudson Power Express (planned)

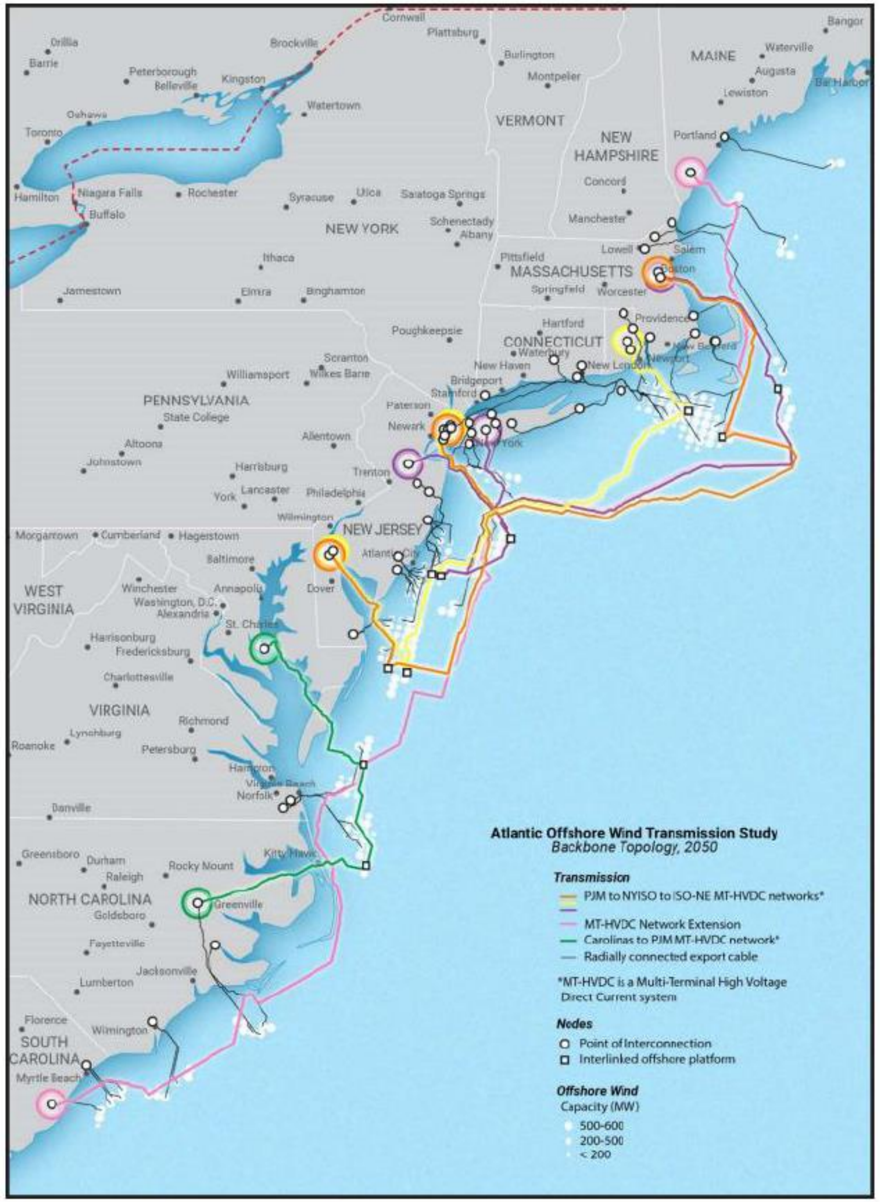
660 MW Neptune (existing)



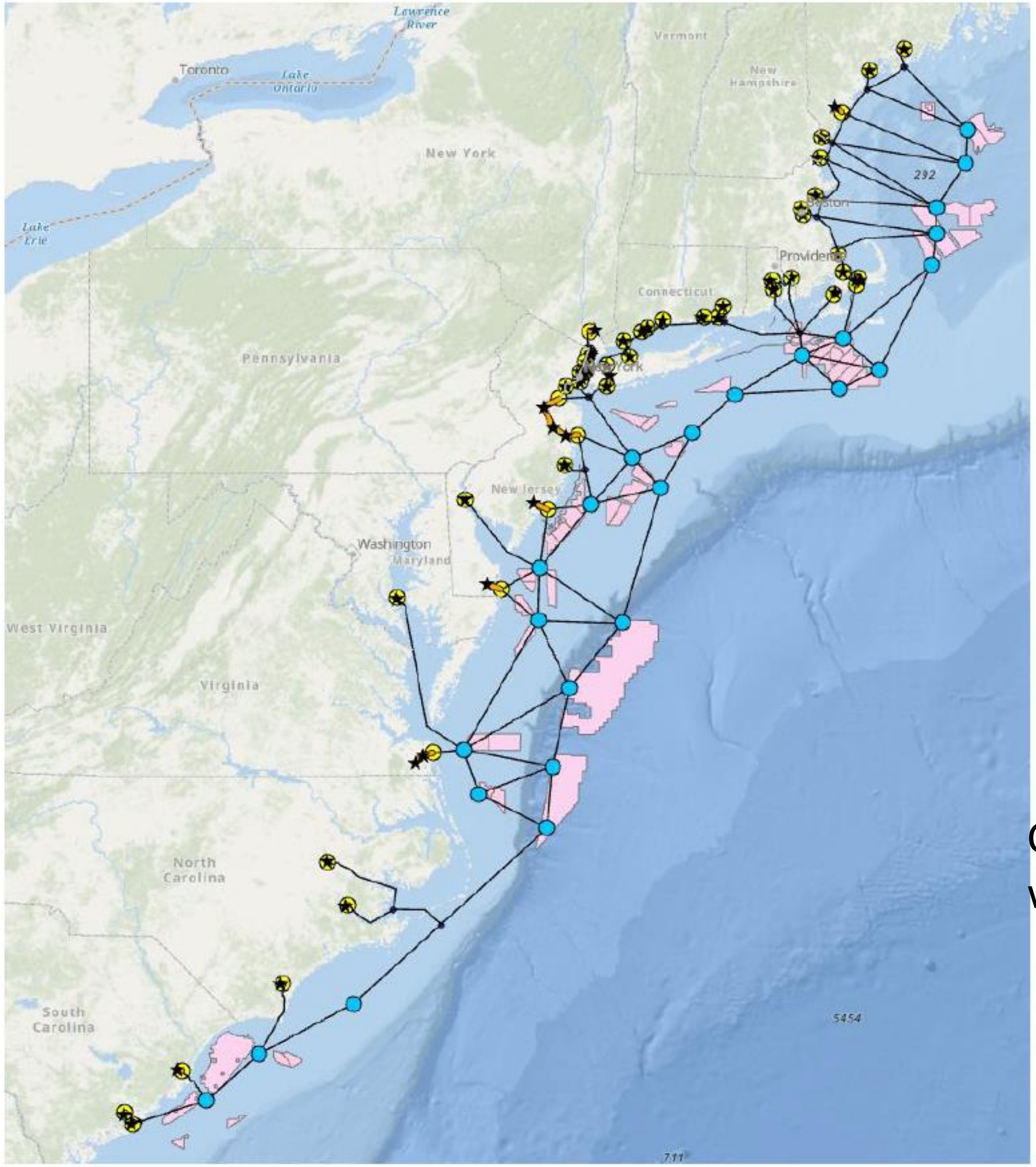
2100 MW SOO Green (planned)

330 MW Cross-Sound (existing)

3. Other PTP Applications: East Coast Offshore



NREL, Atlantic Offshore Wind Energy Study, 2024



Hines, Jahanbani, McCalley, Lof, et al., 2025

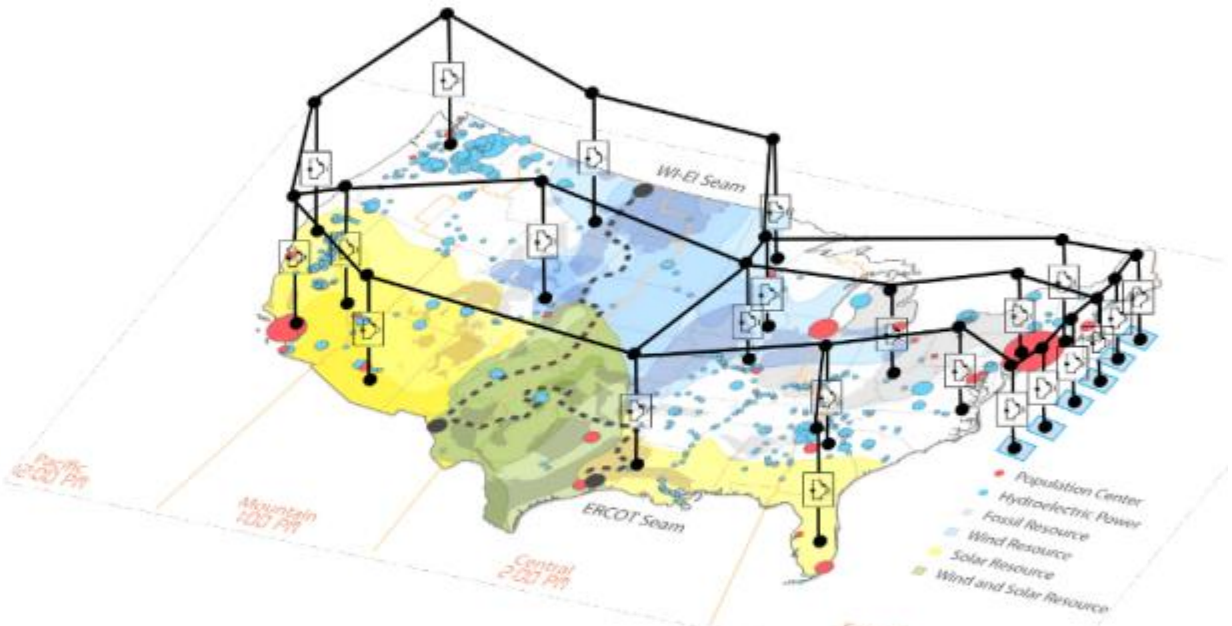
Two separate studies designed similar Atlantic offshore networks.

Significantly reduces onshore AC transmission upgrades.

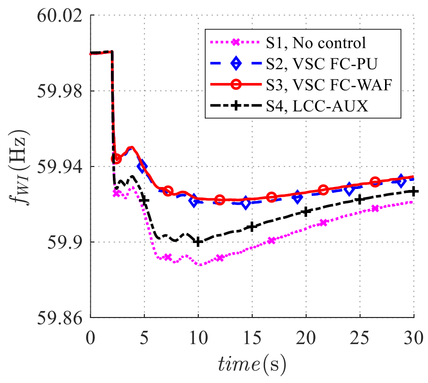
Not only connects OSW but also provides an additional N-S Eastern transmission path.

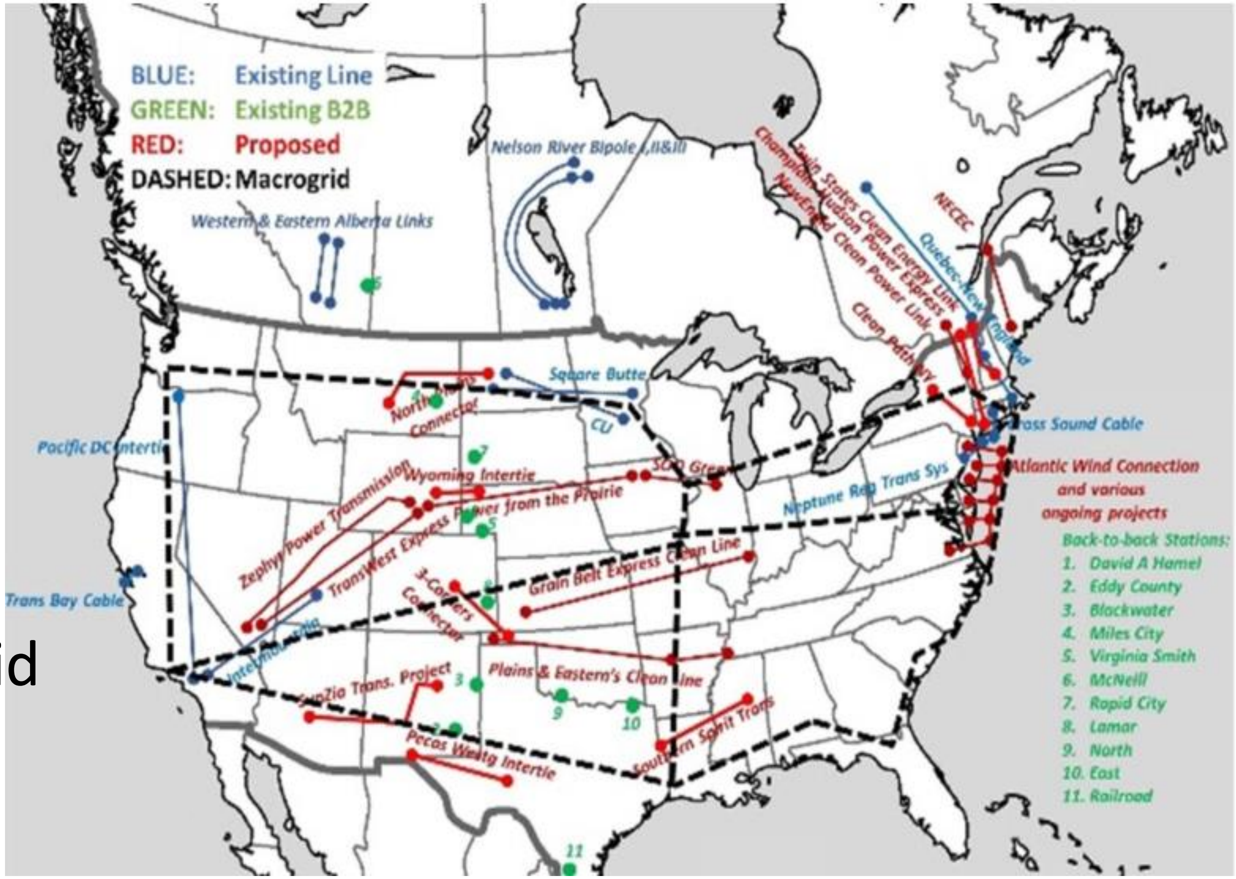
Complements/integrates w/macrogrid development

3. Other PTP Applications: Macrogrid



- Our studies show Macrogrid pays for itself
- Can be entirely PTP, entirely DC grid, or hybrid
- Provides significant control benefits





- Proposed HVDC approximates Macrogrid

4. Main learning points

1. *HVDC designs:* Three main HVDC designs: PTP, multiterminal, and DC grid. This module focuses on the PTP design.
2. *Two basic technologies*:
   - LCC-based HVDC uses thyristors - power handling capability is higher, cost per unit power-handling capability is lower;
   - VSC-based HVDC uses IGBTs - requires smaller land areas and has greater control capabilities.
3. *Electrical configurations*: Two electrical configurations used for LCC-based PTP transmission –
   - asymmetrical monopolar
   - Bipolar: most common.

   VSC-based PTP transmission may be configured in either of these ways but also may use symmetrical monopolar config.
4. *HVDC PTP components*: converters, converter transformers, smoothing reactors, circuit breakers & switches, filters, reactive power compensation devices (LCC-based HVDC only), conductor systems, control and communication systems, and electrodes and return circuits.
5. *Applications*: Most PTP applications in service today are LCC-based, and these systems will remain in operation for at least several decades to come. As a result, it is important to maintain LCC-based HVDC expertise. However, because of the faster and broader control capabilities of VSC-based HVDC, including their ability to be used in HVDC grids, it is likely that most HVDC transmission systems implemented in the future will be VSC-based.

“The future is all VSC,
the past is all LCC,
and the past will be in the future for a long, long time…”