HVDC LEARN

Modules for Maturing HVDC Electric Transmission Knowledge

Funded by the US Department of Energy (DOE)
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HVDC-Learn Short Course

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Module 2b: VSC Converter Station Technologies

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Outline

Part 1: Introduction

- Motivation and Evolution
- VSC HVDC Configurations
- Operating Principles

Part 2: Converter Stations

- Station Layout Overview
- Component Walkthrough
- Case Studies – Transbay Cable Project

Part 3: Summary and Future

- Key Takeaways
- Q&A

Learning Objectives

- Understand the characteristics of VSC HVDC
- Understand the components in VSC HVDC stations

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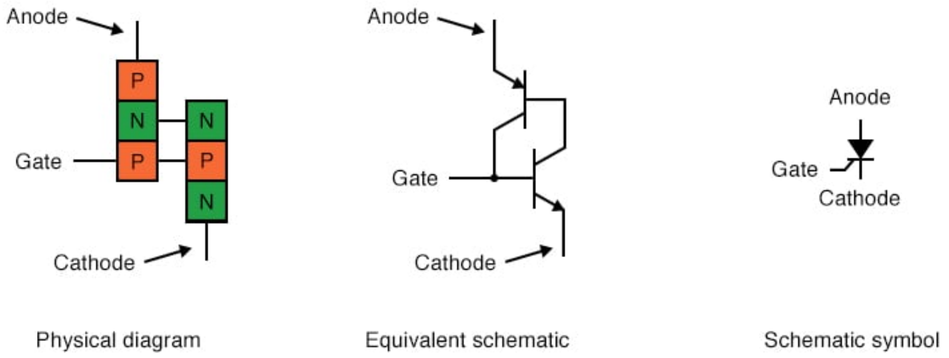
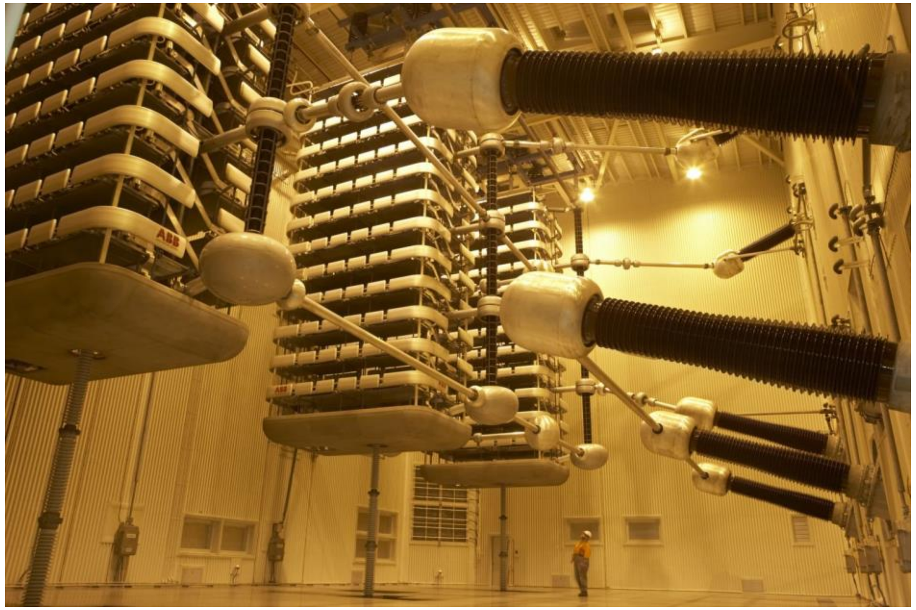
Context and Motivation – LCC HVDC

Line Commutated Converter (Classical)

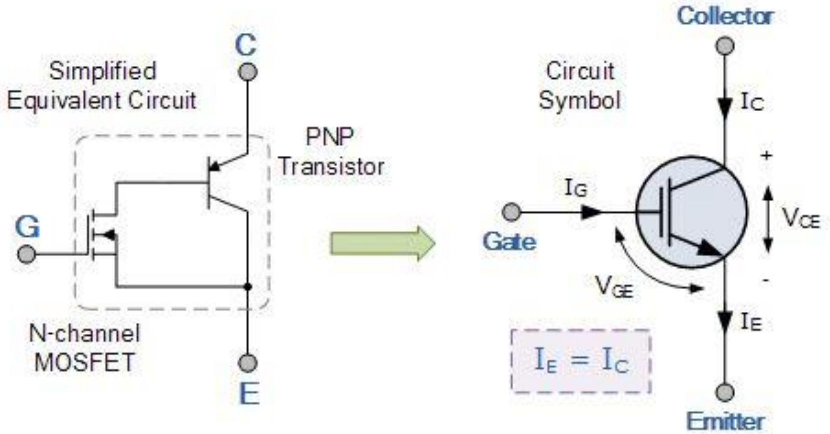
- Thyristor-based technology (Silicon-controlled rectifier)
- Requires external AC voltage for commutation
- Consumes reactive power (current always lag voltage)
- Require harmonics filtering, because six or 12 pulse bridge converter generate significant low-order harmonics





Voltage Source Converter-Based HVDC

- IGBT-based technology enables full control of turning on and off.
- Can operate in weak AC grids
- Can support reactive power
- Less harmonics to filter–smaller footprint
- Fast power flow reversal

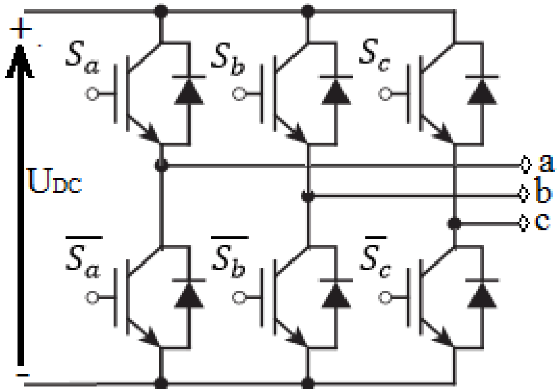


VSC HVDC Evolution (1)

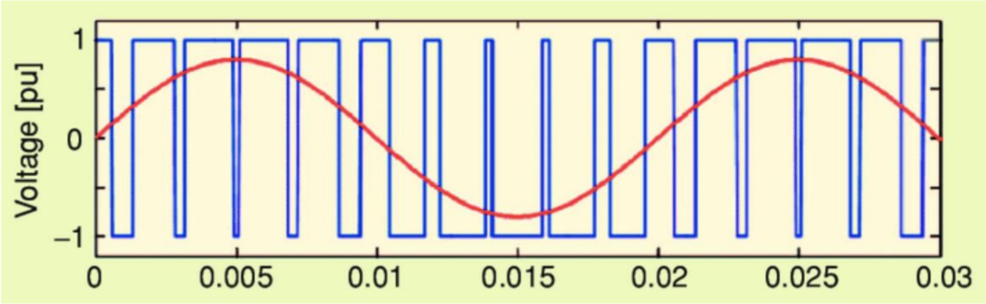
Early VSC: 2/3 level converters (1990s-2000s)

- Capacity in the order of 50 MW
- Voltage level: $\pm 80\ kV$

World's first VSC HVDC in Gotland, Sweden, connecting wind generation (lower-left) to load substation (upper middle)



Simple topology + PWM



Two-level converter output voltage waveform

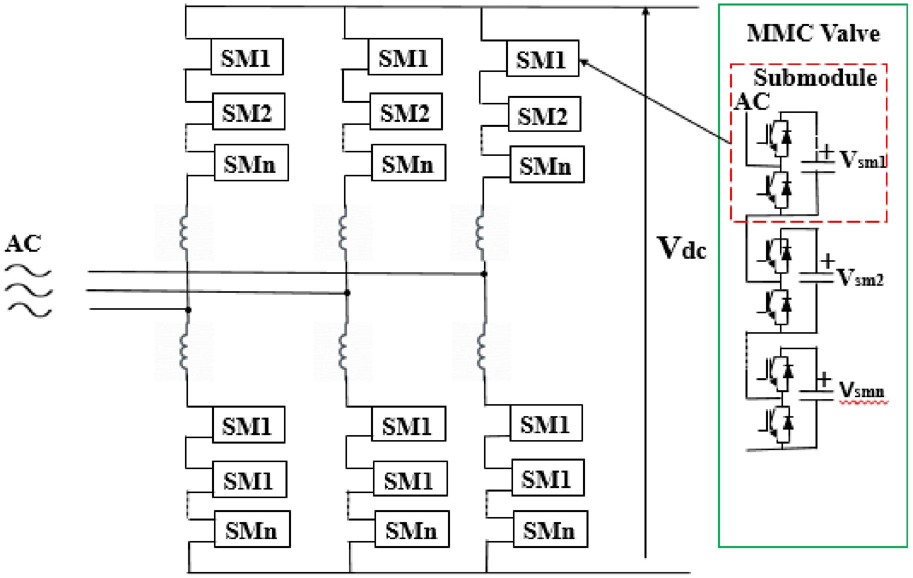
VSC HVDC Evolution (2)

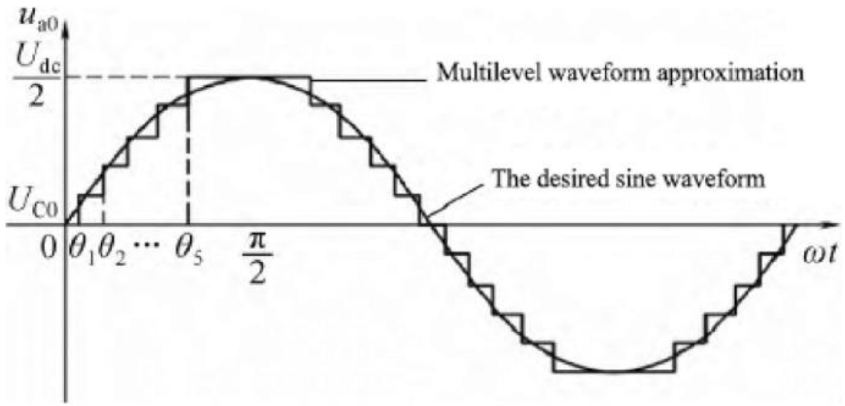
Current VSC Technology: Multi-level Modular Converter (MMC)

- Using a staircase waveform to approximate a sinusoidal wave
- Advantages include lower switching frequency for each module, and lower harmonic distortion.

Growing capacity and voltage levels

- >400 MW
- $\pm 500\ kV$ and more





Evolution of VSC HVDC (3)

VSC HVDC are branded under different names

- Hitachi ABB HVDC Light ®
- Siemens HVDC PLUS ®
- VE Vernova MVDC
- Mitsubishi VSC-HVDC

Early 2000s

- Improvements to cable insulation -> increased DC link voltage
- Three-level active neutral point clamped CSV

Mid 2000s

- Improved IGBT devices support higher switching frequency
- Briefly went back to two-level topology (e.g., the 300 MW Caprivi link; first overhead HVDC)

Late 2000 to date

- MMC-based topology with half-bridge converter cells

A Closer Look at the Gotland VSC HVDC

World's first commercial HVDC project in 1954 (20 MW, 100 kV)

Application: connect remote loads

Bäcks/
Visby

Näs

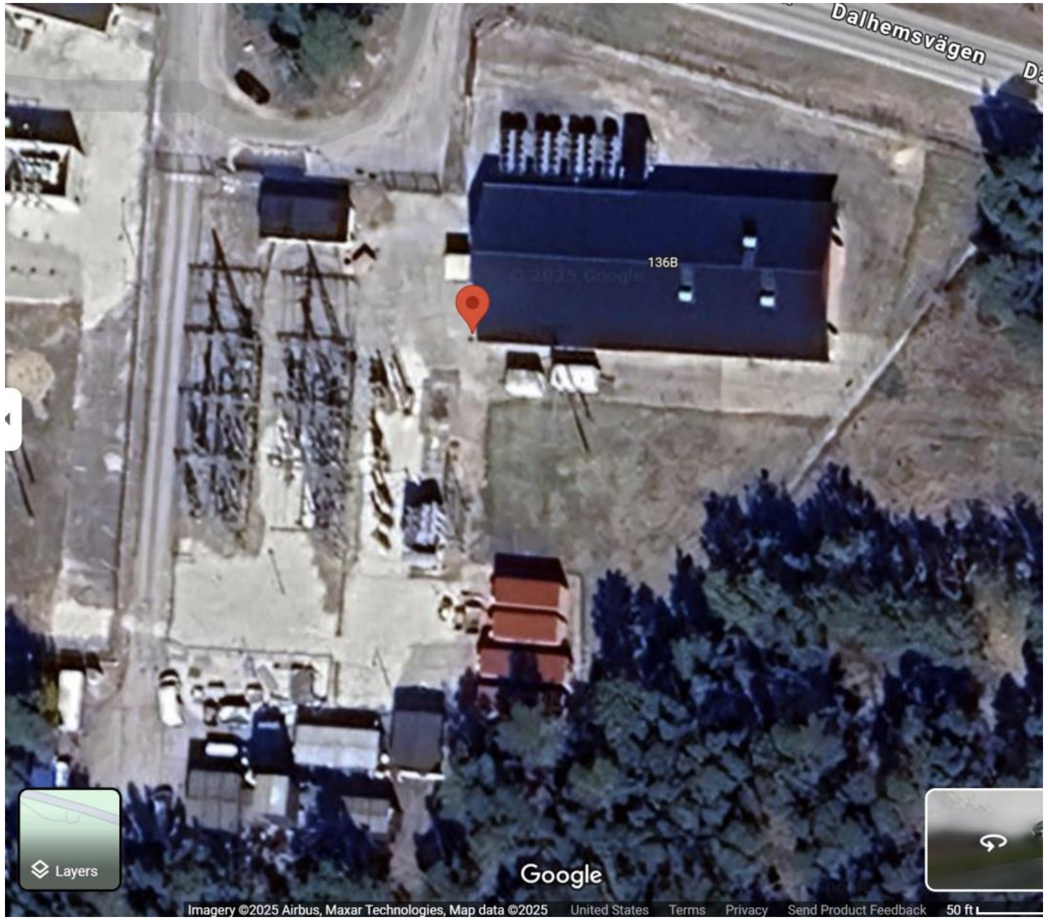
World's first commercial VSC HVDC project (ABB HVDC Light®) in 1999

- 40 MW wind generation in the breezy south; load center in the town of Visby

- 70 km underground cable
- 50 MW power rating
- Symmetric monopole at ± 80 kV

Nas-Visby HVDC Substations

Näs Substation 57°05′58″N 18°14′27″E



Visby Substation 57°37′29″N 18°21′18″E

Wikipedia: HVDC Visby–Näs: https://en.wikipedia.org/wiki/HVDC_Visby%E2%80%93N%C3%A4s
List of Hitachi ABB HVDC Light Project:
https://publisher.hitachienergy.com/preview?DocumentID=POW0027&LanguageCode=en&DocumentPartId=001&Action=launch

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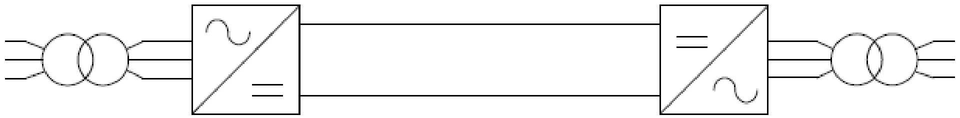
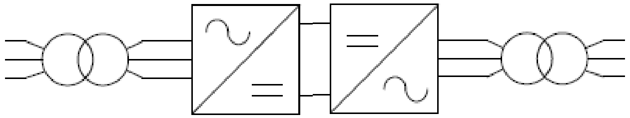
VSC HVDC Configurations: P2P

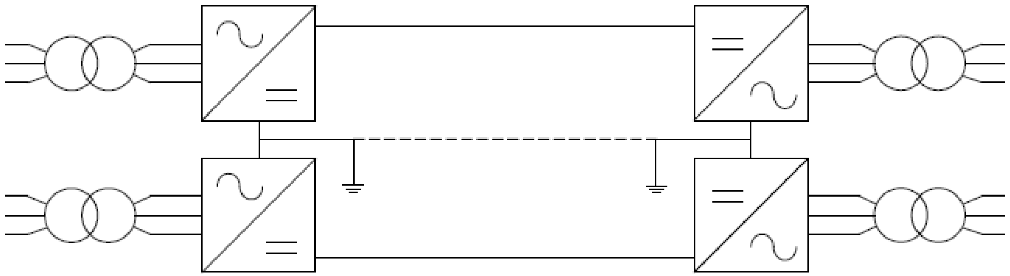
Monopolar system with ground or metallic return



Symmetric monopolar system:
- $\pm\frac{V}{2}$ in DC voltage



Back-to-back system

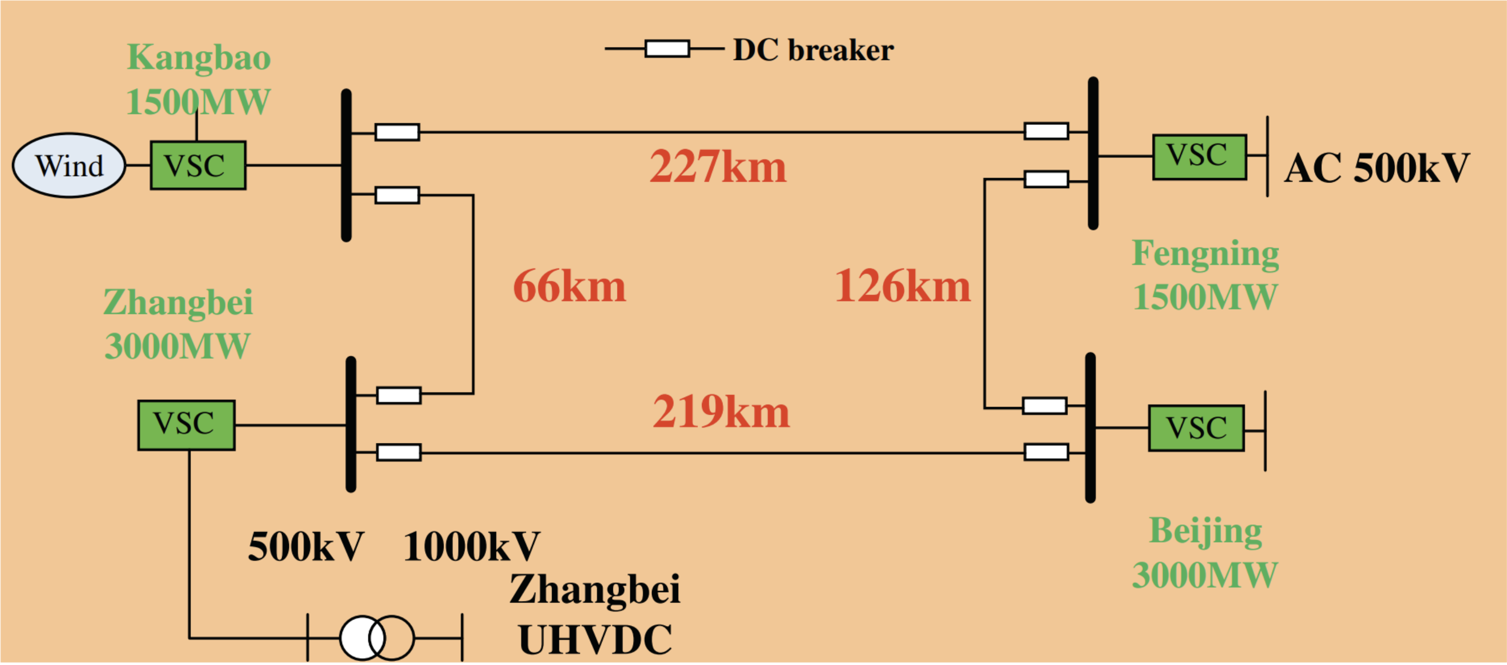


Bipolar system; $\pm$ DC voltage
Metallic return (three lines) or ground return (two lines)
Increases the capacity and reduces grounding requirements

VSC HVDC Configurations: Multi-Terminal

Feed terminals

Solar



Regulating terminal: pumped-storage hydro [DC voltage control]

Receiving terminal

World's first multi-terminal VSC HVDC project in Zhangbei, China
±500 kV, sending 4,500 MW of renewables

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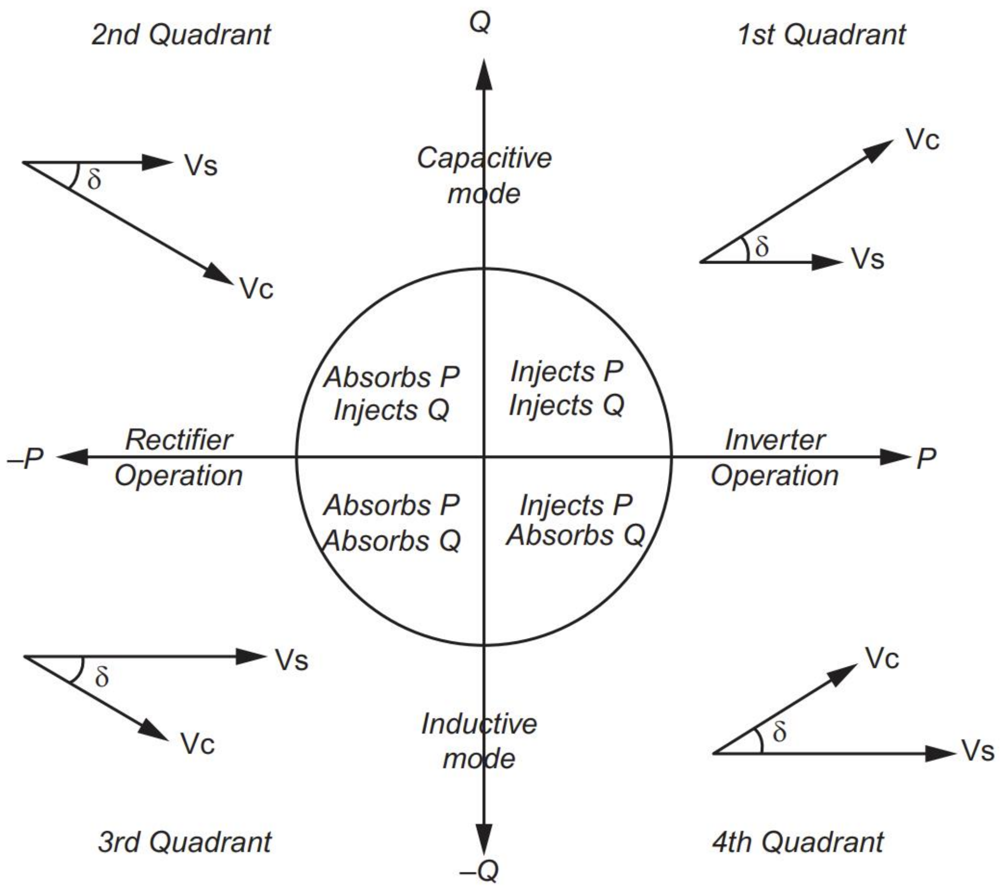
VSC Operating Principles: Four Quadrants



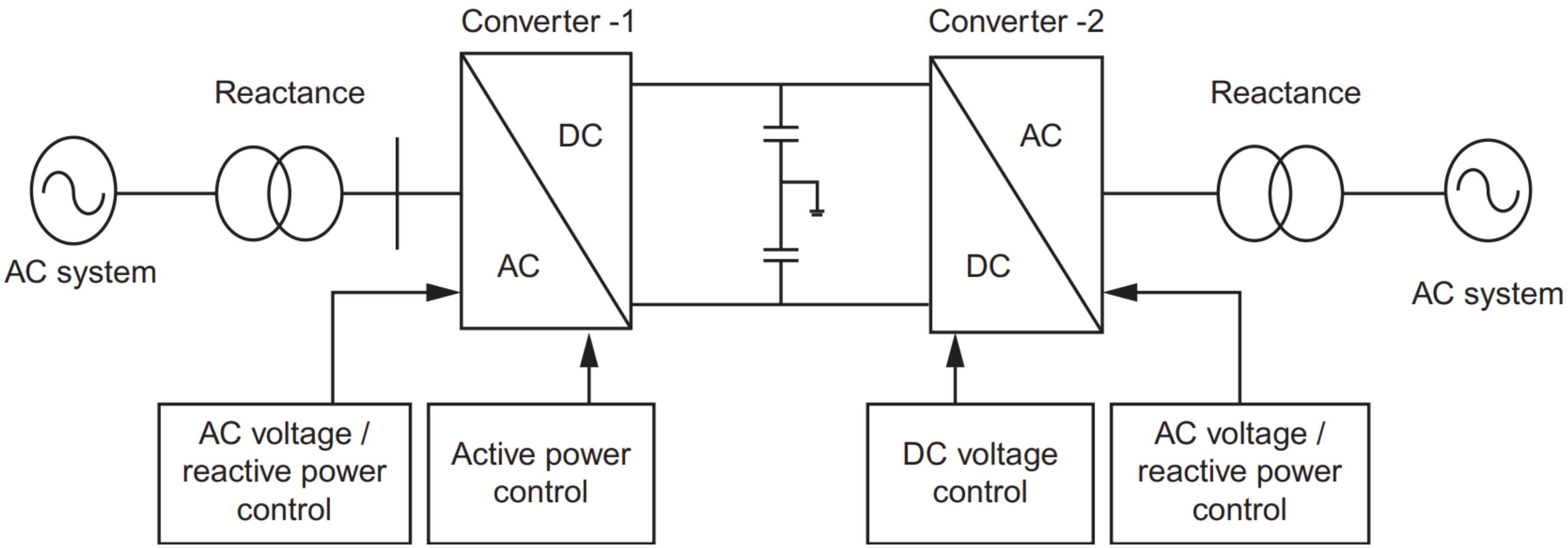
A VSC converter station can operate in one of the four modes

- V_s is the AC system coupling point voltage
- V_c is the converter terminal voltage

Power injection from VSC to grid:

- $P = \frac{V_s V_c}{X} \sin\delta,\ Q = \frac{V_c}{X}(V_c - V_s \cos\delta)$
- δ is positive when V_c leads V_s; negative otherwise

Back-to-Back VSC HVDC Control Principles



In terms of active power control:

- One terminal controls the DC link voltage
- The other terminal controls active power to the setpoint by varying DC current

Reversing the power flow only requires a change of active power reference

- Does not require the reversal of DC voltage polarity

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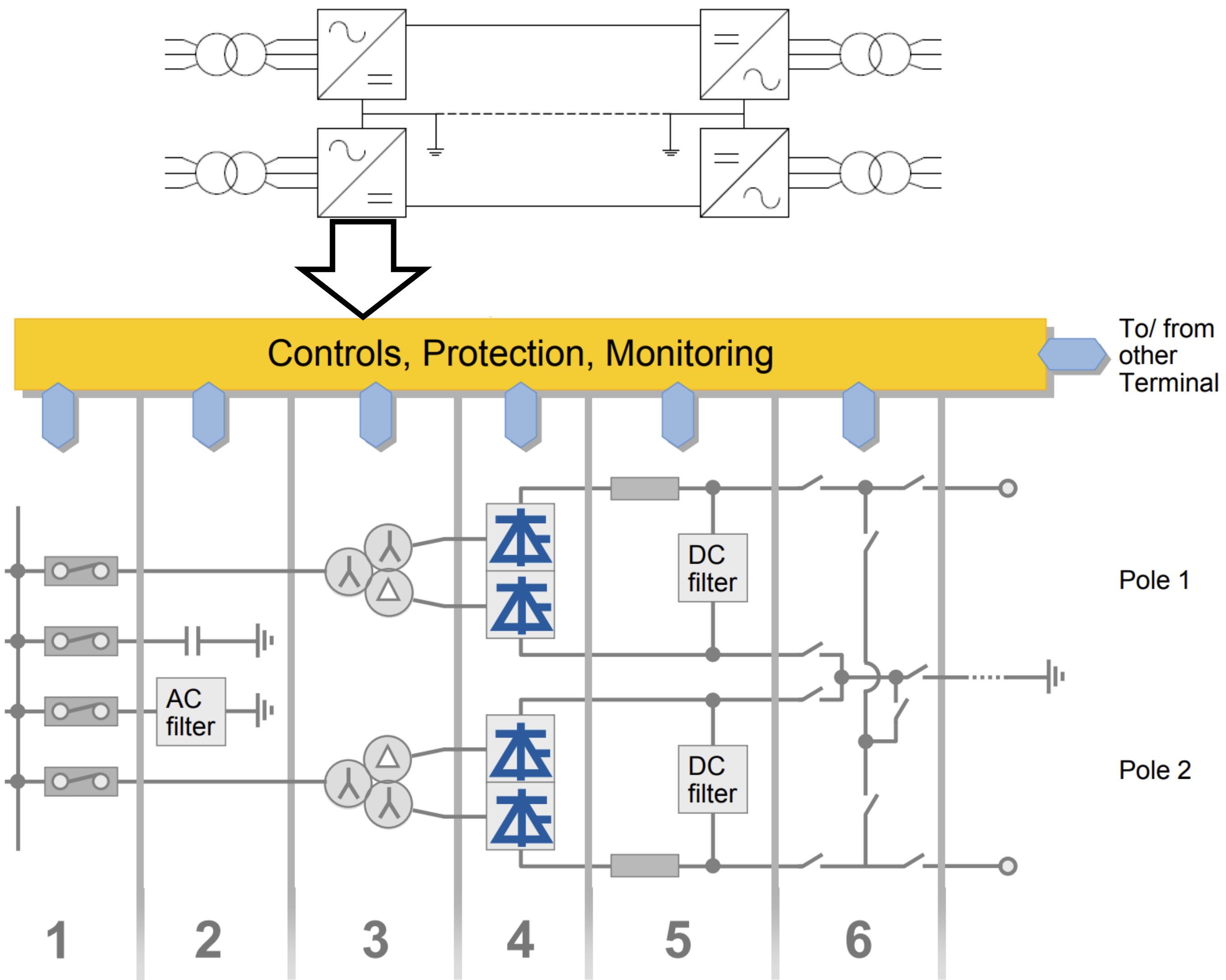
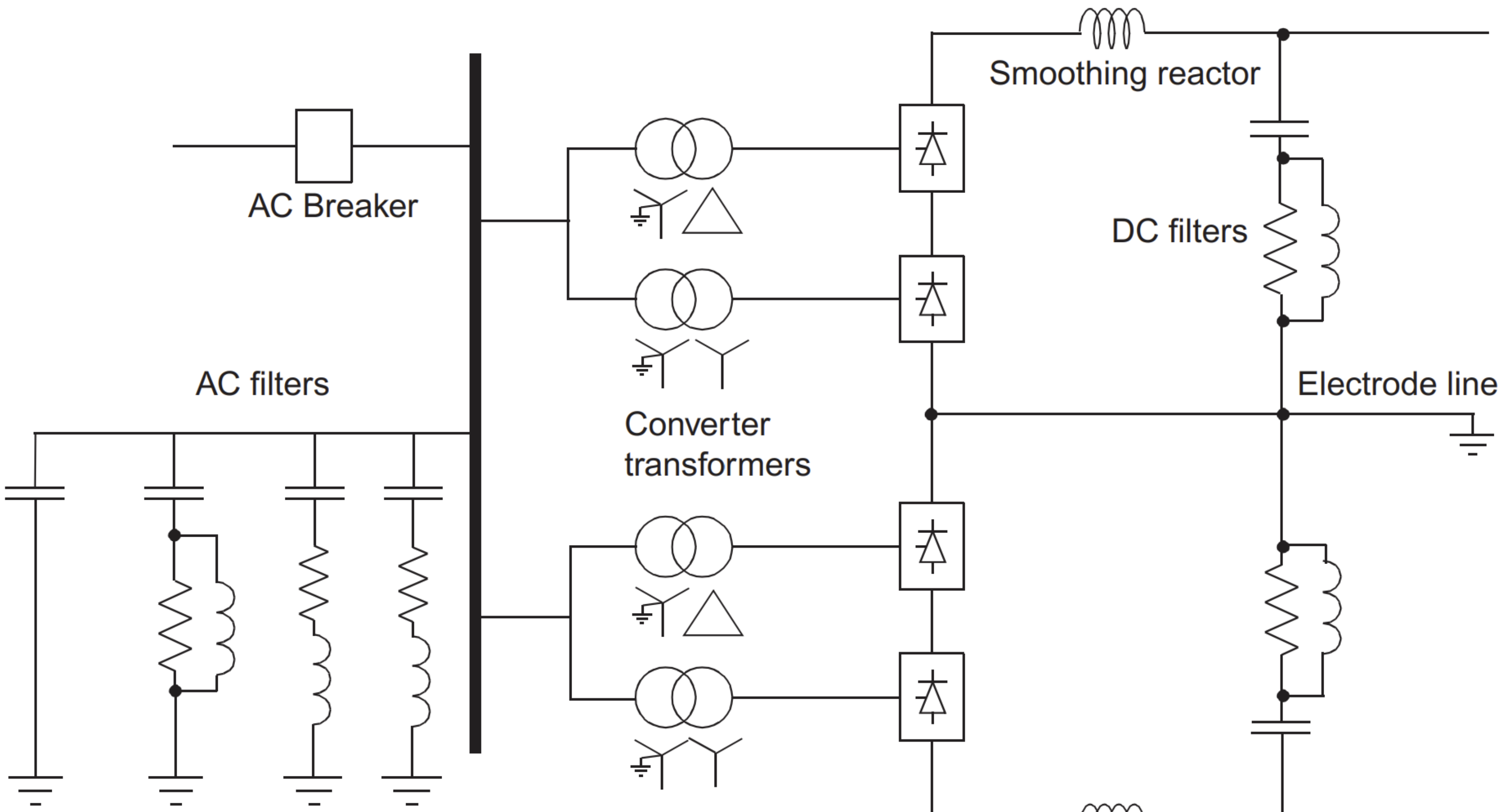
HVDC Station for Long Distance Transmission



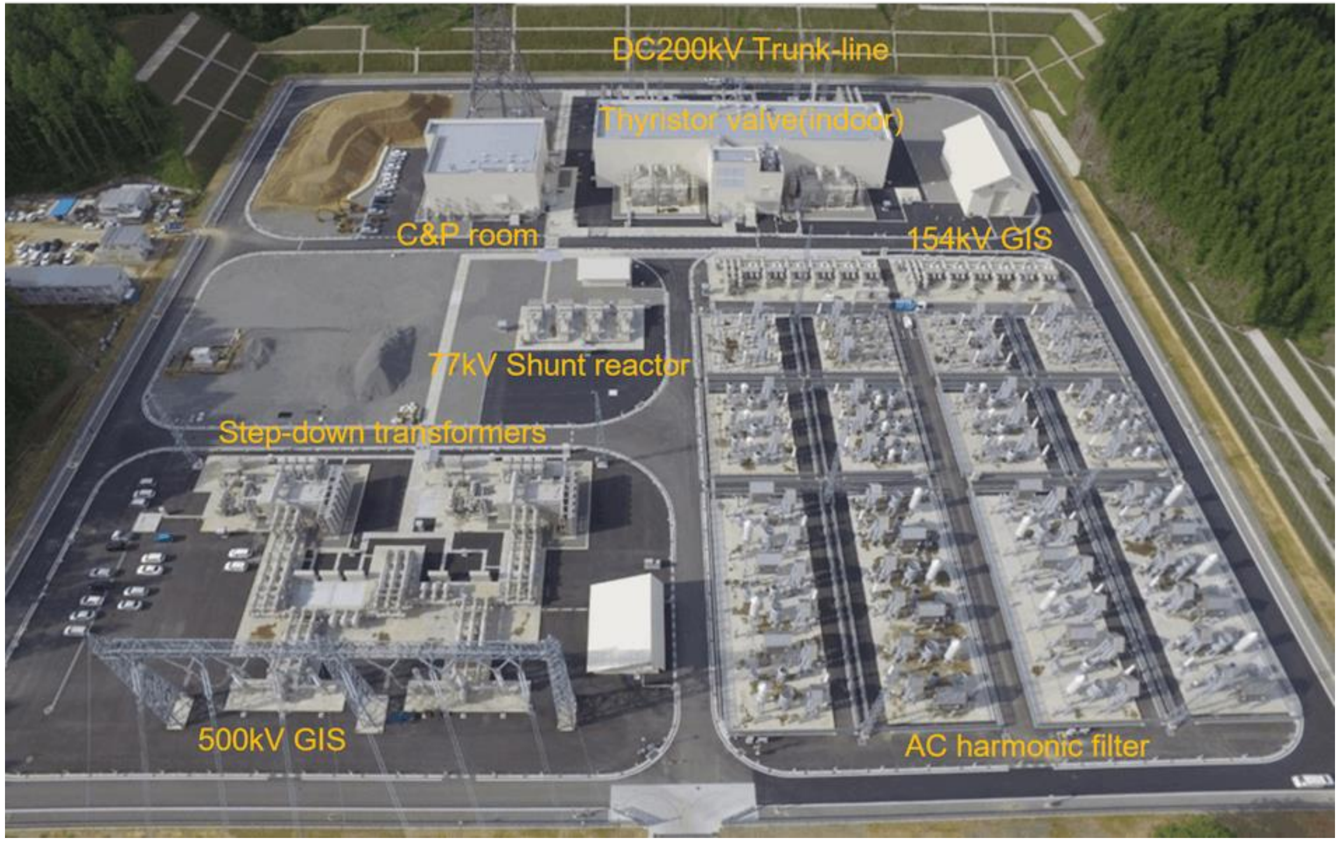
1. AC Switchyard
2. AC Filters & Capacitor Banks
3. Converter Transformers
4. Converters
5. Smoothing Reactors and DC Filters
6. DC Switchyard

The structure is similar for both LCC and VSC

Single-line Diagram of a Converter Station



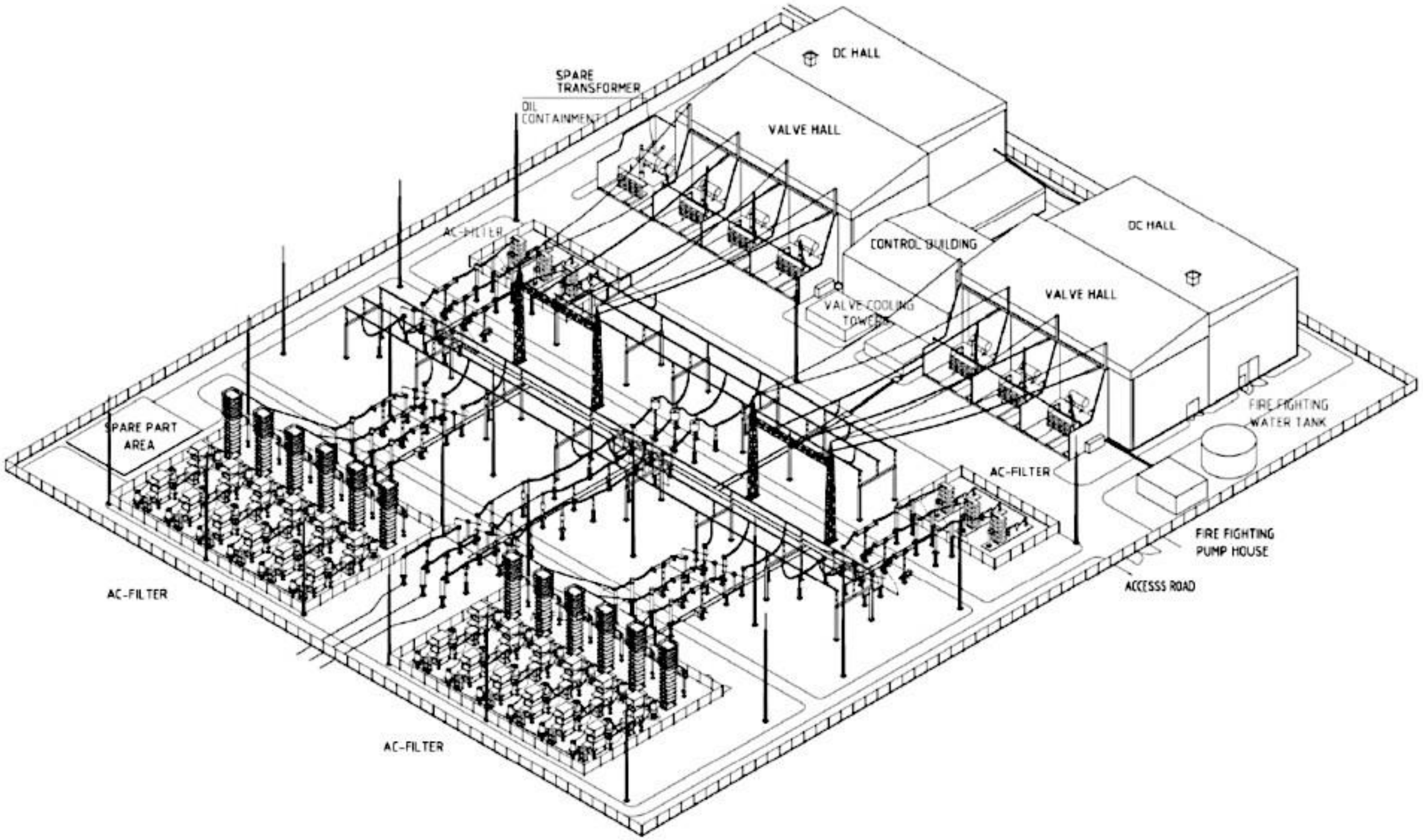
Aerial View of the Hida LCC HVDC Station



- Hida converter station of the Hida-Shinano HVDC Link
- 900 MW, Bipolar, $\pm 200\ kV$ overhead line
- Commissioned in 2021

https://www.tdworld.com/digital-innovations/hvdc/article/21177078/hvdc-link-increases-interconnection-capacity

LCC HVDC Substation – Large Footprint



LCC-HVDC requires significant AC harmonics filtering

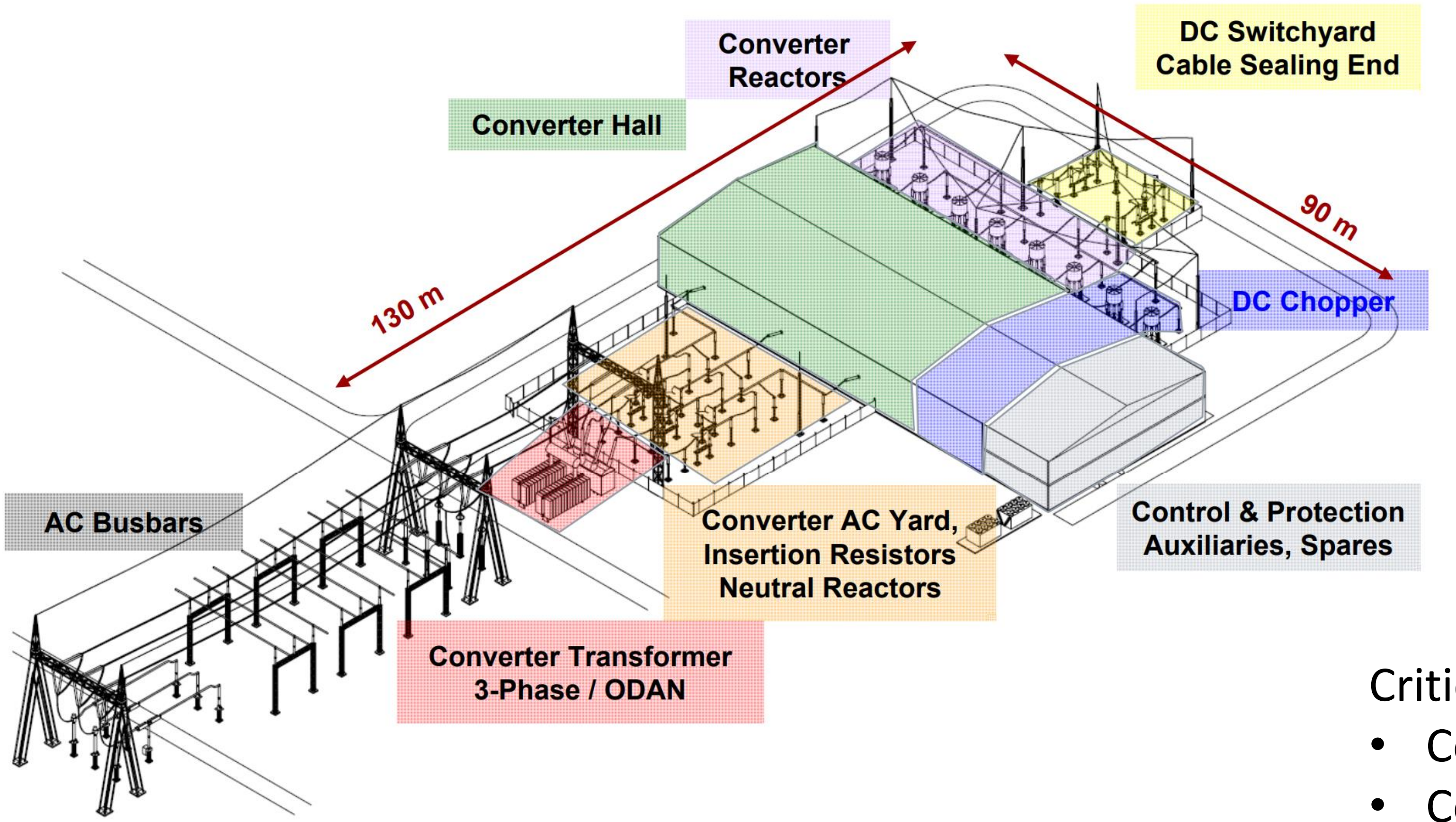
LCC-HVDC substations thus have large footprints

VSC HVDC Converter Station

Aerial view of the EirGrid East-West Interconnector Converter Station

https://www.youtube.com/watch?app=desktop&v=C-J0Ac8v2ho

Key Components



Key components:

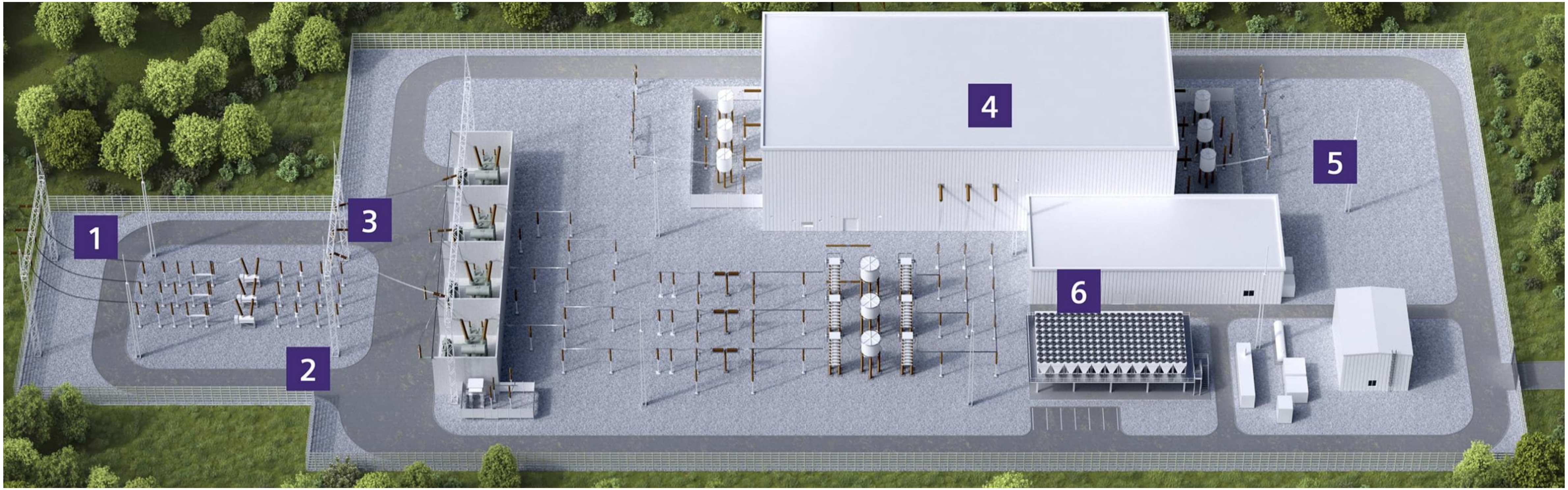
- AC switchyard
- AC equipment yard
- Converter hall
- DC equipment yard (may be integrated in converter hall)
- Control & auxiliary building

Critical supporting systems:

- Cooling systems
- Control and protection
- Auxiliary power supply
- Grounding systems

Live Demo: Siemens HVDC PLUS ®

- https://bluebird-alliance.kugelrundblick.de/siemens_energy_hvdc/



AC Switchyard Components (1)

- AC circuit breakers
- Disconnector
- Surge arresters
- AC filters

Disconnector

AC Switchyard Components (2)

LCC stations require significant harmonics filtering; also requires reactive power supply

Northern Ireland –Scotland link

Basslink HVDC (Tasmania)

Converter Transformer

- Three-winding transformers are common
- Provide the AC voltage needed for converter operation
- Increased insulation levels to withstand transients

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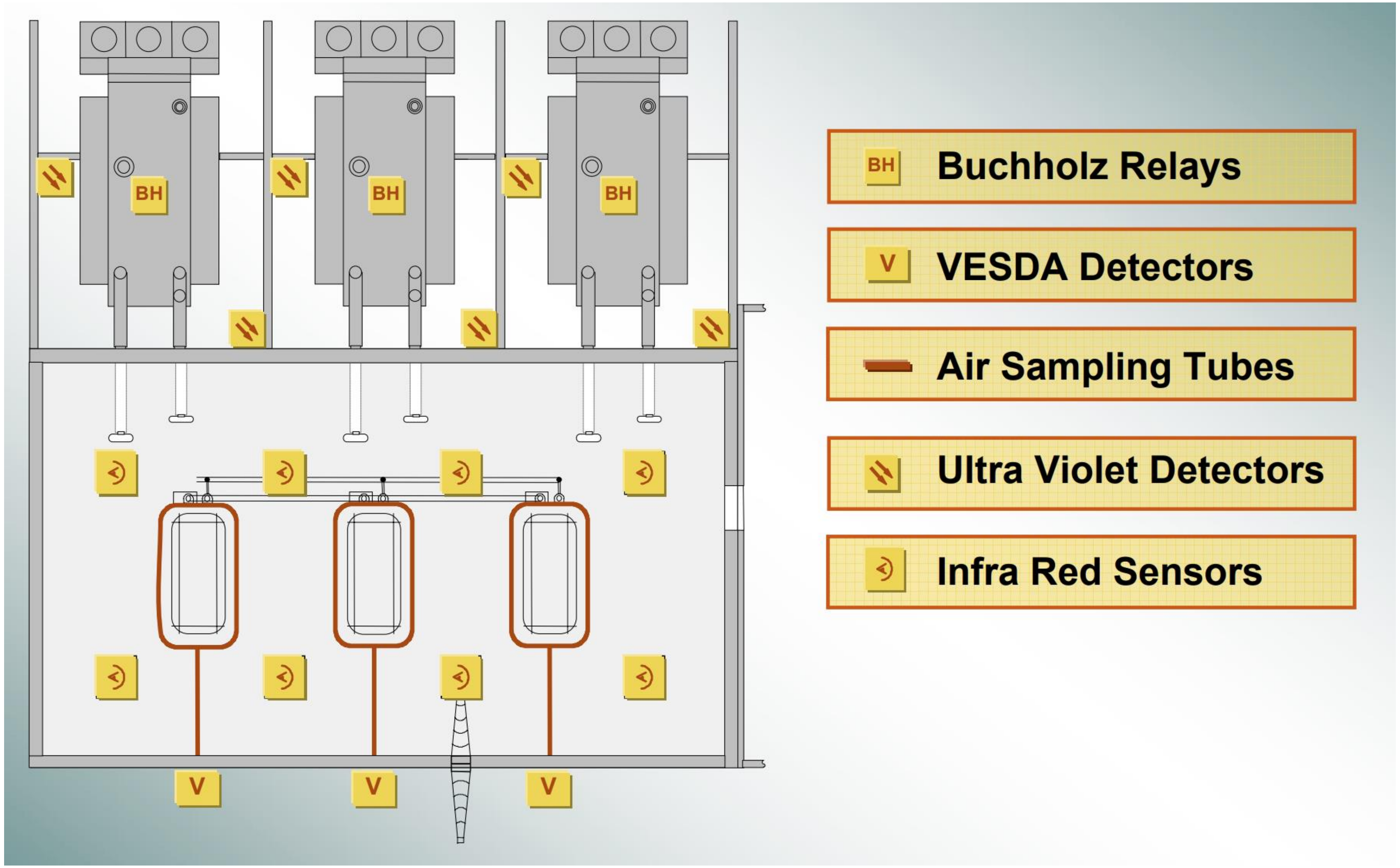
Transformer – Fire Protection



Source: https://ewh.ieee.org/r6/san_francisco/pes/pes_pdf/Transbay_Cable.pdf

Electrical Protection System

- Converter transformer protection
- AC overcurrent protection
- AC filter overload and unbalance protection
- Converter current differential protection
- DC overcurrent protection
- …

Indoor DC Yard Components

Disconnector switch (closed)

DC smoothing reactor

Alternatively, An Outdoor DC Yard (1)

- DC bushing
- Smoothing reactor

Alternatively, An Outdoor DC Yard (2)

Storebælt: Station Herslev – DC Yard

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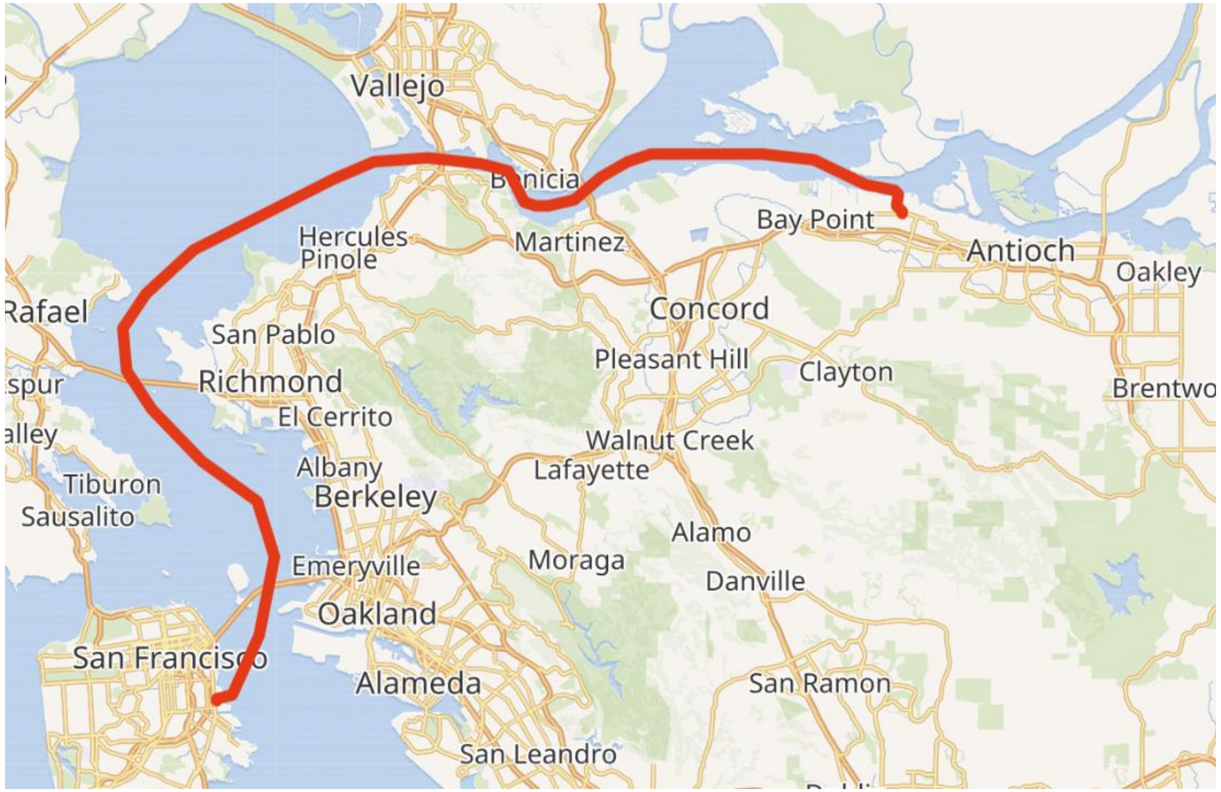
Trans Bay Cable Project – VSC HVDC (0)

CAISO Conducted a Multi-Year Stakeholder Study Process to Solve San Francisco's Electric Infrastructure Problems

- Phase I: Jefferson to Martin transmission line allowed shutdown of Hunters Point transmission line
- Phase II: TBC selected as Long Term Reliability Solution needed by 2012

 - Need date updated to Summer, 2010 in February, 2007 to avoid rolling blackout



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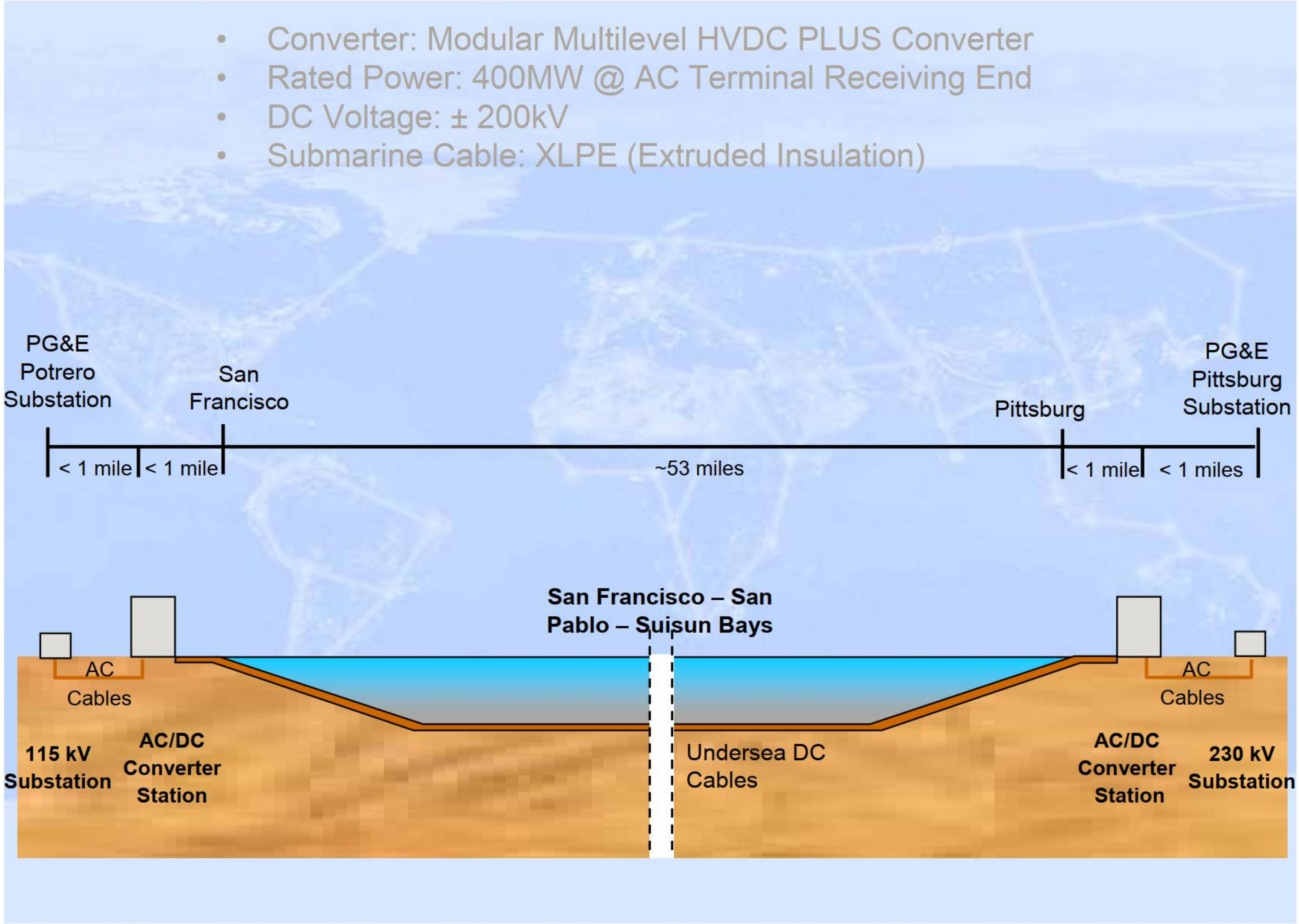
Trans Bay Cable Project – VSC HVDC (1)

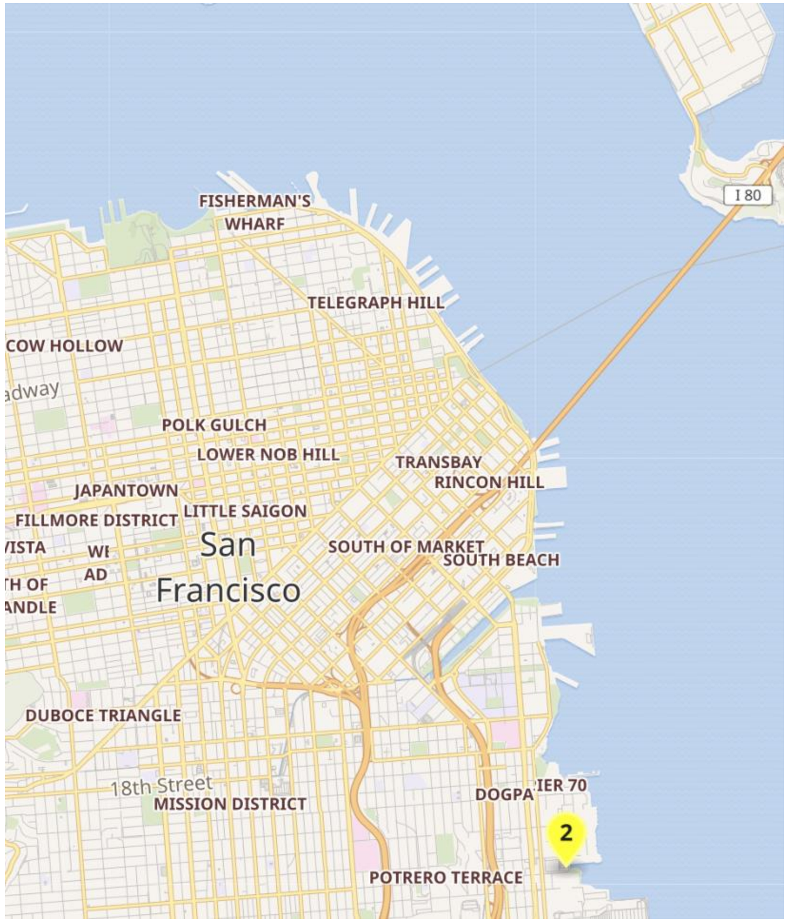


HVDC PLUS® was selected

- 53 miles of cable under SF bay
- $\pm$200 kV
- P = 400 MW (40% of peak load in SF
- Q = $\pm$ 170 to 300 Mvar

Trans Bay Cable Project – VSC HVDC (2)

- Potrero Hill station



Trans Bay Cable Project – VSC HVDC (3)

TBC was commissioned in 2010.

Total project cost was $400M in 2010 (only 33% over its 2004 estimate)

NextEra acquired it for $1bn in 2018

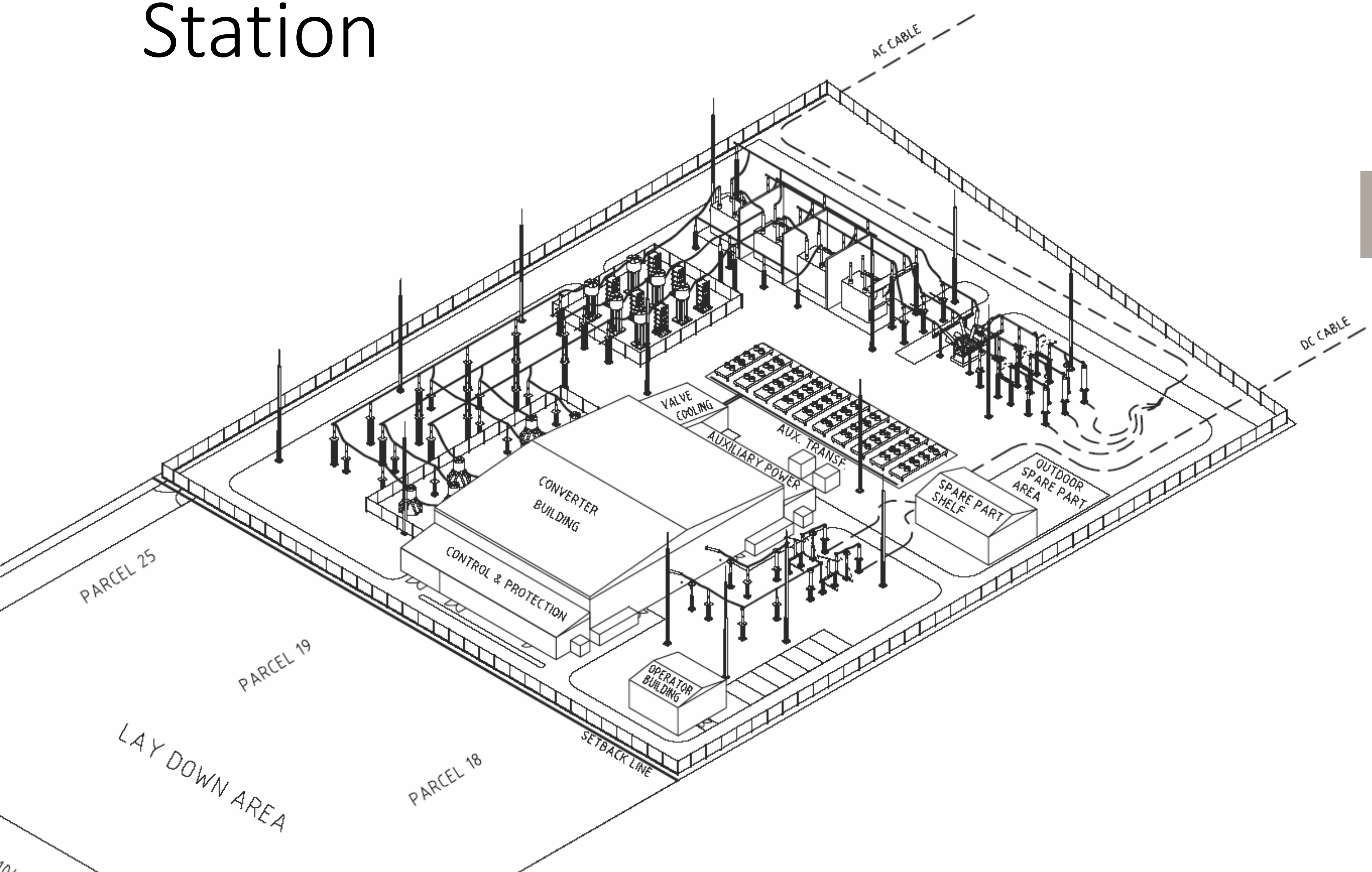
In 2018, Siemens updated control software to allow Pittsburg substation to energize the DC link and feed up to 300 MW into San Francisco.

Trans bay cable project – AC switchyard

TBC's net availability is 99.88% (excluding scheduled maintenance) as of March 2025.

10.74 hours of outage + 1 scheduled maintenance in 2024

Trans Bay Cable Project - Pittsburg Converter Station



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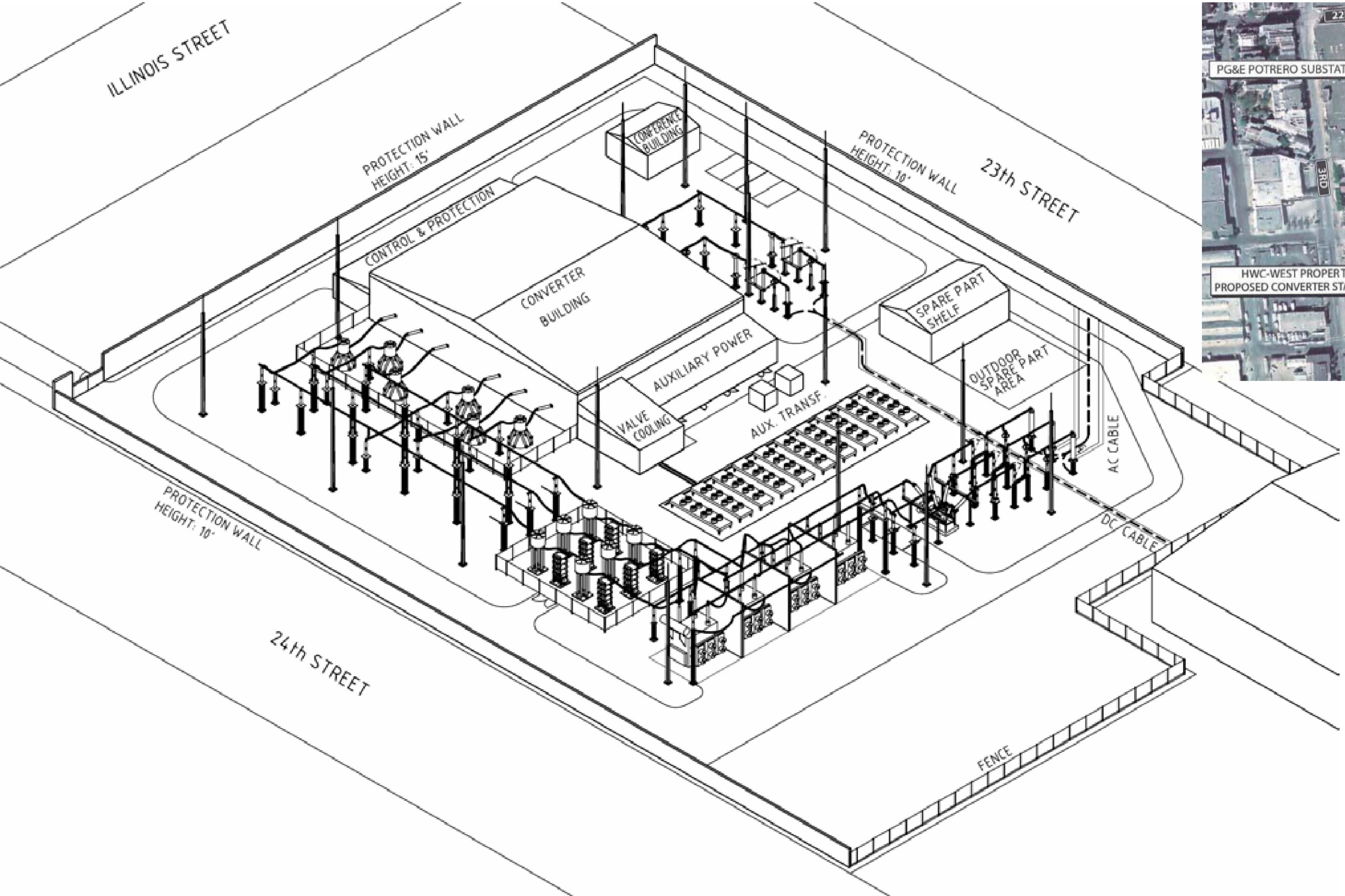
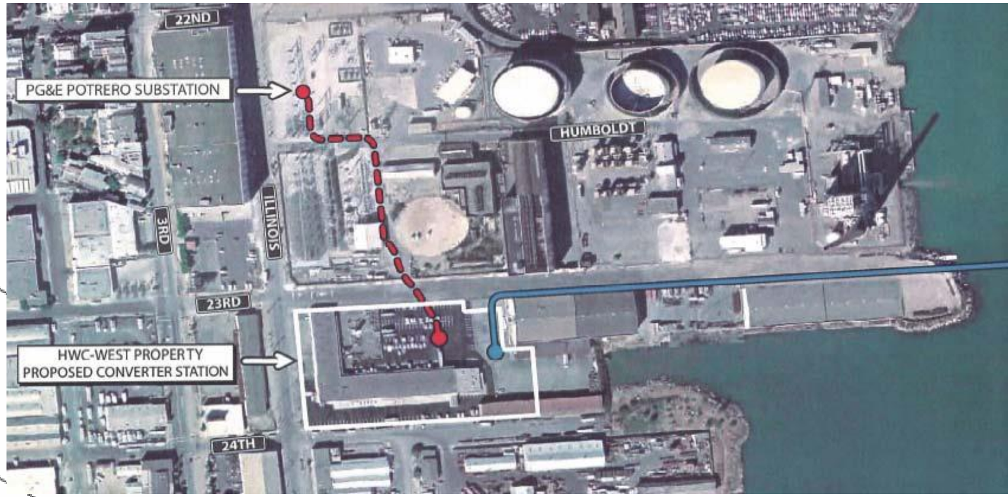
Potrero Hill Converter Station





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Trans Bay Cable Project - Proposed Cable Laying Vessels

Ship: Giulio Verne (Deep Water Cable Installer)

Barge (Shallow Water Cable Installer)

Hydroplow

Trans Bay Cable Project – VSC HVDC (4)

- The project provides a long-term energy and capacity solution for the Bay Area Grid
- The project also contributed to the retirement of the last fossil fuel power plant in San Francisco
- Potrero power station was shut down in January 2011.

Trans Bay Cable Project – VSC HVDC (5)

- 150 years later, power is made available to the San Francisco Bay Area in a more clean, reliable and compact way.

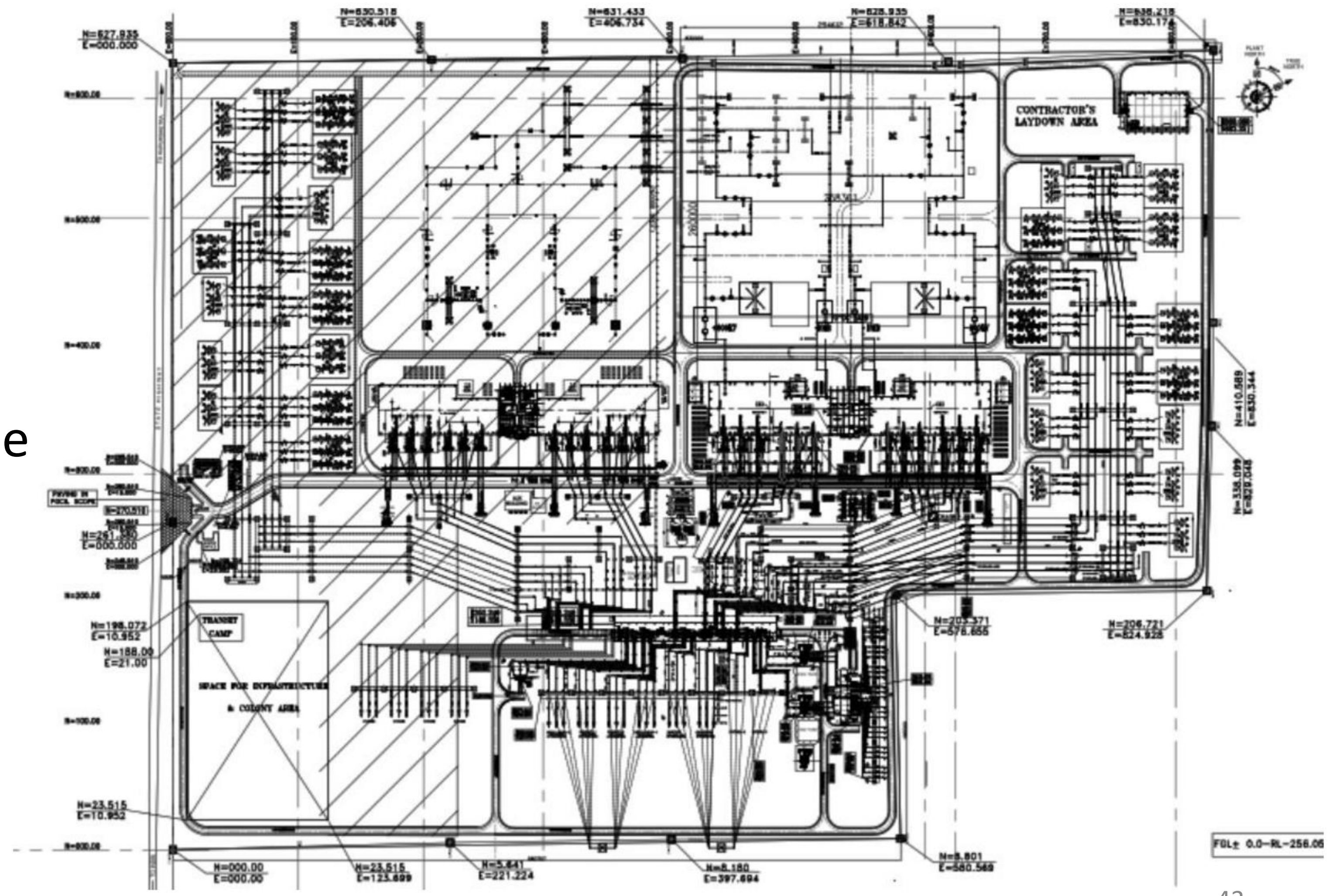
(Google Street View)

Comparison of LCC and VSC Substations (1)

Footprint

- 630 m x 830 m = 53 hectares
- 2,066 ft x 2,723 ft = 130 Acres

LCC Technology : 6,000MW Double Bipole 2 x 3,000MW/±800kV



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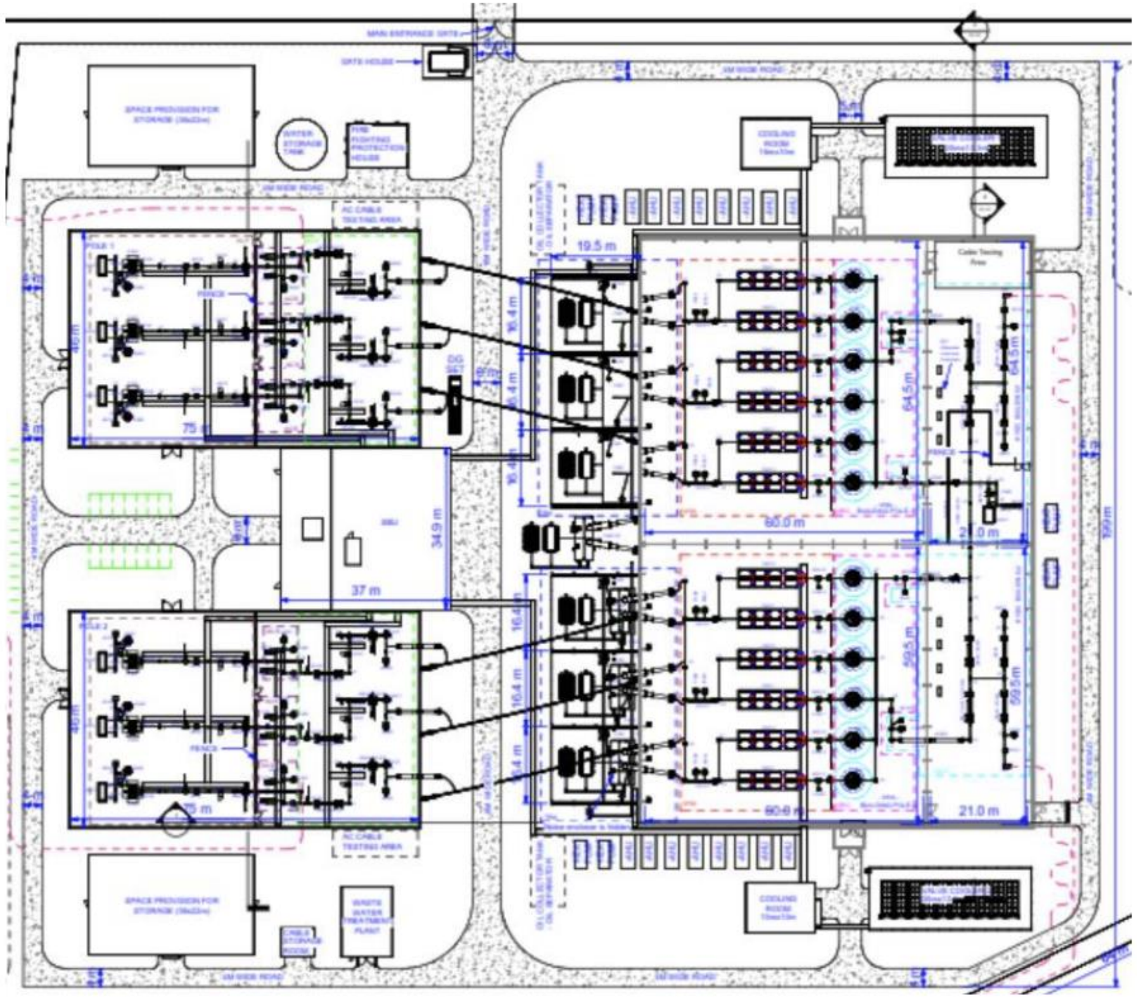
Comparison of LCC and VSC Substations (2)

Footprint

- 250 m x 220 m = 6 hectares
- 820 ft x 720 ft = 14 Acres



Comparison of LCC and VSC Substations (3)

LCC : 6,000 MW / 800 kV

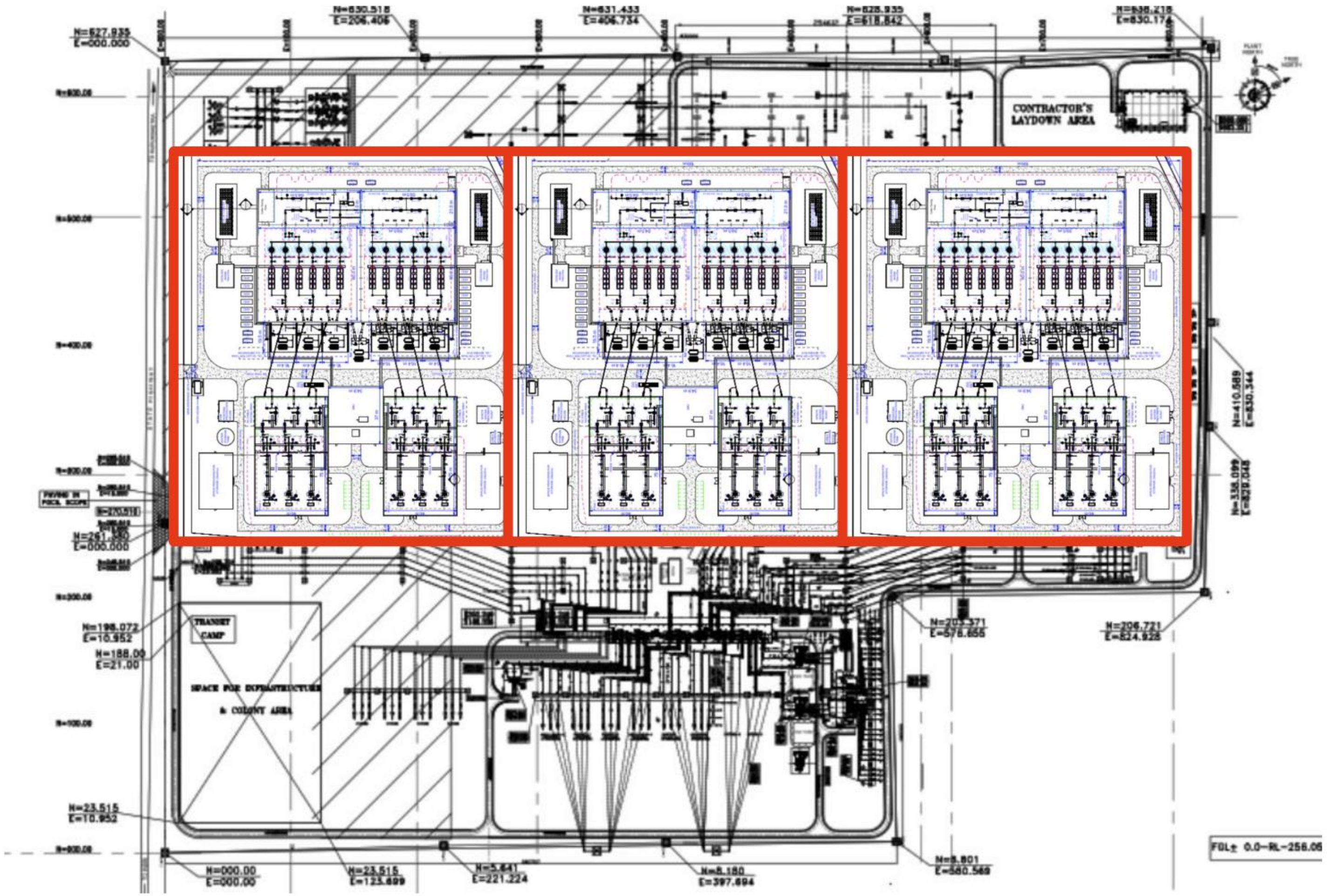
vs.

VSC : 3 x 2,000 MW / 525 kV

Compare 6000MW LCC vs VSC :

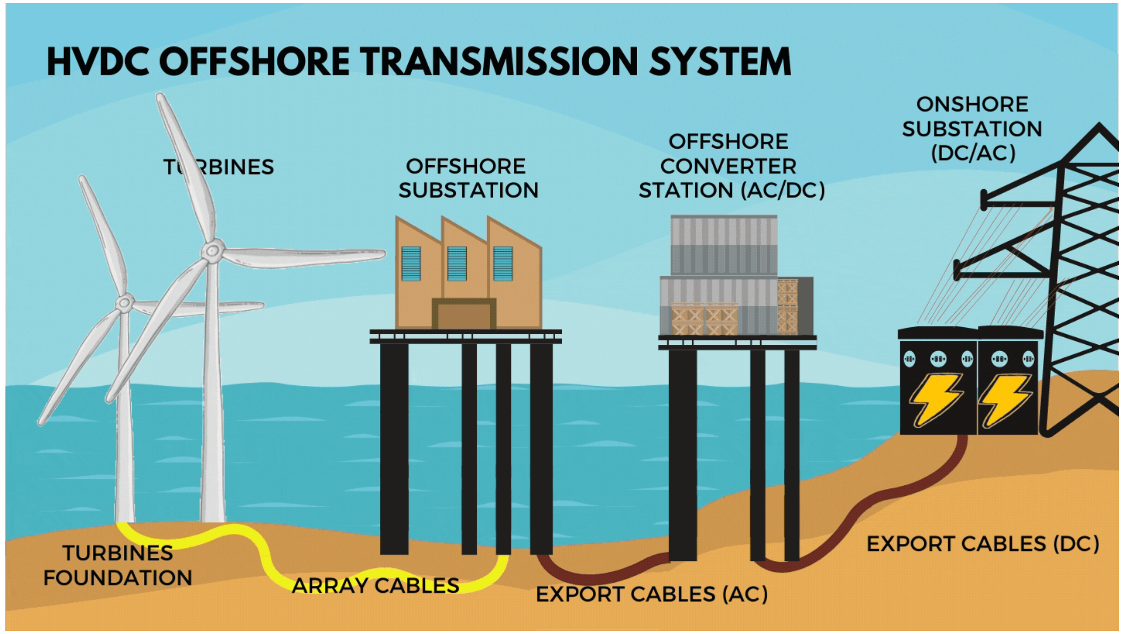
- LCC : 1 x 3,000 MW = 130 acres
- VSC : 3 x 2,000 MW = 42 acres

=> 66% reduction in footprint



VSC HVDC Applications

- Urban power infeed –small footprint like the Trans Bay Cable project
- Offshore wind integration
- Weak grid interconnection
- Asynchronous grid connection



Key Takeaways

- Modern VSC HVDC uses MMC topology to significantly reduce harmonics
- As a result, the converter station footprint is reduced by downsizing AC-side filters
- A typical converter station is composed of an AC switch yard, AC equipment (converter transformer), converter hall, DC switch yard, cooling and auxiliary system, control and protection systems, etc.
- VSC HVDC can operate in any of the four quadrants by changing setpoints without interruptions

References

- Vijay K. Sood, “Power Electronics Handbook – Chapter 25: HVDC Transmission”, 2024, pp. 865-907.
- IEEE PES “HVDC Systems & Trans Bay Cable”, Online, available: https://ewh.ieee.org/r6/san_francisco/pes/pes_pdf/Transbay_Cable.pdf
- D. Retzmann, “HVDC Station Layout, Equipment, LCC & VSC and Integration of Renewables Using HVDC”, CIGRE Grid Access Tutorial, available: https://www.scribd.com/document/364519025/Cigre-AUS-2011-HVDC-GridAccess-tutorial-Re-pdf
- Babcock & Brown, “Trans Bay Cable Project”, Presentation to Board of Governors, CAISO, April 18, 2007.

Acknowledgements

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