Overview of HVDC Technologies and EPRI's HVDC Research

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ERCOT Austin Building
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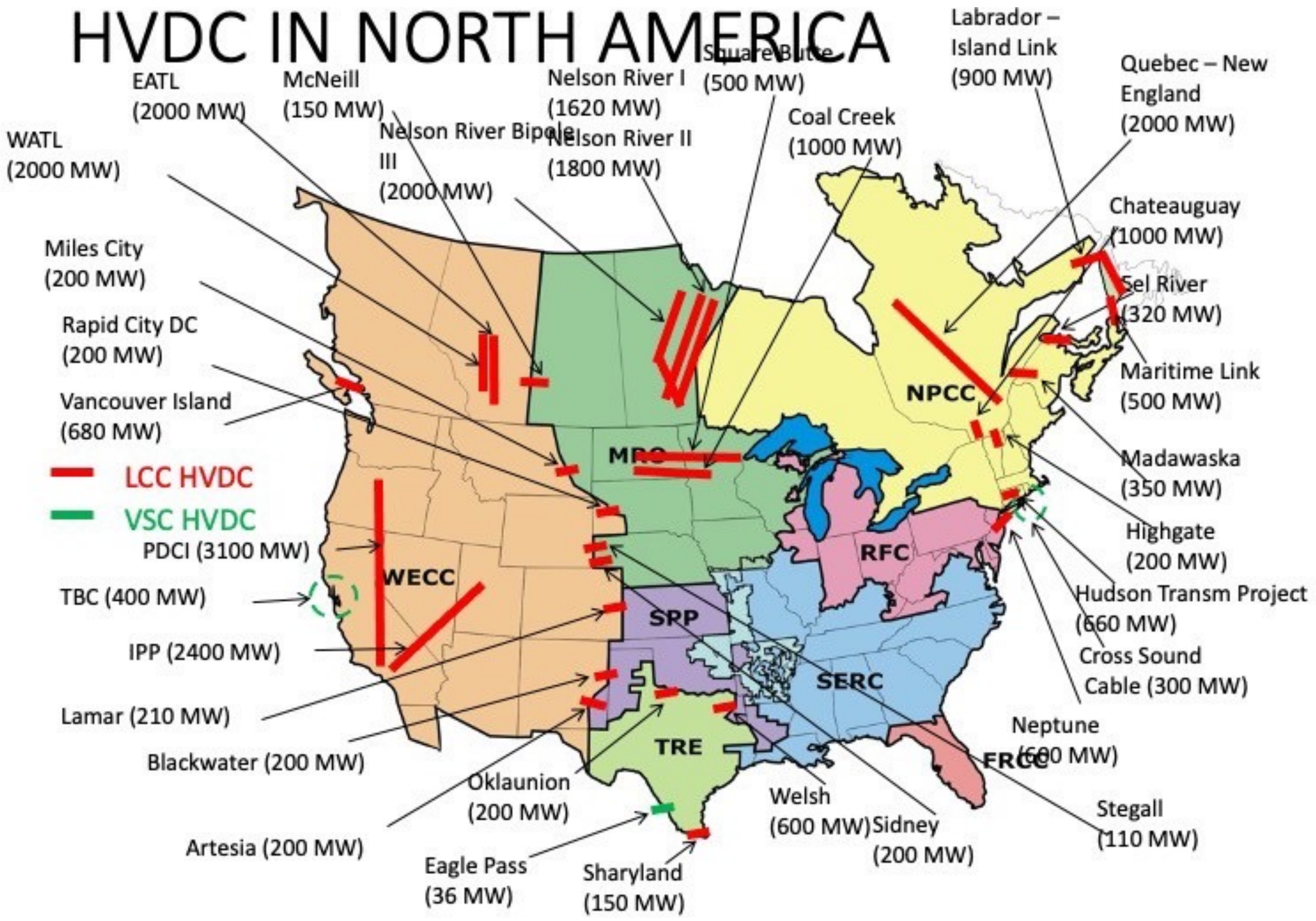
Presentation Outline

- Overview of HVDC
- DC compared to AC
- HVDC Converter Technologies (LCC & VSC)
- HVDC Lines and Cables
- AC to DC Line Conversion
- Overview of EPRI Projects



Overview of HVDC & DC Compared to AC

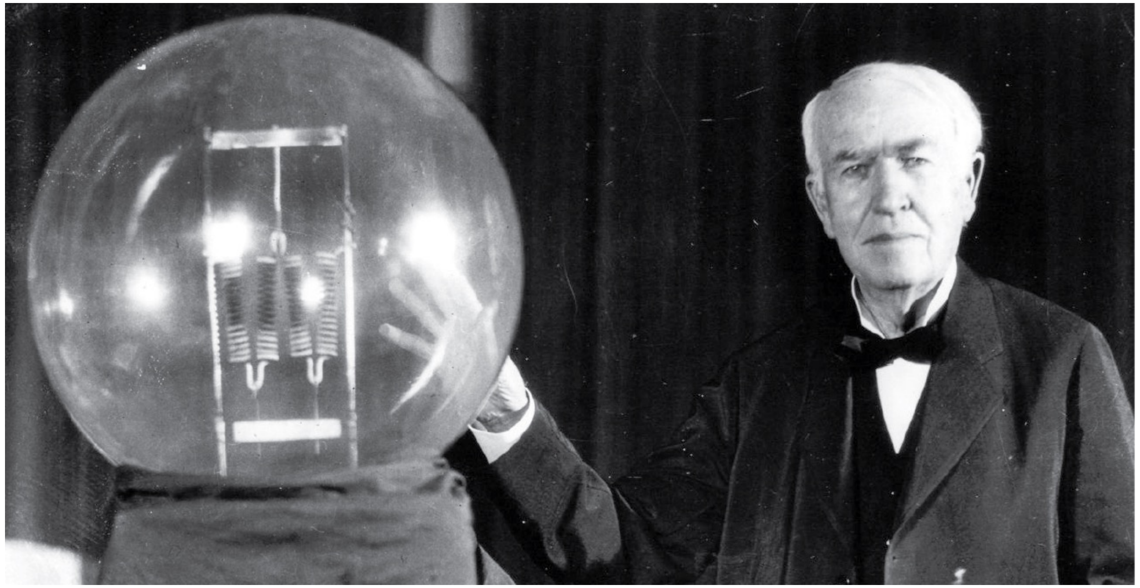
AC versus DC

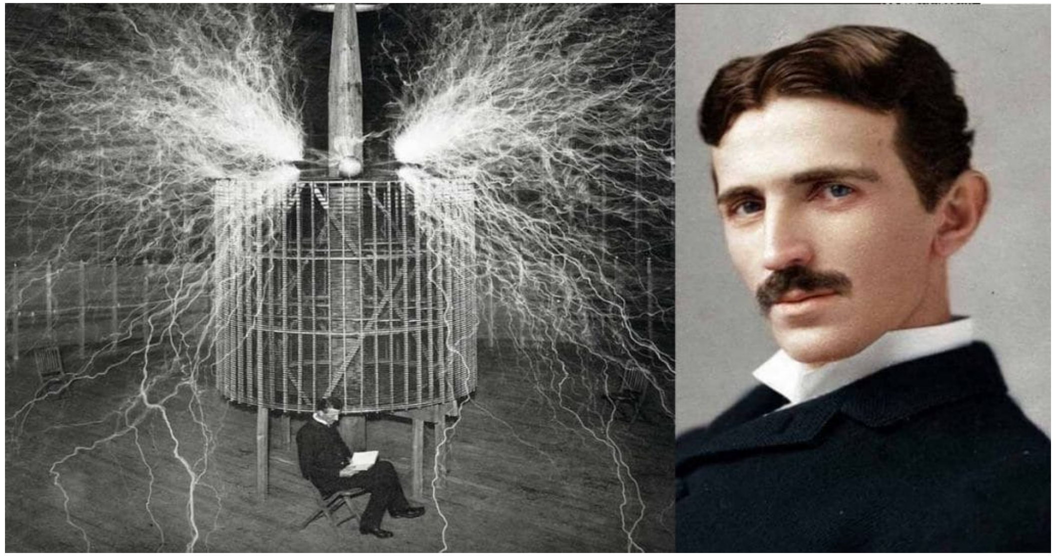
The AC versus DC debate goes back to the beginnings of Electricity

- DC was first (Thomas Edison)
- AC came later (Tesla / Westinghouse)

AC became popular due to equipment

- Transformers
- Circuit Breakers





HVDC Transmission Overview

- Long distance transmission for bulk power transfer.
- Asynchronous interconnection. For example, it allows for connecting networks of 50 Hz and 60 Hz frequencies.
- Higher system controllability with at least one HVDC link embedded in an AC grid.
- Lower overall investment cost.

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Long Distance AC Transmission	Allows step up and step down of voltages
	Intermediate substations are possible to serve load
	Reduces current & losses at high voltages
	Limited maximum MW capability due to steady state stability limits (surge impedance loading limits) & transient stability limits
	Series capacitor compensation can increase loading on the lines but sub synchronous resonance issues need to be addressed
	Needs reactive power support (shunt capacitors, SVCs, STATCOMs) to keep acceptable voltages
	Lines operating at ratings lower than the thermal capability of the lines

Long Distance DC Transmission	Converts AC to DC, transmits dc power over long distances, and inverts DC to AC
	Controls the power flow on the DC line to a desired value
	Most economical for long distance transmission
	Can operate the DC lines close to thermal limits
	DC can provide direct control between regional AC grids
	DC converter stations are more expensive than AC substations
	Intermediate substations require multi-terminal DC which is not prevalent in use because of complexity

HVDC Advantages

Lower losses. Typically, because HVDC comprises active power flow and one less conductor (3-phase versus Bipole).

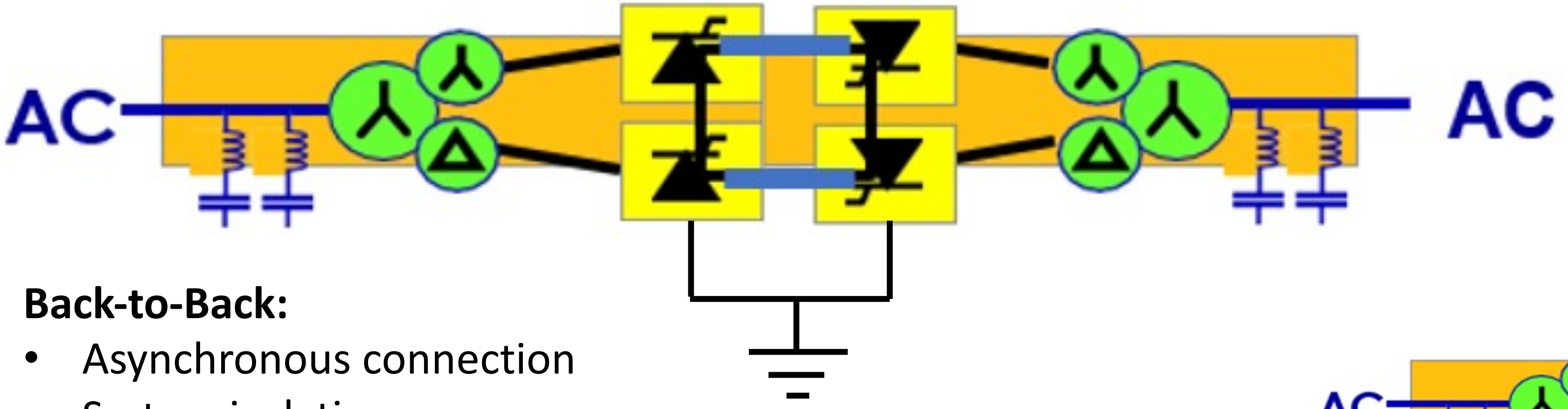
Less expensive circuit breakers, simpler bus-bar arrangements in switchgear, and simpler safety arrangements.

Increased stability and improvements in power quality.

Capability of providing emergency power and black start during grid restoration following major transmission contingencies.

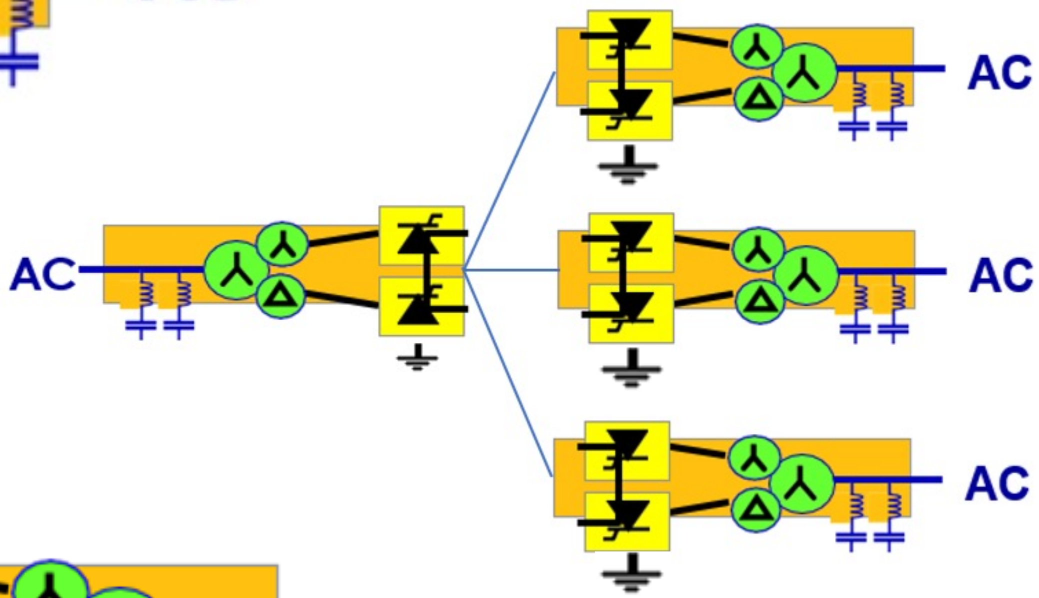
HVDC Offers several Advantages and Benefits

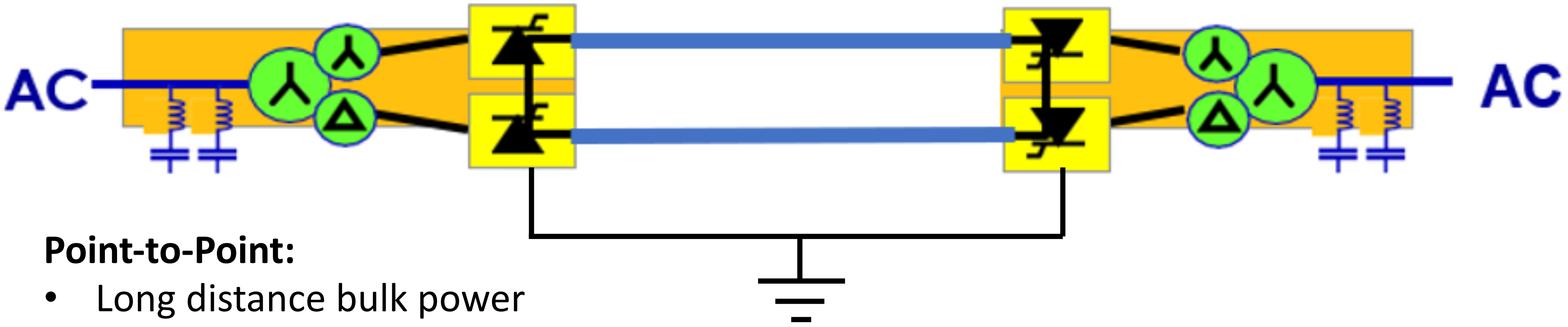
HVDC Scheme Types



Back-to-Back:
- Asynchronous connection
- System isolation

Multi-Terminal:
- Supply to multiple loads





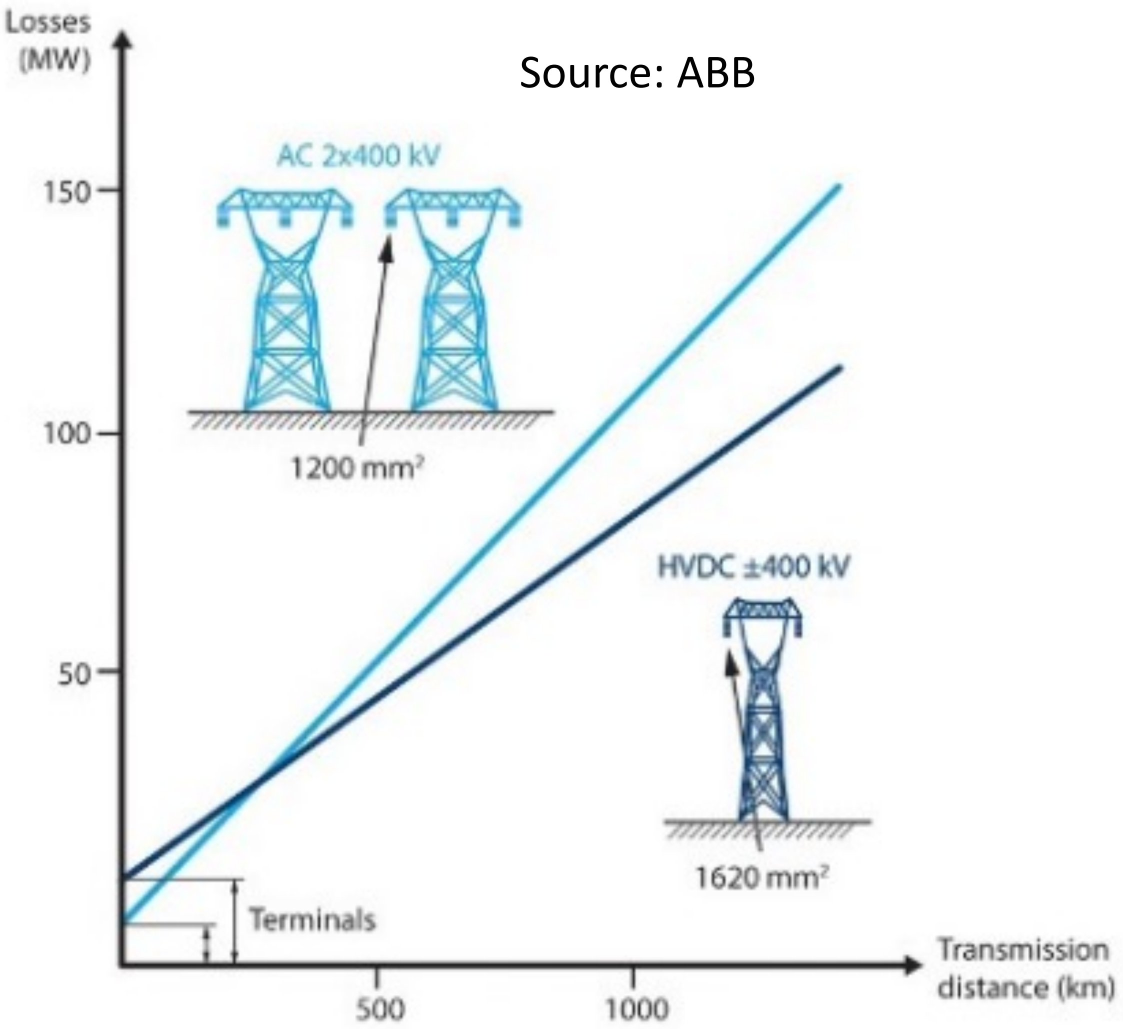
Point-to-Point:
- Long distance bulk power

Line Losses

HVDC lines have lower losses than AC lines for the same power

Converter losses are extra (~ 0.6% of total power)

Total HVDC System losses are lower than AC system losses

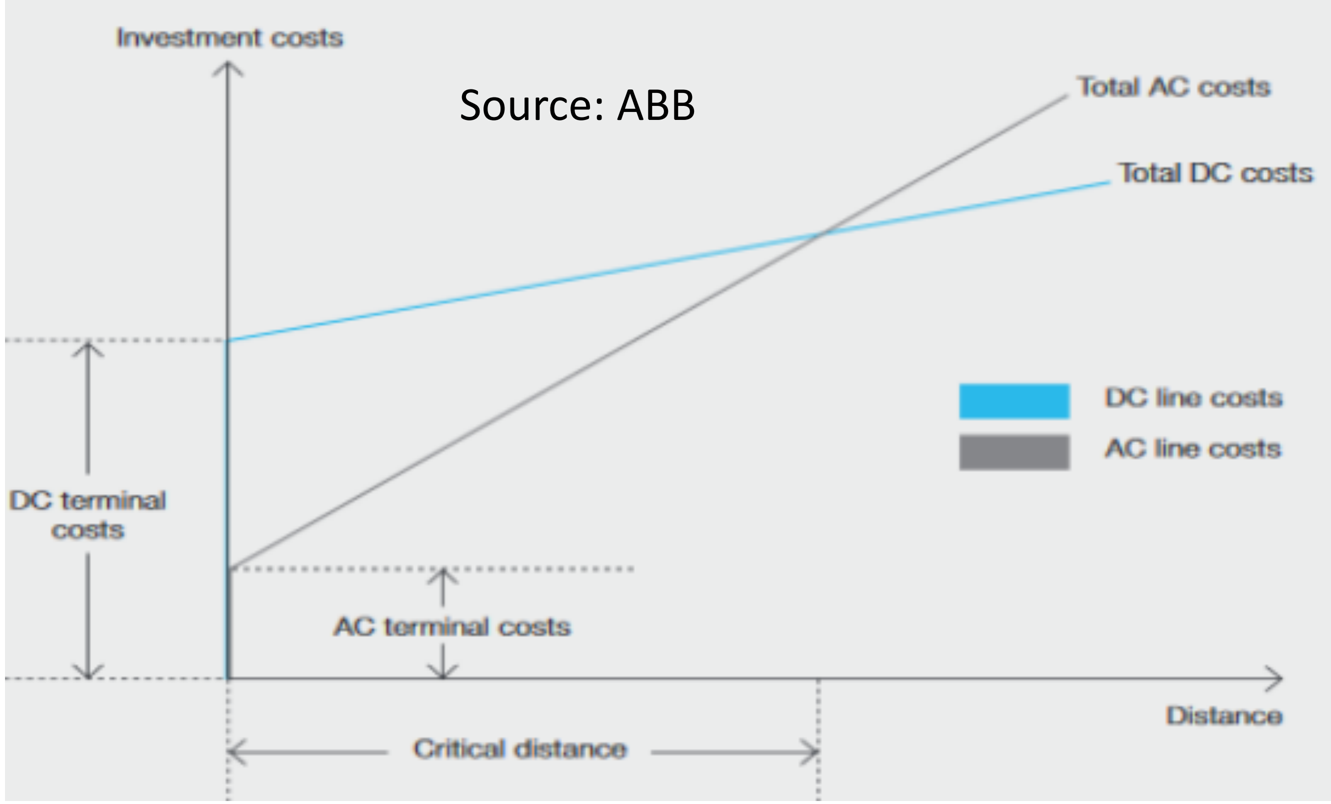


HVDC has Lower Losses than AC for the same Power Transfer

Breakeven Distances

- The cost of a DC link depends on:
  - the cost of the substations
  - the cost of the line or cable

- HVDC is more economical than AC when the transmission distance is:
  - >300 miles for Overhead lines
  - >30 miles for Underground cables



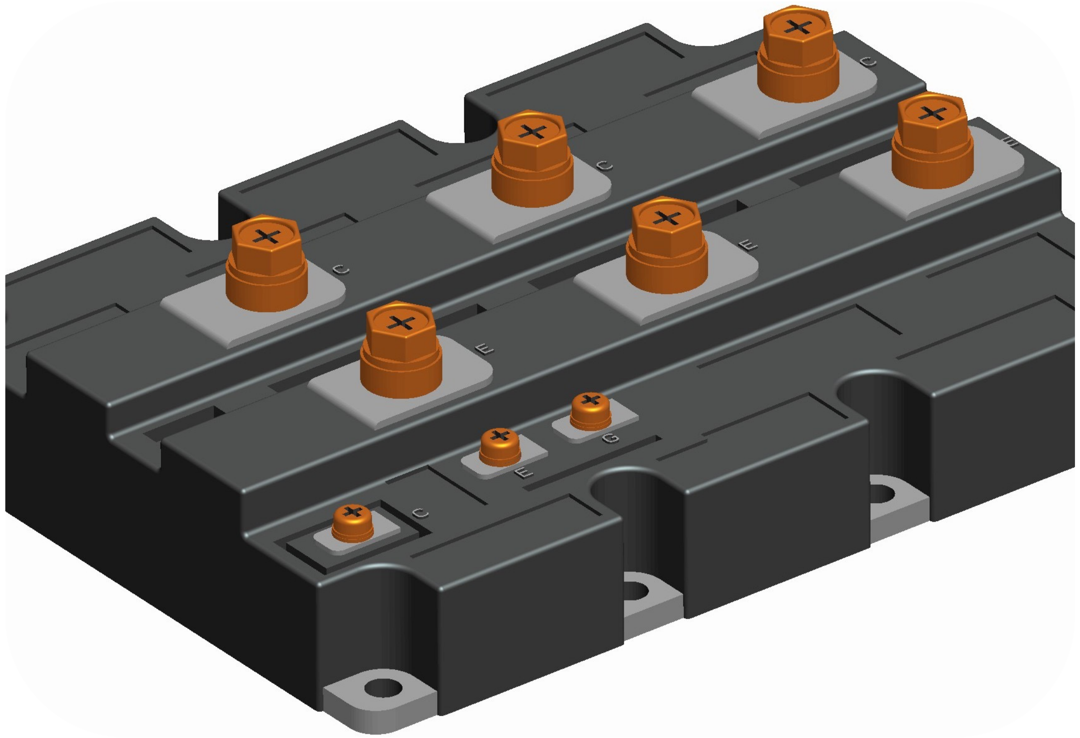
ROW Costs are the Same for AC or DC Lines

HVDC Converter Technologies

HVDC Converter Technologies

- First HVDC Systems
  - Lyon–Moutiers DC transmission up to 125 kV HVDC scheme (1906 – 1936) over 110 miles
    - Electromechanical
    - Overhead and Underground Cables
- First commercial HVDC line
  - Gotland in Sweden
    - Submarine cable
    - 100 kV upgraded to 150 kV
- From the 1930s
  - Mercury Arc Valves
- From the 1970s
  - Thyristors (Line Commutated Converters (LCCs))
- Recent Technology 1990's: Voltage Source Converters (VSCs)
  - Integrated Gate Bipolar Transistors (IGBTs)

HVDC Converter Technology: LCC Versus VSC



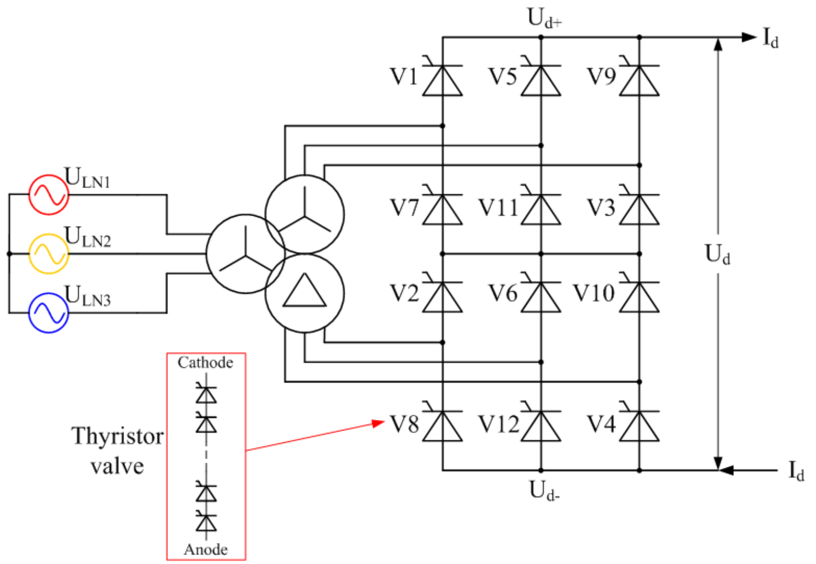
Line Commutated Converter (or Current Source Converter)

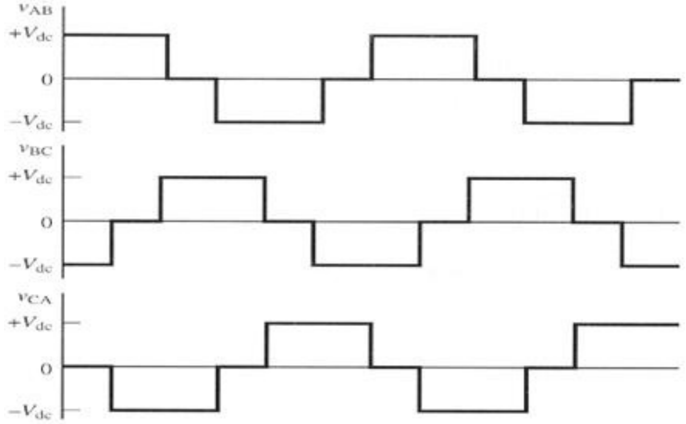
- Thyristor based
- Switches on-off one time per cycle
- Large filters required due to low order harmonics generated

Voltage Source Converter

- IGBT Based (Insulated Gate Bipolar Transistor)
- Switches on-off many times per cycle
- 2 Level requires high harmonic filters (PWM)
- 3 Level still requires filtering but lower harmonics – surpassed by MMC (Modular Multilevel Converters)

Line Commutated Converters

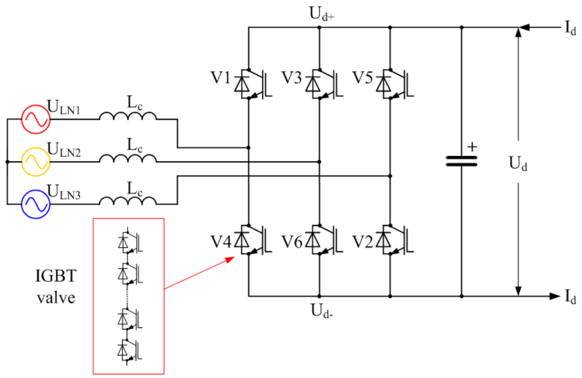


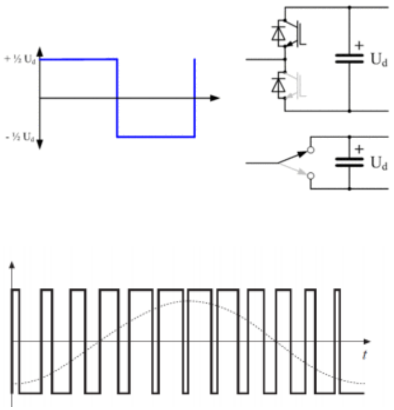


Line to line output voltages

- Large filters required due to low order harmonics generated

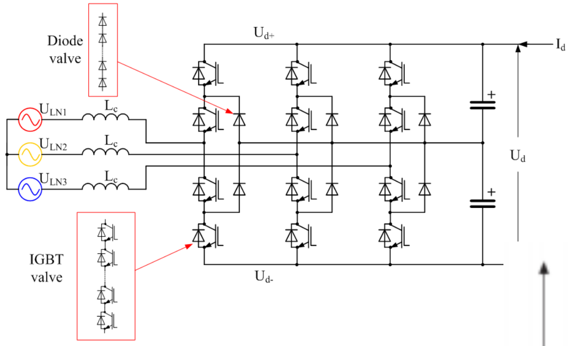
Voltage Source Converters

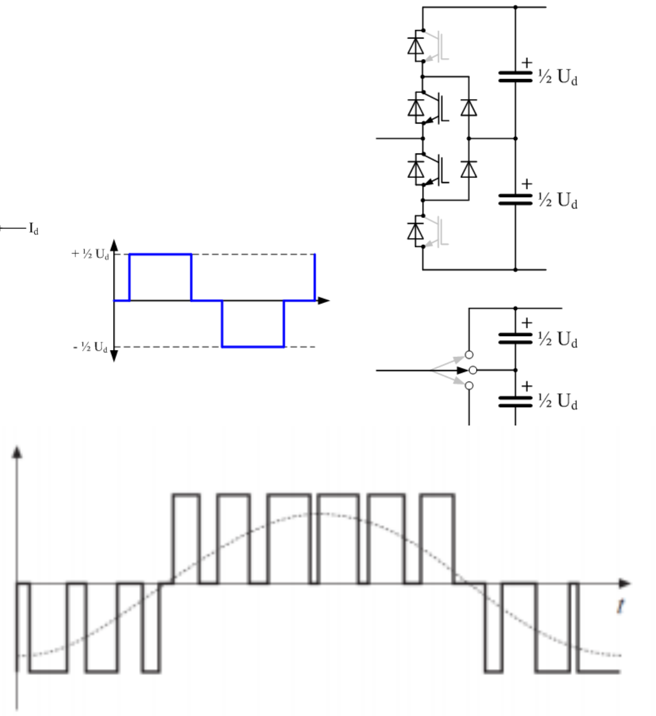




2 Level

- Most simple VSC design
- Requires high harmonic filters
- High switching frequency required
- 1st generation VSC
- Uses PWM

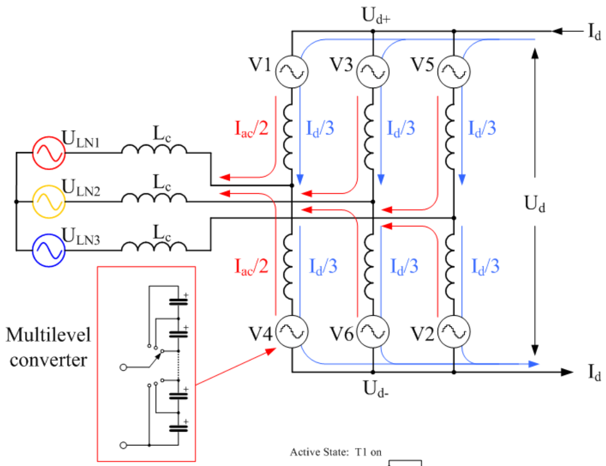


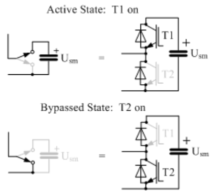


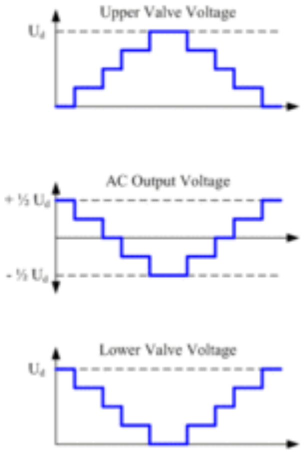
3 Level

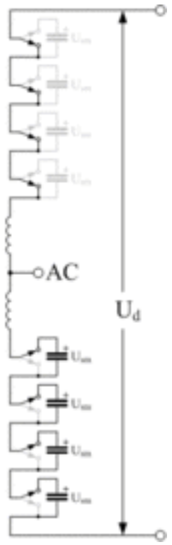
- Slightly more refined than 2 level
- Still requires filtering but lower harmonics
- Used in some installations but surpassed by MMC

Modular Multi Level Converters

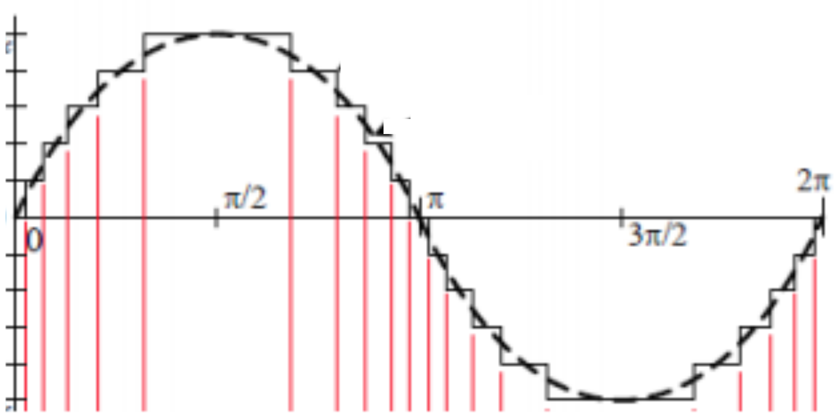








- Much more complex control
- Almost no requirement for AC filters
- Most expensive and complex topology
- Lower losses due to lower switching frequency per switch
- Inherent redundancy
- Modular design



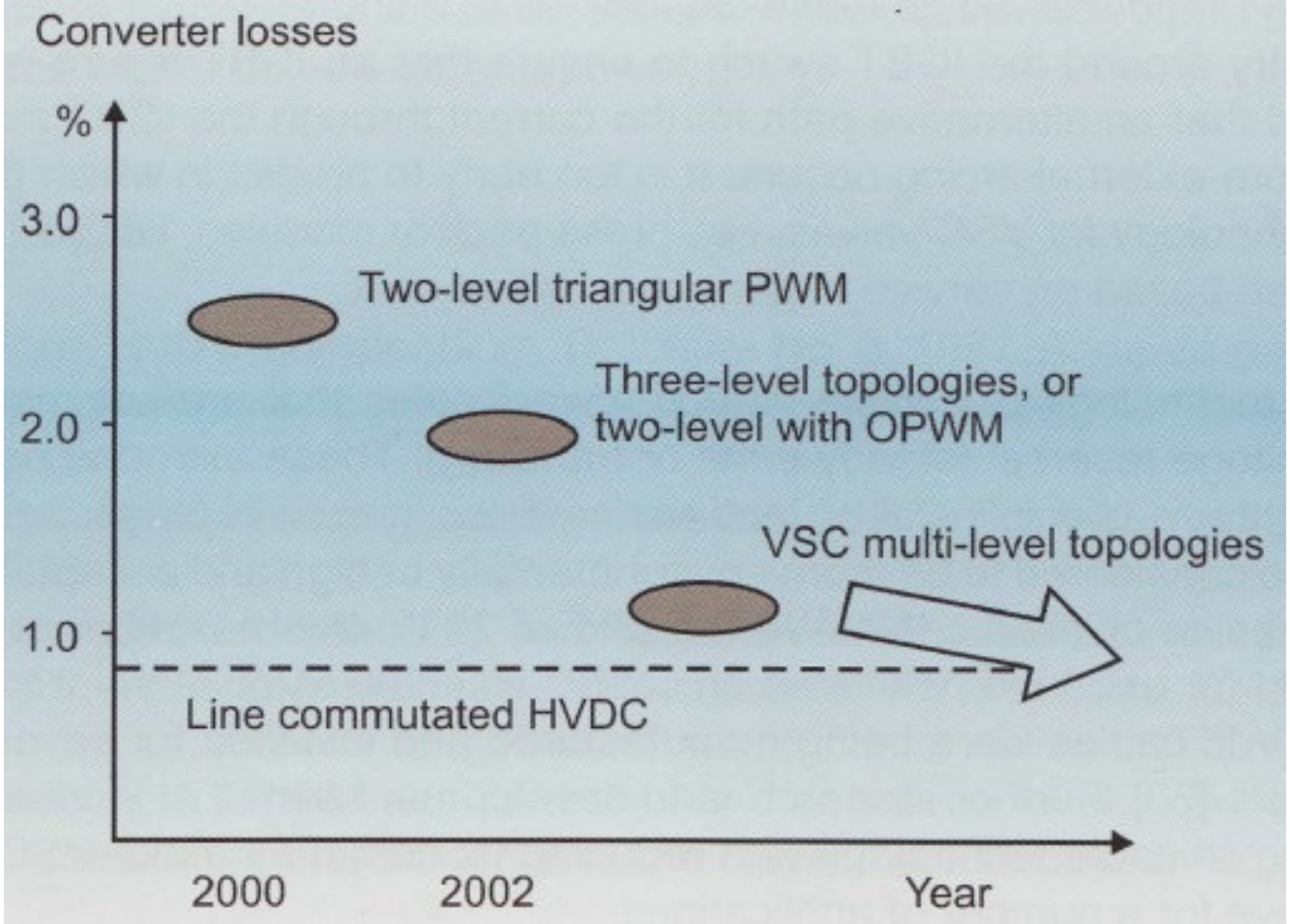
HVDC Converter Technology: LCC vs. VSC

Function	LCC	VSC
Semi-Conductor Device	Presently thyristors devices are of sizes 4, 5, and 6 inches which has a rating of 8.5 kV and up to 6300 Amps.	IGBTs with anti-parallel free-wheeling diode, with controlled turn-off capability. Device ratings of 4.5 kV and 2500 A are available
DC transmission voltage	± 1100 kV with an overhead transmission line and up to ± 600 kV with an PPL-MI cable	Up to ±600 kV with an overhead transmission line and +/- 525 kV with a cable
DC power	Up to 12000 MW on a single bipole and DC voltage of ±1100 kV	Typical ratings of 1200 MW in a symmetrical monopole and as high as 3000 MW utilizing either parallel devices or converters
Reactive Power requirements	Consumes reactive power between 50% and 60% (depending on the design) of its rating at each terminal.	Does not consume any reactive power and each terminal can independently control its reactive power. The converter can supply reactive power to the system.
Filtering	Requires large filter banks	Requires moderate size filter banks or no filters at all.
Black start	Limited application –with sync condenser	Capable of black start and feeding passive loads

HVDC Converter Technology: LCC vs. VSC

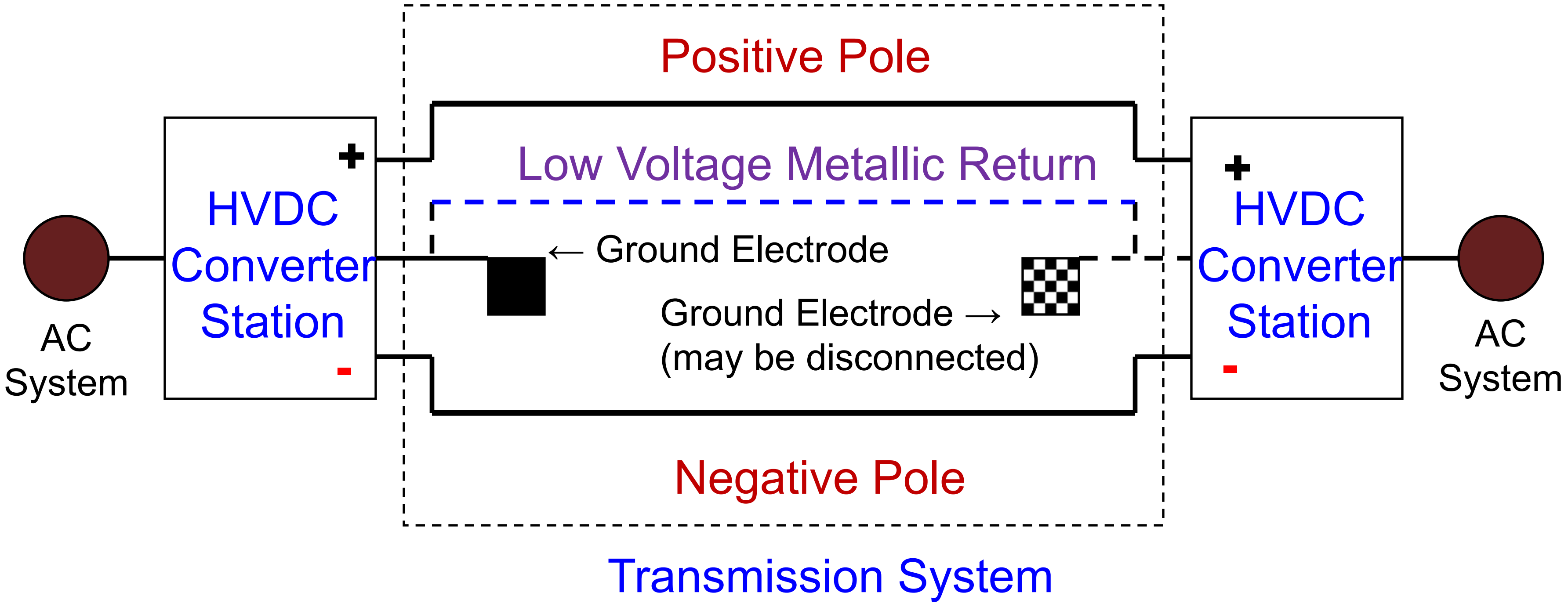
Function	LCC	VSC
Footprint	Can be large	Small for the comparable rating to an LCC
Offshore wind farms	Can be applied with some dynamic voltage control	Straight forward application
Power losses	Typically 0.8% per converter station at rated power	Typically 0.8 to 1.0% per terminal with multilevel converters

VSC and LCC Power Loss Comparison



HVDC Lines – Overhead and Cables

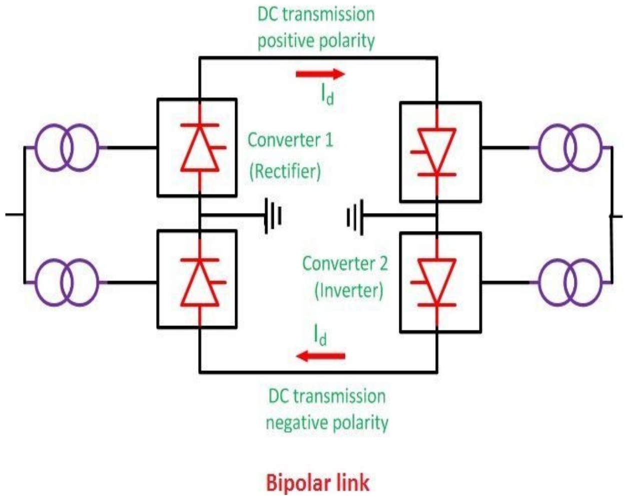
Overhead HVDC Transmission Line



Two modes:

- **Bipolar** – Common – little ground current
- **Monopolar** –a) significant ground current if ground return used (rare)
  b) zero ground current if metallic return used.

HVDC Line Configurations



Bipolar

Two Poles – Positive and Negative Polarities

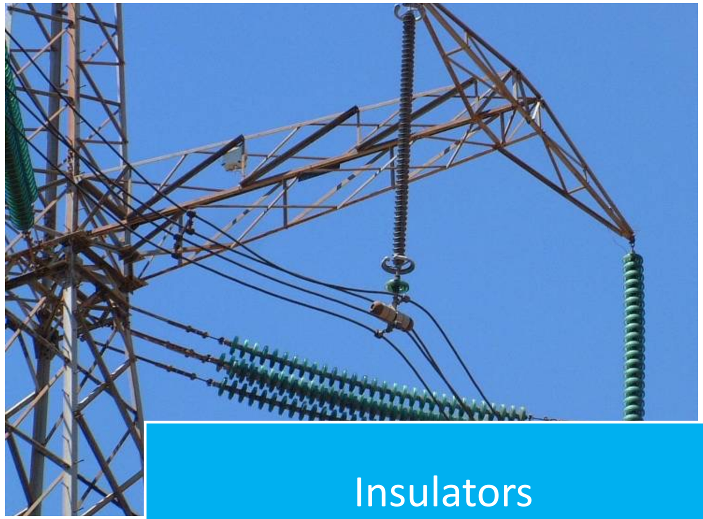
Monopolar

Single Pole

Homopolar

Two Poles – Same Polarity

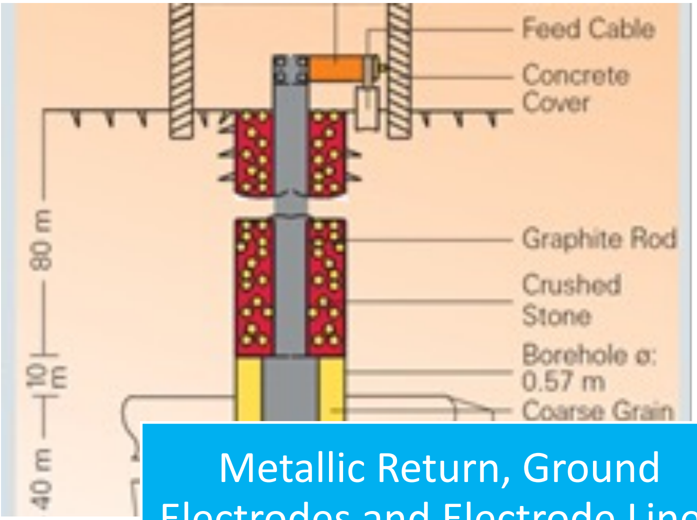
Some Differences in DC vs AC OHL



Insulators

Corona and Field Effects

Conductor Selection



Metallic Return, Ground Electrodes and Electrode Lines

Insulator Material

Glass

Porcelain

Polymer

Same Materials Used for AC and DC

Differences between AC and DC Cables

- Challenges of dc cables are mainly related to the ac/dc/ac converters:
  - Capital and operating costs
  - Losses (~ 1% per station)
  - Operating and maintenance complexity
  - Land requirements

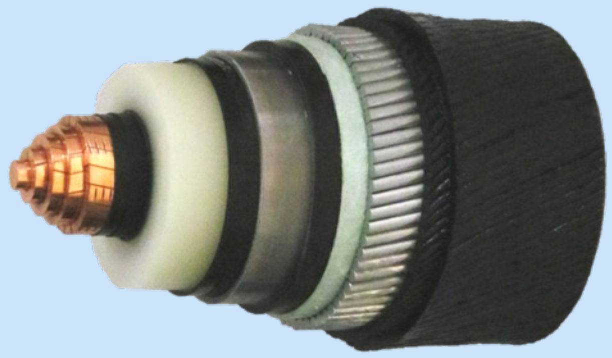
AC Cables	DC Cables
DC Ohmic losses in conductor	DC Ohmic losses in conductor
AC skin & proximity effect losses in conductor	nil
Dielectric losses	nil
Losses due to flow of charging current	nil
Induced losses in sheath	nil
Induced losses in armor	nil
Induced losses in neighboring cables	nil
Reactive compensation to offset charging current	nil
Perceptions of harmful magnetic fields	Less perceptions of harmful magnetic fields
Three cables for 3-phase circuit	One or two pole cables for `circuit`

CABLES USED FOR HVDC TRANSMISSION

- Mass Impregnated (MI): Insulated with special paper, impregnated with high viscosity compound
- Self Contained Fluid Filled (SCFF): Insulated with special paper, impregnated with low viscosity oil
- Extruded: Insulated with extruded polyethylene-based compound

Mass Impregnated

Self-Contained Fluid Filled

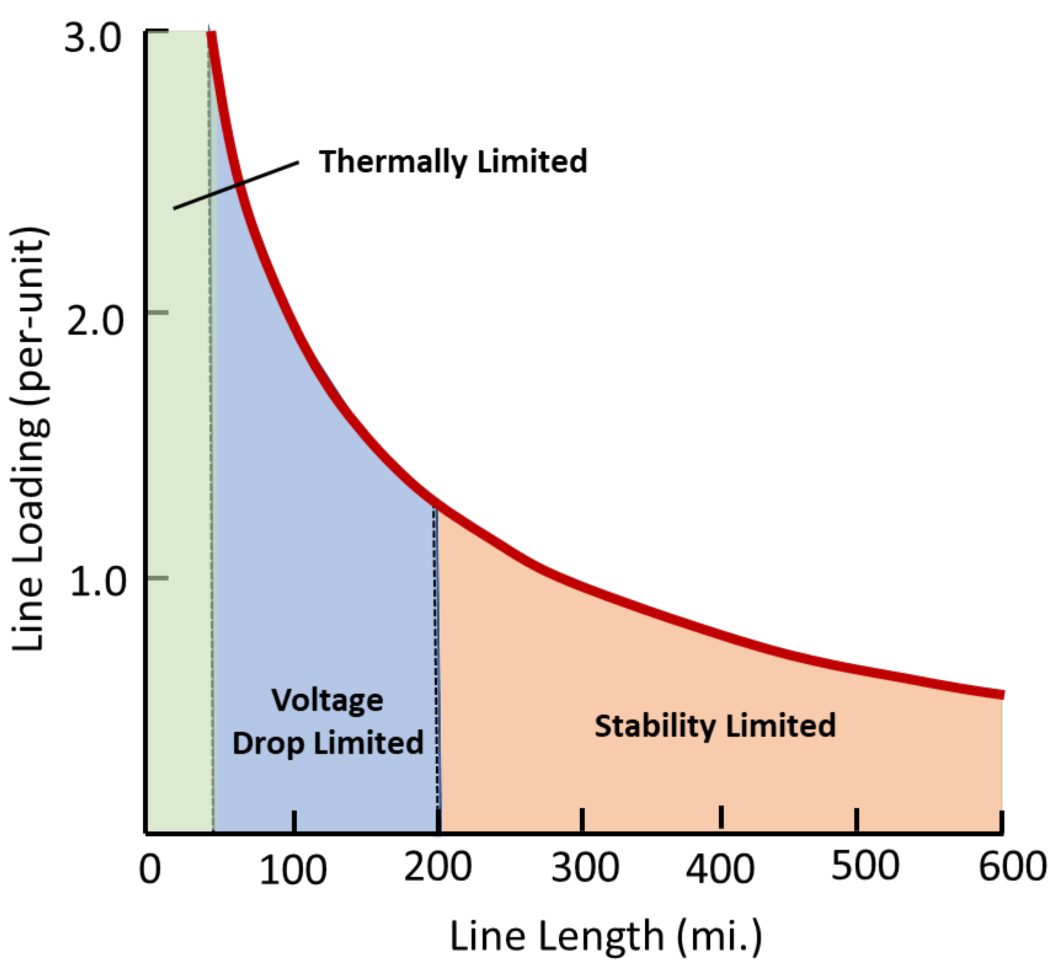


Extruded

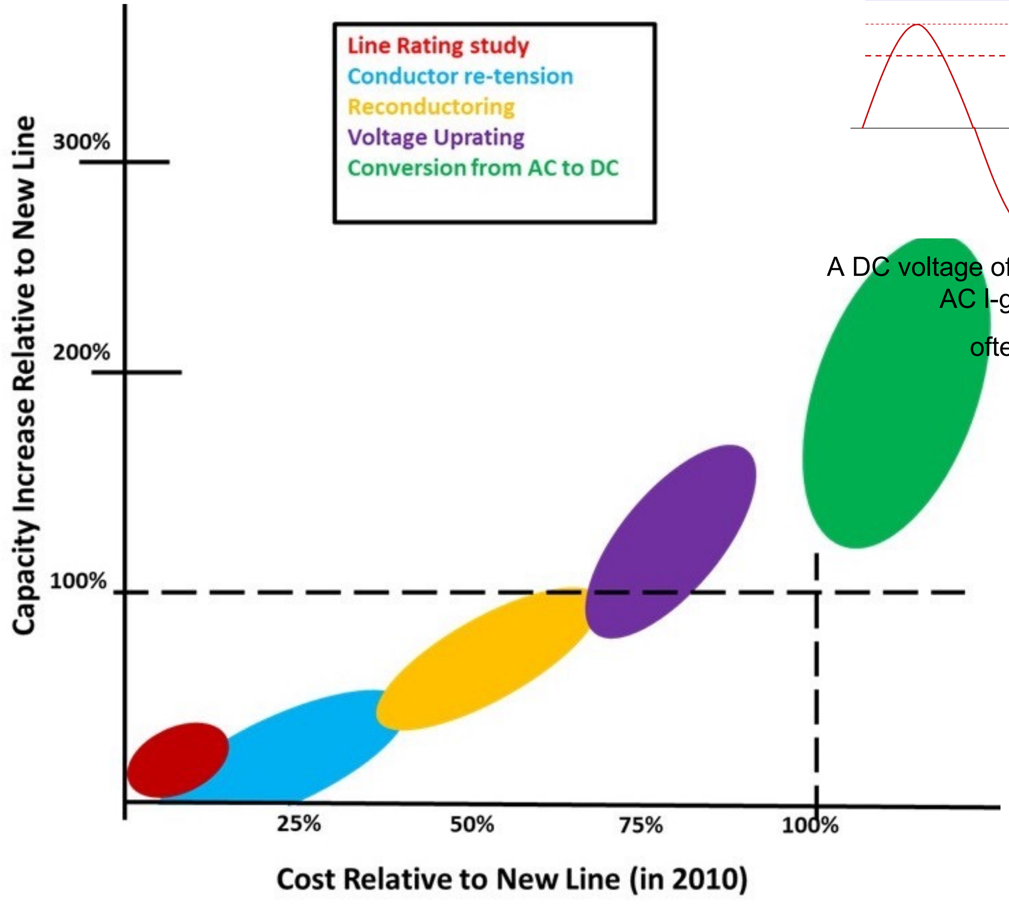
Source of pictures Prysmian

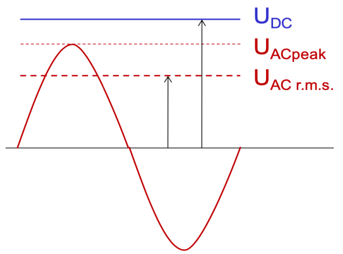
AC to DC Line Conversion

Increasing Capacity of Existing OH Transmission Lines



Universal Loadability Curve of ac Lines





A DC voltage of up to 1.5 times the AC l-g peak voltage can often be achieved.

Potential capacity increase vs. relative cost

What does AC to DC Conversion Mean / Implications

Structures – No change

Conductors – No change

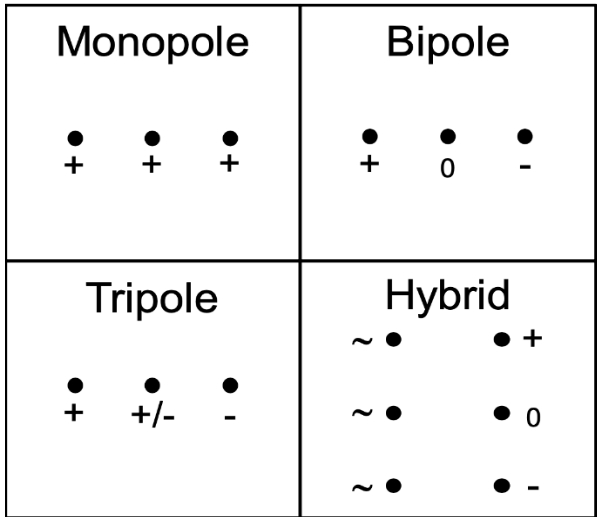
Insulators – Re-insulation may be required

Evaluation of Electric Field Effects

Terminal substations – DC converter stations must be built

Re-permitting for DC

Line Configuration Options

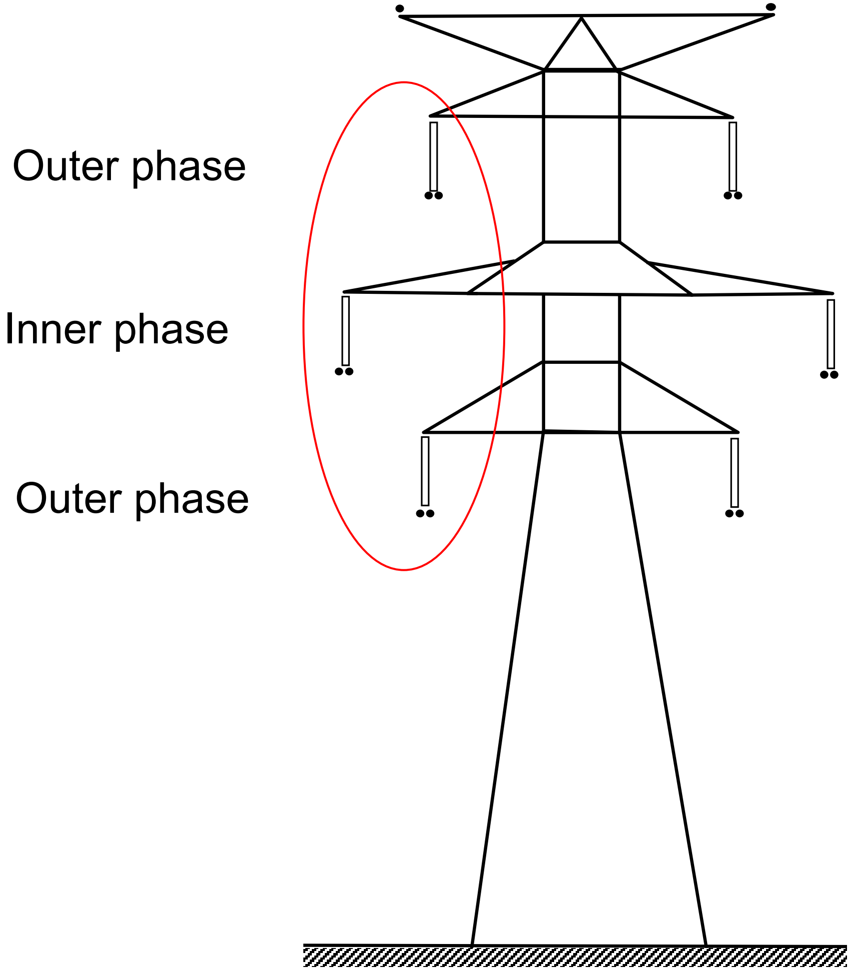


Single Circuit

- Outer phases used as a traditional Bipole – centre phase used as emergency metallic ground return
- Tripole configuration

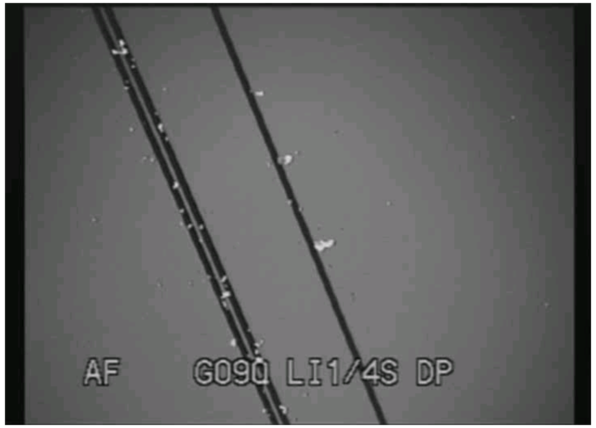
Double Circuit

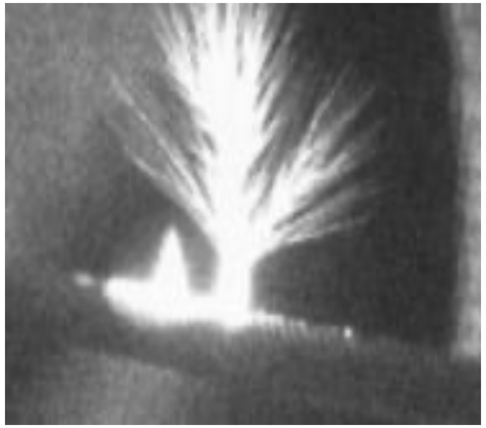
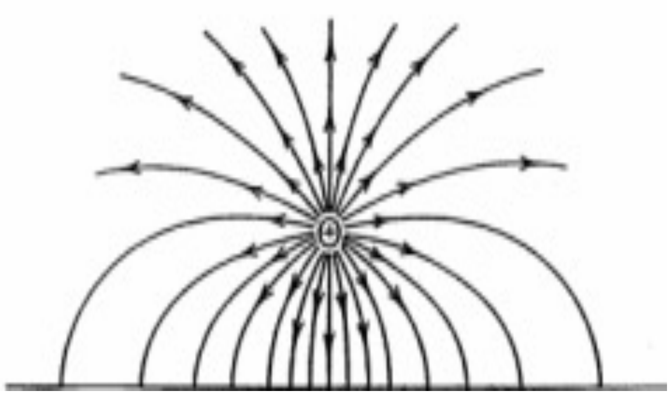
- One circuit converted – as above
- Three conventional Bipoles
- A single Bipole (3 bundles making up a single pole)
- Two Tripoles



AC to DC Conversion: Key Considerations

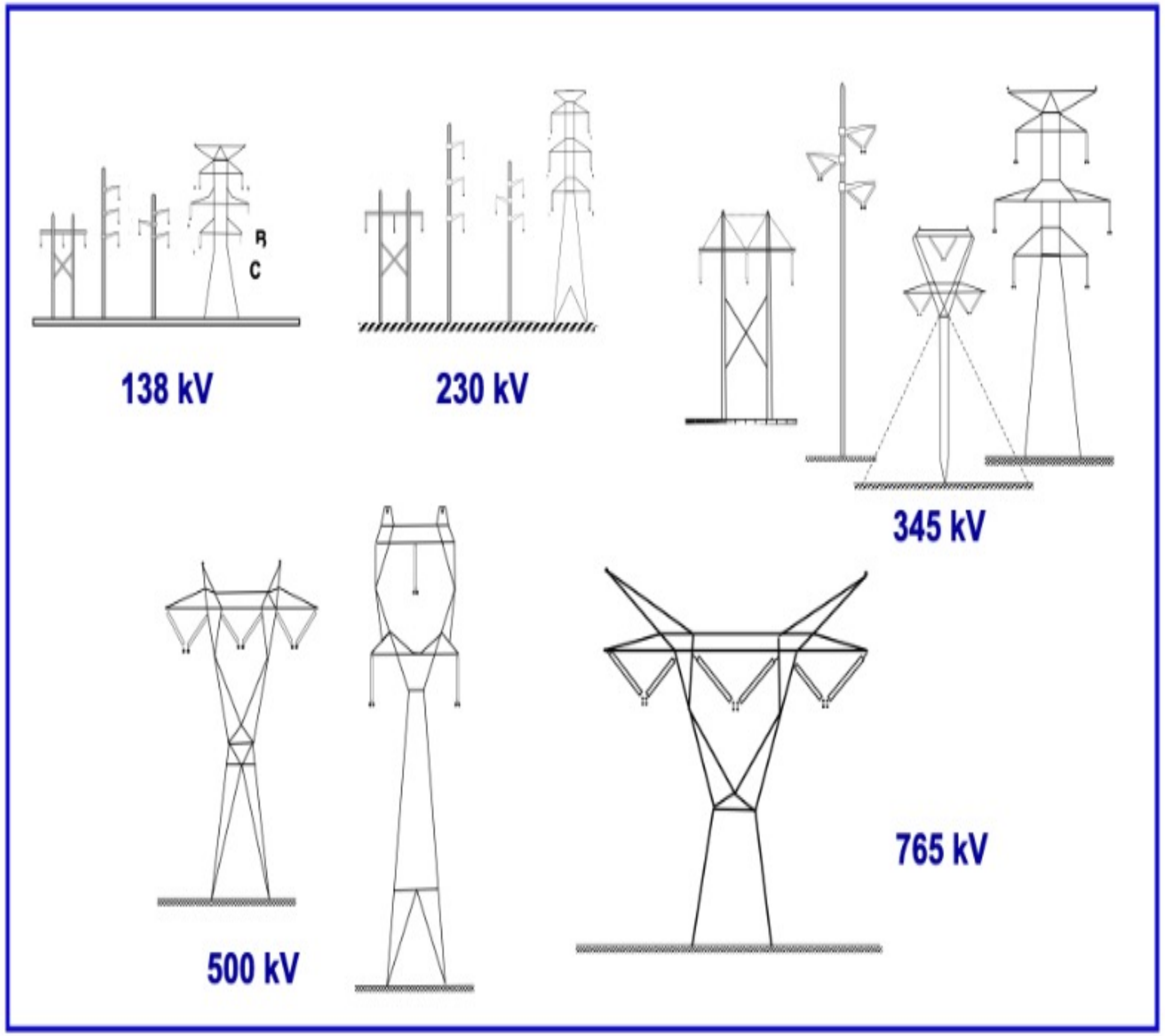
- Conductor gradient
  - Conductor & Hardware Corona
  - Audible Noise
- Ground-level electric field
- Insulator Contamination
- Clearance for insulators at the structure
- NESC clearance to ground
- Live Working Clearances

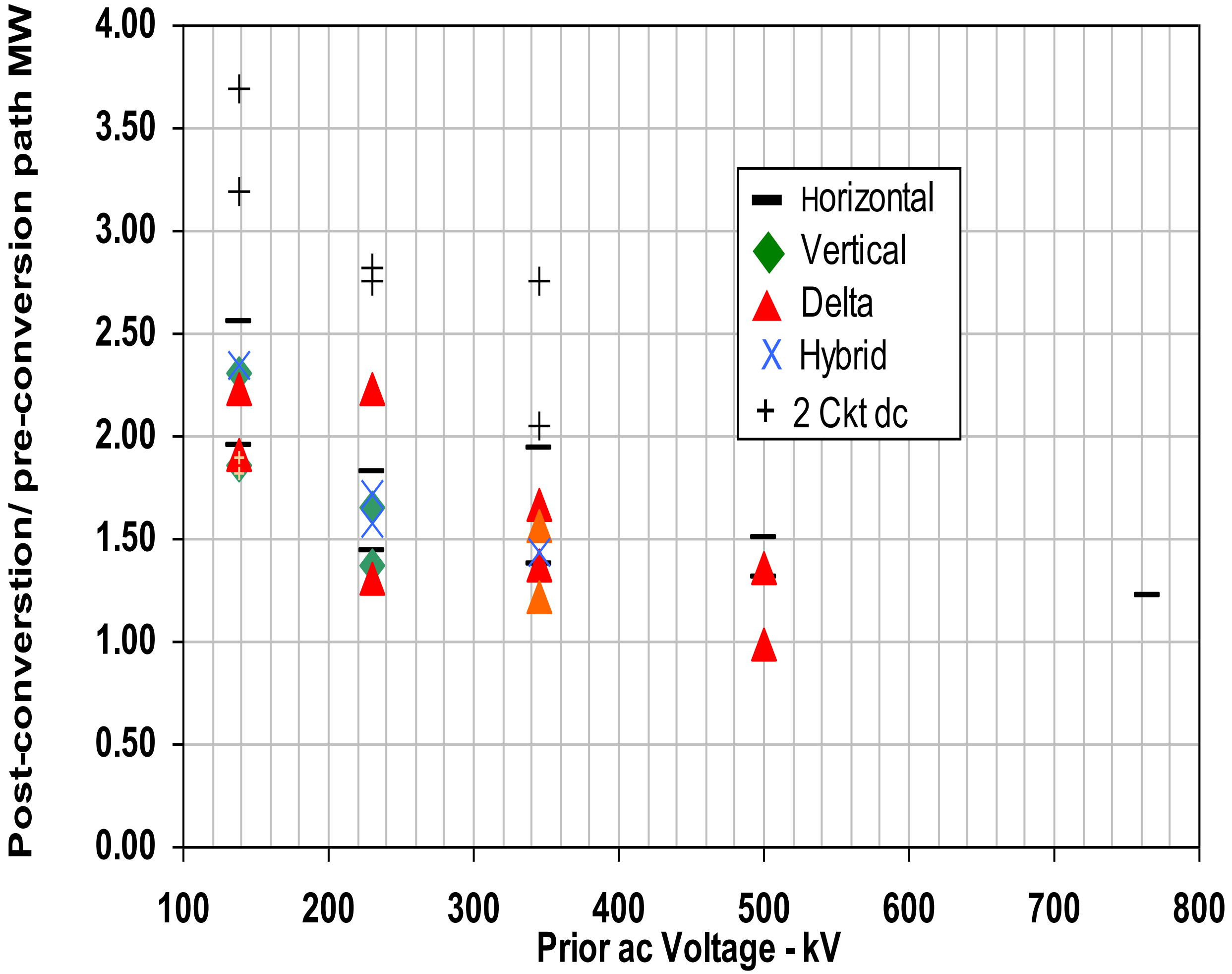



Requires Studies & Testing to Confirm Performance

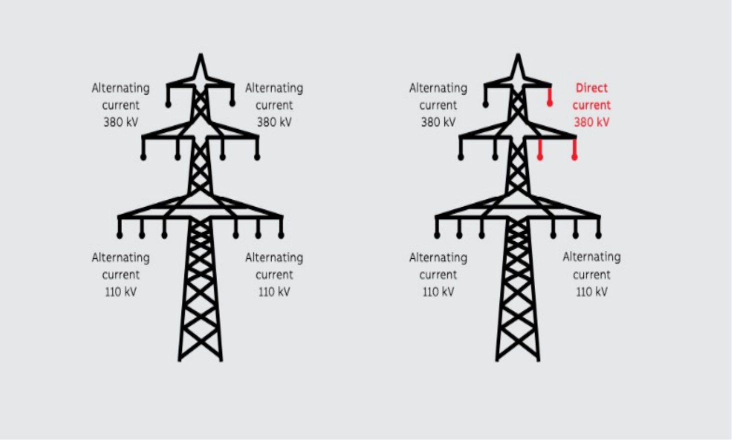
North American Transmission Structures & Possible Capacity Gains





Recent AC to DC Conversion -One circuit of a Double Circuit 380 kV AC line in Germany being converted to DC – Hybrid AC / DC on Same Tower

- UltraNet project in Germany
- Line runs between North Rhine Westphalia and Baden-Württemberg
- Line Length 340 km
- Two 380 kV & Two 110 kV AC circuits on the same tower
- One 380 kV AC circuit was converted to +/- 380 kV DC
- Facilitate transmission of about 2,000 MW (about 40% increase in capacity) from wind farms in the North Sea to the industrial towns in the south of Germany.
- Other AC lines have also been studied with a view to conversion.



EPRI's HVDC Research

EPRI HVDC (Virtual) Program Structure

HVDC

- → P37 (Substation)

  P37.116 HVDC Converter Stations & FACTS Technologies

- → P35 (Overhead Transmission

  P35.019 HVDC Overhead Lines

- → P36 (Underground Transmission)

  P36.008 HVDC Cable and HVAC Submarine Cable Systems

- → P40 (Grid Planning)

  P40.E HVDC Planning

P37.116 HVDC Converter Stations and FACTS Technologies

Project Overview

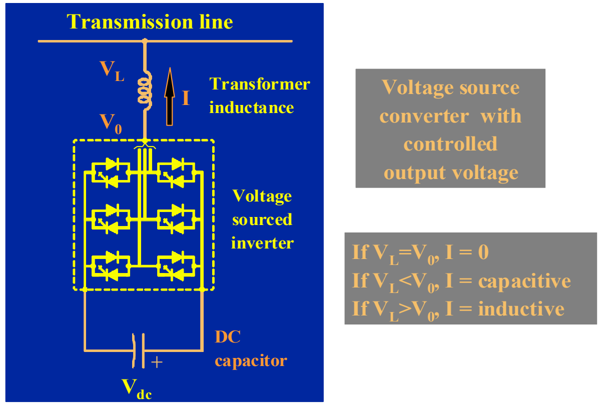
HVDC Converter Stations and FACTS Technologies (P37.116): *Research Tasks*

1. Assessment and evaluation of HVDC & FACTS technologies
2. Provide State-of-the-art information on HVDC & FACTS
3. Assist members selecting options for renewable integration and increased transmission capacity
4. Develop Operation, Maintenance, and Replacement Strategies
5. Update the HVDC Reference Book (Olive Book)
6. Innovate and Demonstrate New Concepts
7. Identify opportunities to reduce costs of HVDC & FACTS
8. Technology Transfer – Newsletter, workshop, and conference

Value:

- Keeping utilities abreast of HVDC & FACTS technologies
- Additional revenue to utilities by increasing transmission capacity using HVDC & FACTS
- Assisting utilities with best practices for operation & maintenance
- Providing a technical forum to interact & share with other utilities

STATCOM – Shunt FACTS Device



HVDC Converter Stations and FACTS Technologies (P37.116)
2022 Deliverables

Name	Scheduled Date	Type
Novel Concepts for DC Circuit Breakers and DC-DC Transformers (3002024631)	12/31/2022	Technical Update
Performance and Cost Comparison of SVC, STATCOM, and Synchronous Condenser (3002024629)	04/29/2022	Technical Update
EPRI High Voltage Direct Current (HVDC) Transmission Reference Book (Olive Book): 2022 Update (3002024652)	12/31/2022	Technical Update
HVDC and FACTS Tech Watch Newsletter (3002024633)	12/31/2022	Newsletter

HVDC Reference Book – 30 Chapters

1 Introduction
2. Overview of HVDC Transmission
3. Analysis of Converter Operation
4. Configurations of HVDC Transmission Systems
5. Components of an HVDC Transmission System
6. Planning and System Design
7. Control and Protection
8. Reactive Power
9. AC-DC Interactions
10. Interference Effects from Converter Operation
11. Insulation Coordination
12. Converter Station Equipment
13. DC Transmission with Voltage Source Converters (Update in 2022)
14. DC Trans with Series Cap Compensated Converters

HVDC Reference Book – 30 Chapters

15. Overhead Lines for HVDC Transmission
16. HVDC Cables – (Updated in 2021)
17. Simulation of HVDC Systems
18. Reliability and Availability
19. System Efficiency
20. HVDC System Cost Estimates
21. System Studies
22. Commissioning of HVDC Systems
23. HVDC Project Implementation
24. Operation and Maintenance
25. Life Extension of HVDC Systems
26. AC to DC Line Conversion
27. HVDC Ground Electrodes
28. Integrating HVDC into AC Grid
29. DC Grids
30. HVDC Live Line Work Practices

HVDC Converter Stations and FACTS Technologies (P37.116)
2023 Deliverables

Name	Scheduled Date	Type
Best Practices for Operation, Maintenance, and Refurbishment for Life Extension of FACTS Controllers – SVC & STATCOM Life Extension Guidelines	12/31/2023	Technical Update
Technical Performance and Cost Comparison of UPFC and other FACTS Controllers such as SVC, STATCOM, and Synchronous Condenser	12/31/2023	Technical Update
EPRI High Voltage Direct Current (HVDC) Transmission Reference Book (Olive Book): 2023 Update	12/31/2023	Technical Update
HVDC and FACTS Tech Watch Newsletter	12/31/2023	Newsletter

HVDC Lines: P35.019

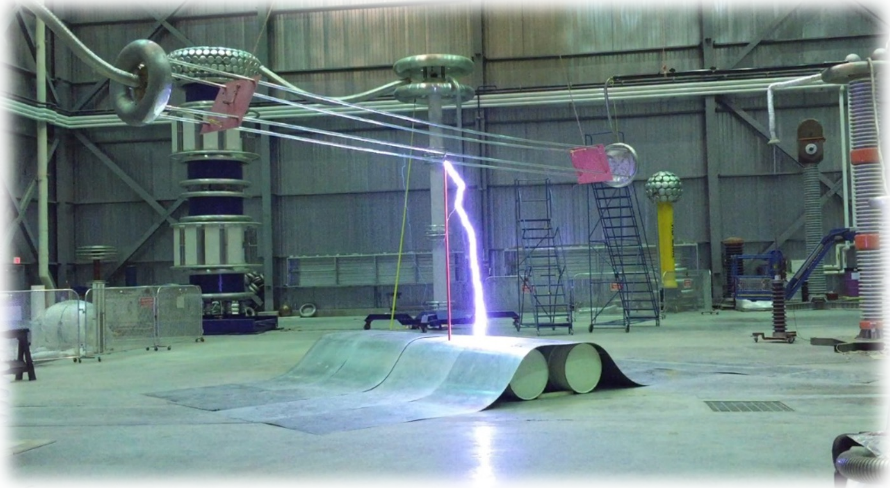
Project Overview

HVDC Performance and Effects(P35.019)

Provide Performance Data on HVDC Line Components

Provide benchmarking results of HVDC system performance and identify areas for improvement

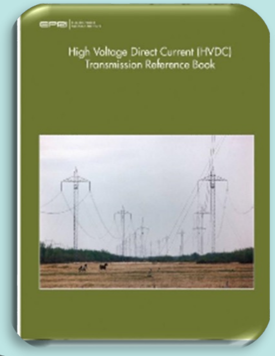
Study Electrical Effects



2022 Deliverables

Product ID	Deliverable Title	Schedule
TBD	Pre-SW TLW Gen 2 – HVDC Electrical Effects Module (BETA)	12/31/2022
3002024470	TLW-Gen2 – HVDC Calculations	12/31/2022
3002024471	HVDC Overhead Line Design Guide - Update	12/31/2022
3002024652	HVDC Reference Book: Olive Book - Update	12/31/2022
3002024472	Voltage Detector Evaluation	12/31/2022

HVDC Lines: Performance and Effects – P35.019



Specification and Performance

- Line Design Guide – updated each year
- Insulator Performance
- Live Line Work

Software and Measurements

- Voltage Detector Evaluation
- AC/DC Hybrid Software

Reference Material

- HVDC Reference Book (Olive Book)
- Corona Testing Guidelines

Information, and Tools to assist in the Design, Inspection and Maintenance of HVDC Lines

2023 Proposed Tasks

- Update HVDC TLW Software
- Collaborate on HVDC Reference Book update
- Design Guide Update
- Anomalous HVDC Flashovers
- Continued Corona Study Evaluation
- Insulator Aging Evaluation
- Corrosion due to HVDC Lines

Not all tasks will lead to a deliverable in 2023

P36.008 HVDC Cable Systems

Project Overview

EPRI Program 36: Underground Transmission Structure

Drivers	Reduced Costs	Improved Reliability	New Technologies	Increased Capacity

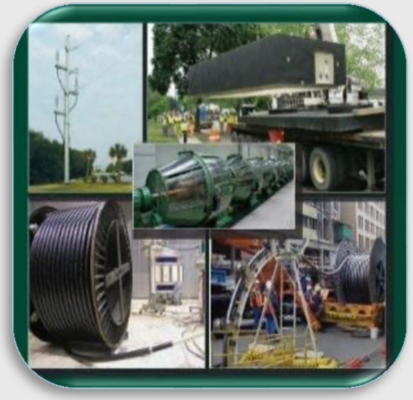
Research Portfolio

001: Design, Construction, Rating, & O&M

002: Extruded Dielectric Cable Systems

003: Laminar Dielectric Cable Systems

006: Principles and Practices



008: HVDC Cable Systems

Member Value Examples	Improved System Design and Construction	Enhanced Inspection Technologies	Reduced Construction and O&M Cost	Paper to Extruded Cable Conversion	Failure Evaluation and End-of-Life Decision	Embracing Remote Energy Transmission

P36.008 HVDC Cable Systems

Approach:

- Investigate & Evaluate design tools to prepare feasibility studies
- Evaluate cable insulation materials and aging characteristics for optimal designs
- Develop methods to extend the life of HVDC cables
- Evaluate operational practices in application of HVDC cables based on technical and economic benefits
- Evaluate condition assessment, maintenance, inspection, and fault location methodologies

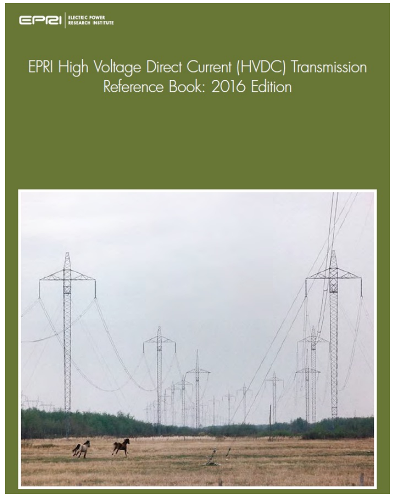
Research Value:

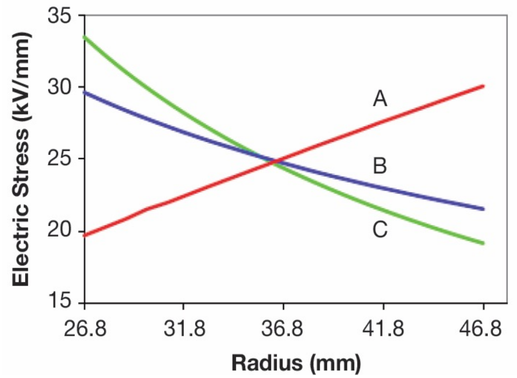
- Research produces new understanding, methods, and tools for utility engineers and designers for HVDC cable applications, operation, and maintenance
- Use of reference books and design tools may result in more effective designs
- Effective inspection and monitoring of assets may lead to increased asset utility and improved reliability
- Better understanding of failure mechanisms and prevention procedures may extend asset life and prevent unexpected outages

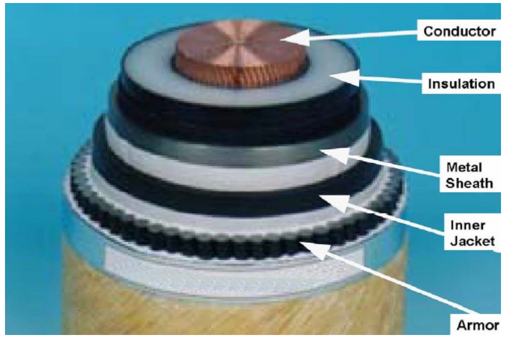
P36.008 HVDC Cable Systems

2022 Deliverables:

- EPRI High Voltage Direct Current (HVDC) Transmission Reference Book: 2022 Edition (Olive Book)
- Underground Transmission Workstation—DC Ampacity (Update and Case studies)
- Guide on HVAC and HVDC Array and Export Power Cables for Offshore Wind Farms: 2022 Edition







EPRI Guide on Inter Array and Export Power Cables for Offshore Wind Farms (Published in 2022 & will be updated in 2023)

1 INTRODUCTION

2 OVERVIEW OF TYPICAL OFFSHORE WIND GENERATION CABLE APPLICATIONS

3 TYPICAL INTER ARRAY CABLE APPLICATIONS

4 TYPICAL AC EXPORT CABLE APPLICATIONS

5 TYPICAL HVDC EXPORT CABLE APPLICATIONS

6 CABLES FOR FLOATING WIND GENERATION SYSTEMS

7 MAINTENANCE OF INTER ARRAY AND EXPORT CABLE SYSTEMS

8 SUMMARY, TRENDS, AND EPRI R&D

9 REFERENCES AND BIBLIOGRAPHY

EPRI Guide Outline

What EPRI is doing on HVDC cables and Multi Terminal DC & DC Grids

Completed or On-going:

- HVDC Transmission Cable Ratings (2018)
- Underground Transmission Workstation Software for AC and DC Cable Ampacity Calculations (2020)
- Off-Line Fault Location Systems for Long HVDC Cables (2020)
- Impartial Forensic Analysis of Cable Failures

2023 and Future Plan:

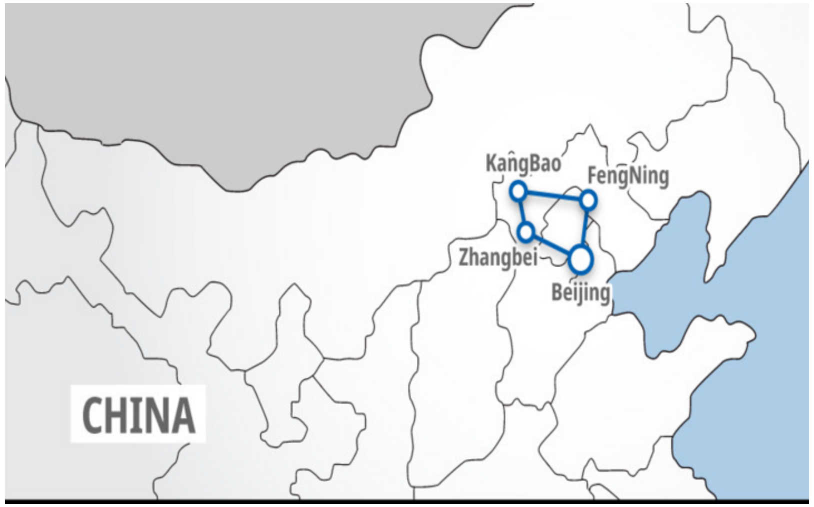
- Guide on HVAC and HVDC Array and Export Power Cables for Offshore Wind Farms (first edition in 2021)
- Forensic Analysis of Cable Failures (Engaging Cable Users)
- Thermo-mechanical Performance/Aging Tests (Planning and acquiring cable samples)

Supplemental Project

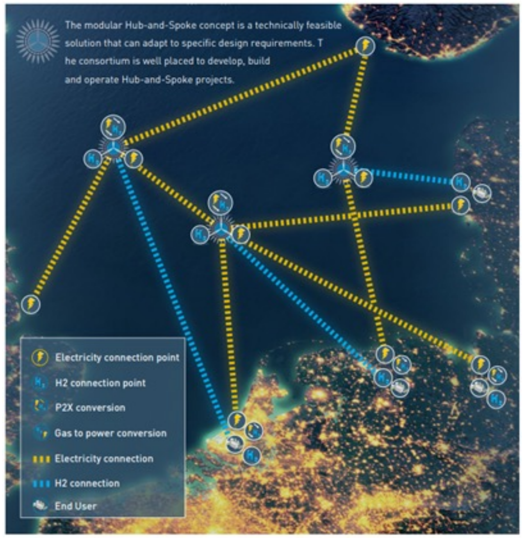
- MTDC and DC Grid Applications for Offshore Wind Energy Resource Integration - Technologies, Challenges, and Recommendations

Multi-terminal DC & DC Grids

- Multi-terminal DC & DC grids will become increasingly important for interconnectors and offshore wind farms.
- Atlantic Wind Connection project proposed this development, but unfortunately did not gain sufficient regulatory and political traction at the time. Variations are expected.
- Other proposals are gaining momentum in Europe, such as the Northsea Wind 'hub-and-spoke' Power Hub.
- The world's first 5-terminal ±200 kV VSC-HVDC project was put into service in 2014. This project connects China's mainland to five isolated islands.
- Zhangbei 4-terminal HVDC in China is the world's first HVDC project using modular multi-level voltage sourced converter (VSC) technology at ±500kV started operation in June 2020.



Atlantic Wind Connection Project Overview



Northsea Wind Power Hub (Credit: www.northseawindpowerhub.eu/)

P40.E HVDC Planning

Project Overview

HVDC Planning Project - *Objective and Activities*

- Understand benefits and challenges of HVDC technology
- Provide systematic approach and tools for planning transmission solutions with HVDC
- Develop methodologies and software tools
- Assess benefits and implementation of new HVDC technologies and concepts

Deliverables

2021

Product ID	Product Name	Deliverable Type	Published Date
3002021760	Use of HVDC to facilitate integration of renewable generation - Case Study	Technical Update	Dec. 2021
3002021764	High Voltage Direct Current (HVDC) Planning Guide - 2021 Update	Technical Update	Dec. 2021
Link to recording	Multi Terminal HVDC Offshore Grids	Webcast	May 2021
3002020640	2021 Transmission Infrastructure Cost Estimating Guide	Technical Update	Dec. 2021
3002021570	Transmission Infrastructure Techno-economic Analysis – Interactive Tool	Software	Dec. 2021

2022

Product ID	Product Name	Deliverable Type	Published Date
3002024624	Embedded (point to point) VSC-HVDC with grid-forming capability - Assessment of challenges and solutions	Technical Update	Dec. 2022
3002024627	High Voltage Direct Current (HVDC) Planning Guide - 2022 Update	Technical Update	Dec. 2022

HVDC Planning in 2022 & beyond (P40.E)

- System reliability and security impact of increased number of HVDC connections
- Grid forming capability implemented in point-to-point HVDC-VSC – Analysis and Case Study
- Representative cost and performance of HVDC and AC transmission infrastructure technologies

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