Powering positive change

The Hatch H.G. Acres symposium

April 15-16, 2025 | Hotel X, Toronto, Canada

Your guide to the event:
Scan the QR code for speaker bios, topic previews, and the complete agenda

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HATCH

Power packed technical tutorial – HVDC and FACTS

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Agenda

1. Safety Moment, Welcome and Introduction
2. HVDC Technology
3. HVDC Station Overview
4. System Studies and Planning
5. Typical Project Phases
6. Discussion

HATCH

Safety Moment


2
1
3

Energy Service Offerings

Energy Services Offerings

Other Capabilities

Thermal Power

Nuclear Power

Hydropower & Dams

Power Transmission & Integration

Cables

System Studies

T-Lines

HVDC & FACTS

Stations

Storage & Renewable Power

Solar

Onshore Wind

Offshore Wind

Energy Storage

Energy Efficiency

Distribution & Smart Grid

Distribution Design

Grid Ops

Grid Mod

EV Infrastructure

ICS

AM

Microgrid/Hybrid

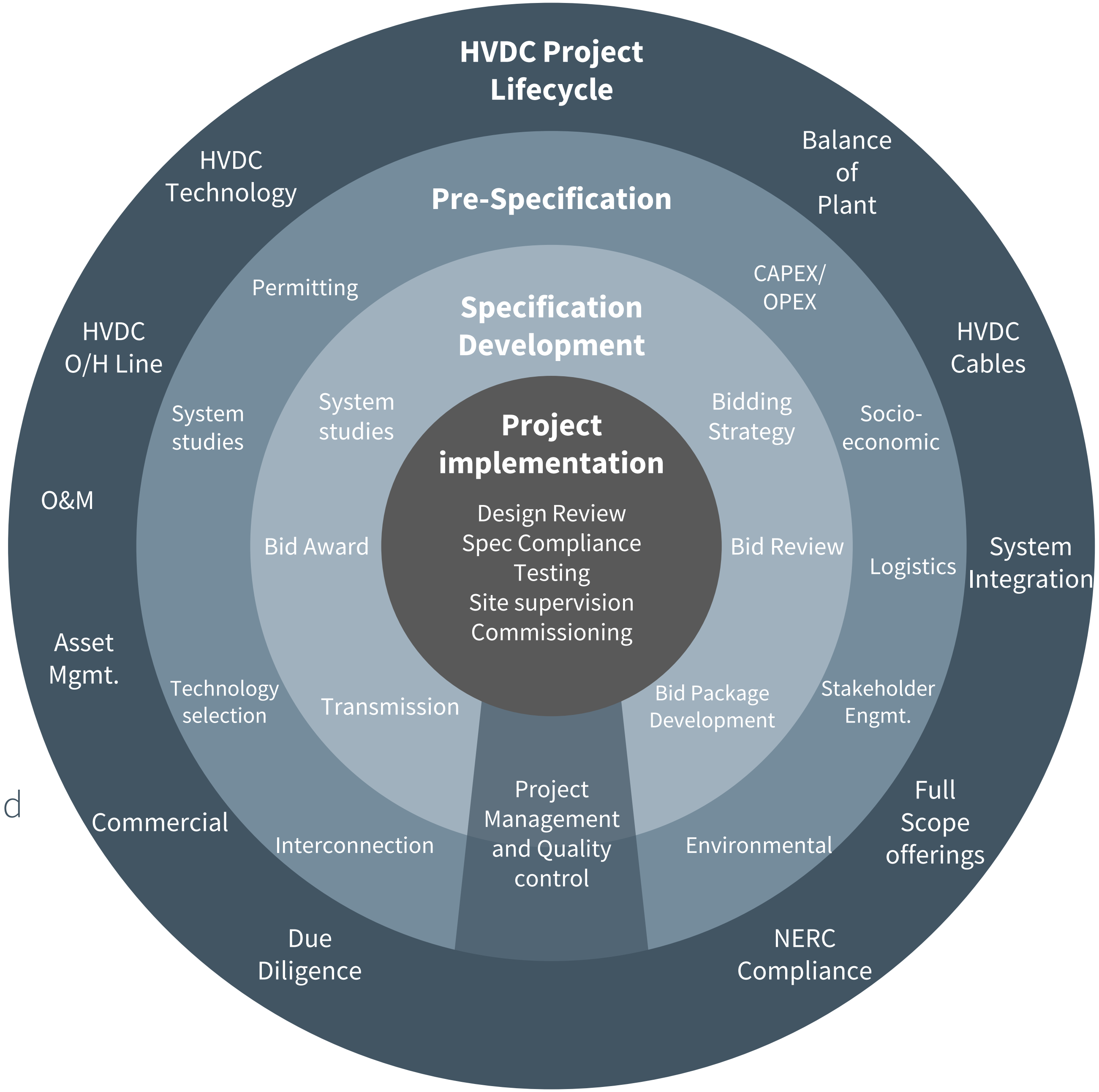
HVDC

HVDC

- Full suite of services
- Long track record of implementing large projects across various sectors
- High-level HVDC expertise
- Support every aspect of a project and can control the specialized expertise

+ VALUE ADD

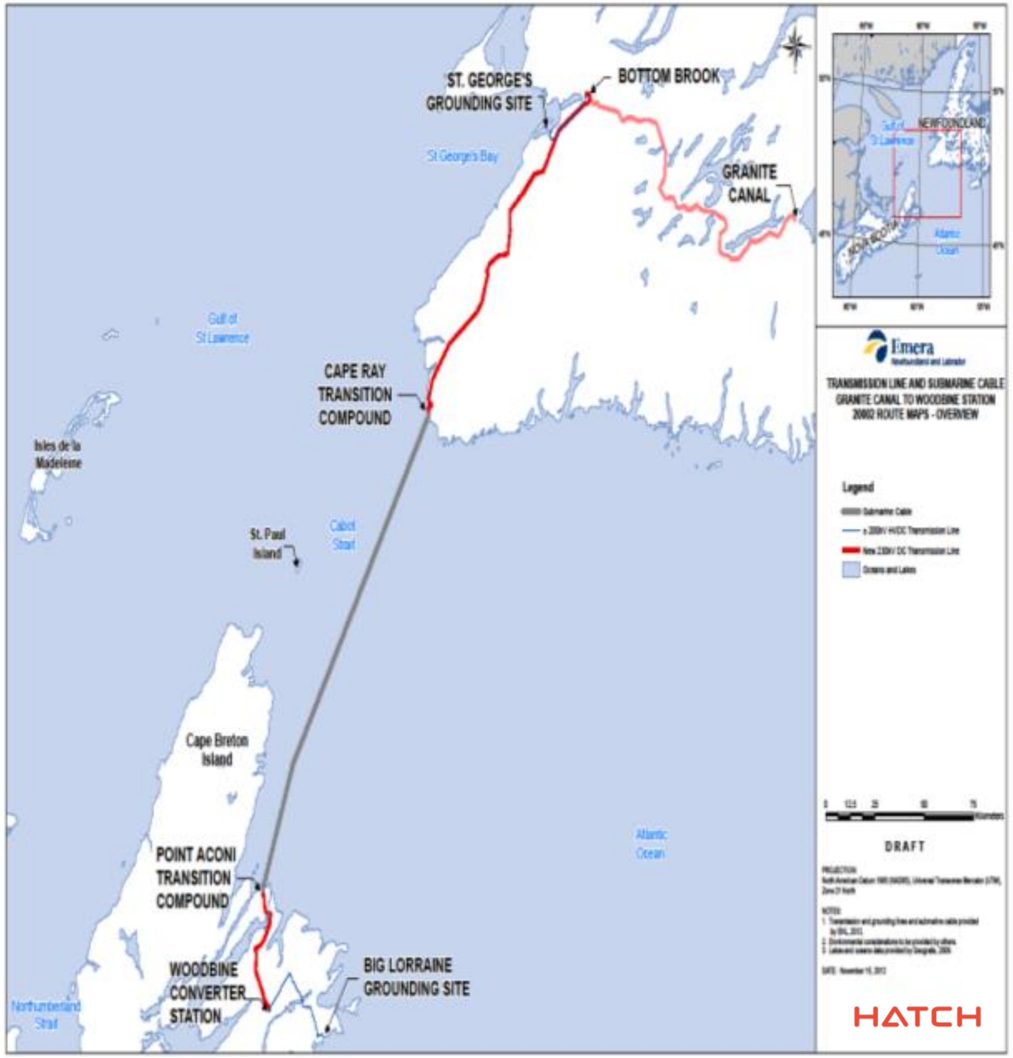
- ✓ Can act at integrator
- ✓ Long- term commitment (ISO9001 certified)
- ✓ Our team combines decades of utility, OEM, OE and academic experience
- ✓ We are here to get the projects built



Hatch VSC Project Experience

Maritime Link	(+/-) 200kV	500 MW
Dolwin 3	(+/-) 320 kV	700 MW
Grain Belt Express*	(+/-) 525 kV	5000 MW
CobraCable	(+/-) 320 kV	700 MW
Skagerrak 4	500 kV	700 MW
Atlantic Link	(+/-) 320 kV	1000 MW
Jeju Island #3	(+/-) 150 kV	200 MW
EuroAsia Interconnector	(+/-) 500 kV	1000 MW
SunCable*	(+/-) 525 kV	4000 MW
SOO Green*	(+/-) 525 kV	2000 MW
SunZia	(+/-) 525 kV	3000 MW
Tennet 2GW Program (7)	(+/-) 525 kV	2000 MW
Cleanpath New York	(+/-) 400 kV	1200 MW
New York OSW Mesh Grid		
NY OSW HVDC*	(+/-) 320 kV	1300 MW
TransWest Express*	(+/-) 525 kV	3000 MW

*Project under development



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SOO Green HVDC Cable

- 2,100 MW, ±525KV underground HVDC transmission system
- Length: 350 mi
- Location: Running along existing rail corridors from Iowa to Illinois.

Services:

✓ Concept studies
✓ System design studies and technical specifications
✓ Management of EPC tendering
✓ Owner's Engineer

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Australia Asia Power Link (Sun Cable)

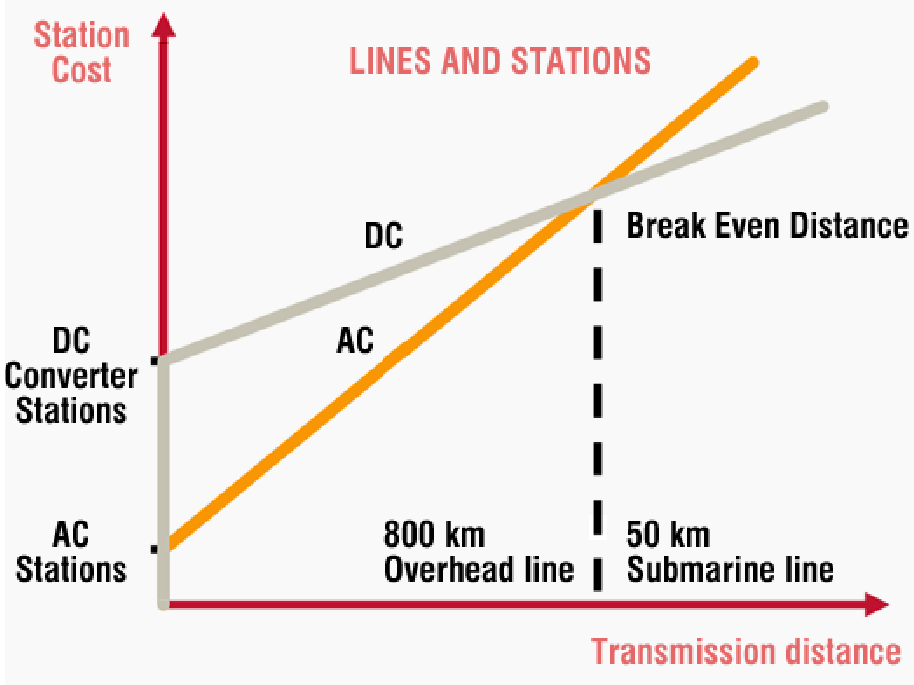
- ~2000 MW delivered to Singapore from Australia at +/-525 kV
- Integrating 20 GW of solar PV with 33 GWh of batteries
- Hatch is engaged as Owner's Engineer for the development of this project

Location	Australia to Singapore
Length	~750km of OHL and 3800km of subsea cable

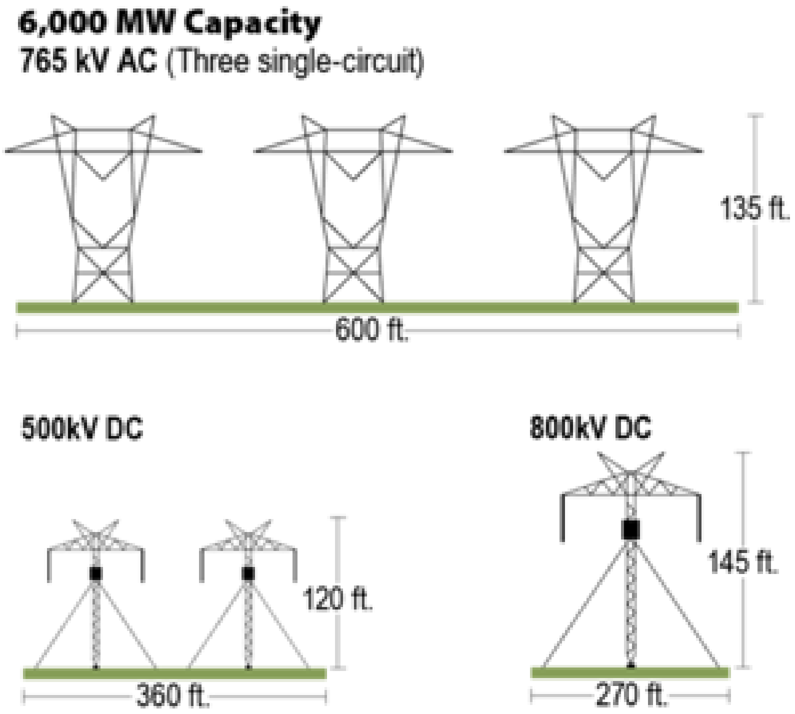
HVDC Technology

HVDC Technology
Application

- Moving power overland long distances



- Congested Corridors



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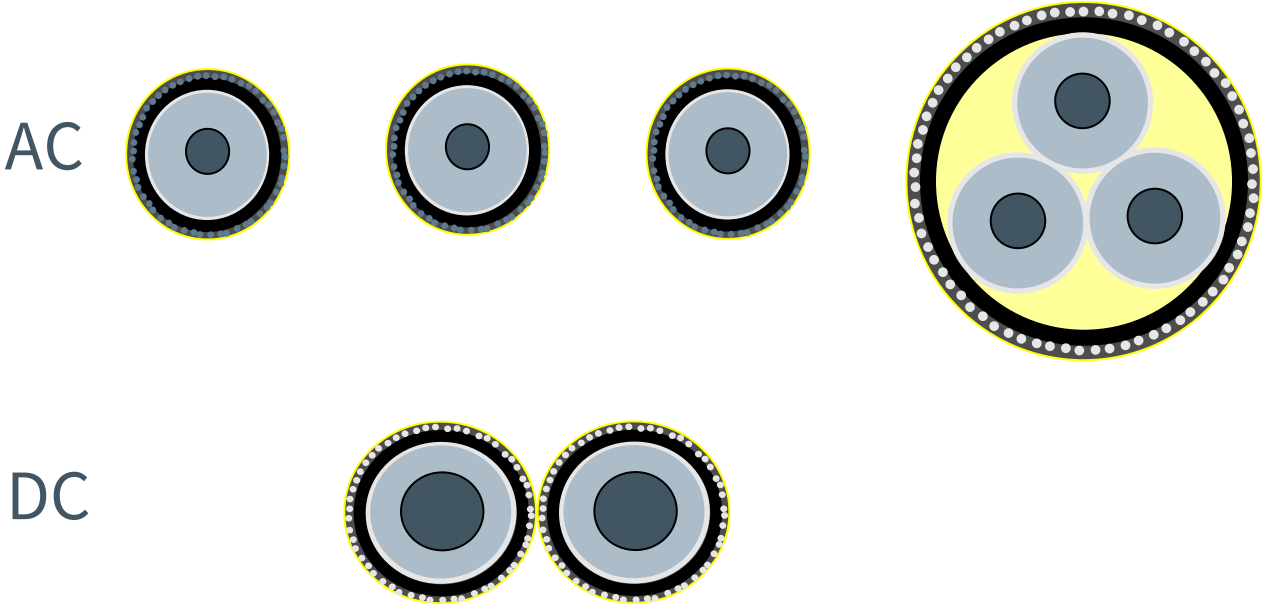
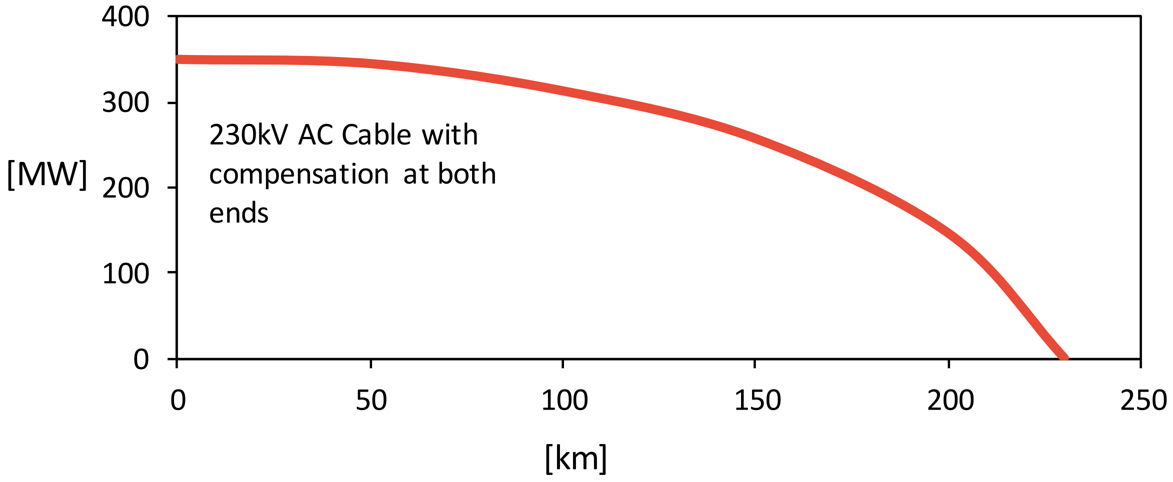
HVDC Technology
Application

- Moving power via sub-sea cable
  - DC has theoretically no distance limit





Power Level	DC	AC
1000MW	2 x 320kV DC cables	3 x 3ph 220kV AC cables 9 x 1ph 220kV AC cables
1300MW	2 x 320kV DC cables 2 x 400kV DC cables	4 x 3ph 220kV AC cables 12 x 1ph 220kV AC cables
2000MW	2 x 500kV DC cables	5 x 3ph 220kV AC cables 15 x 1ph 220kV AC cables

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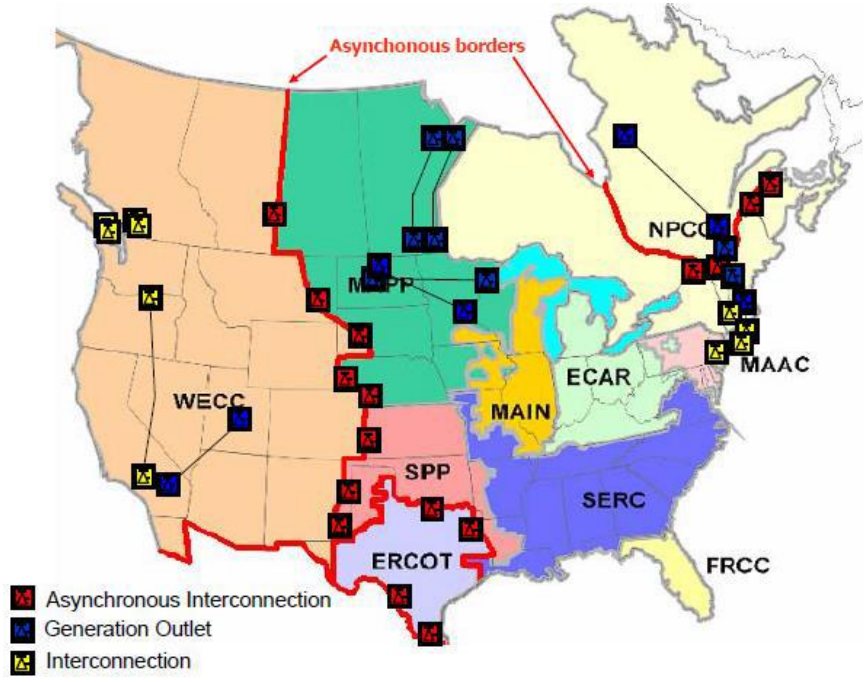
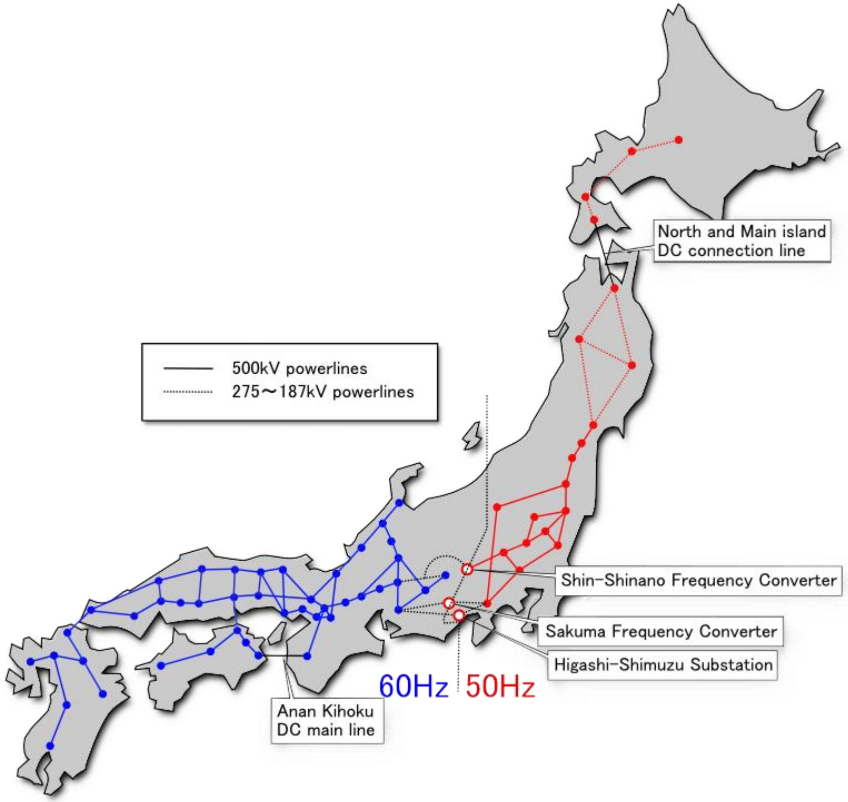
HVDC Technology
Application

- Moving power between asynchronous systems

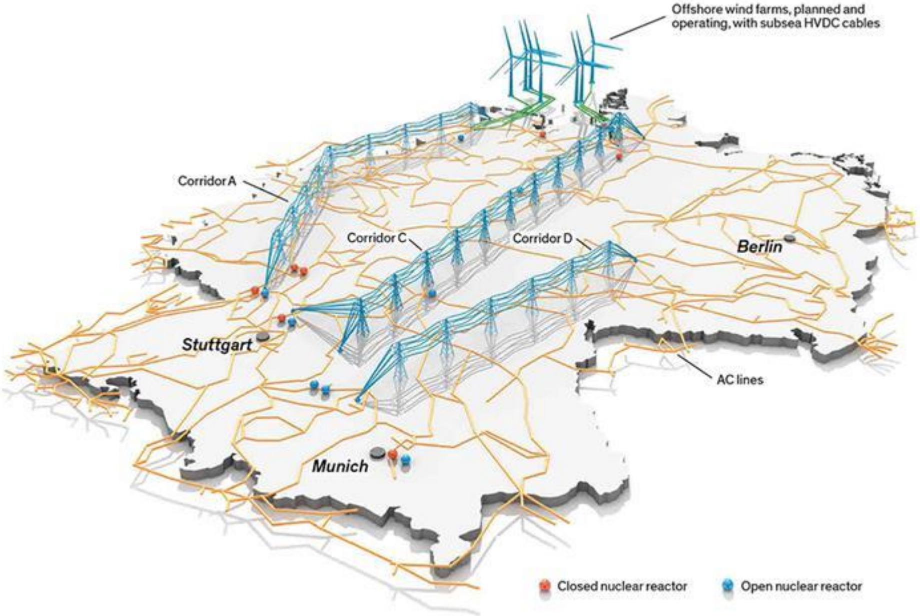


- Connecting systems with different Frequencies



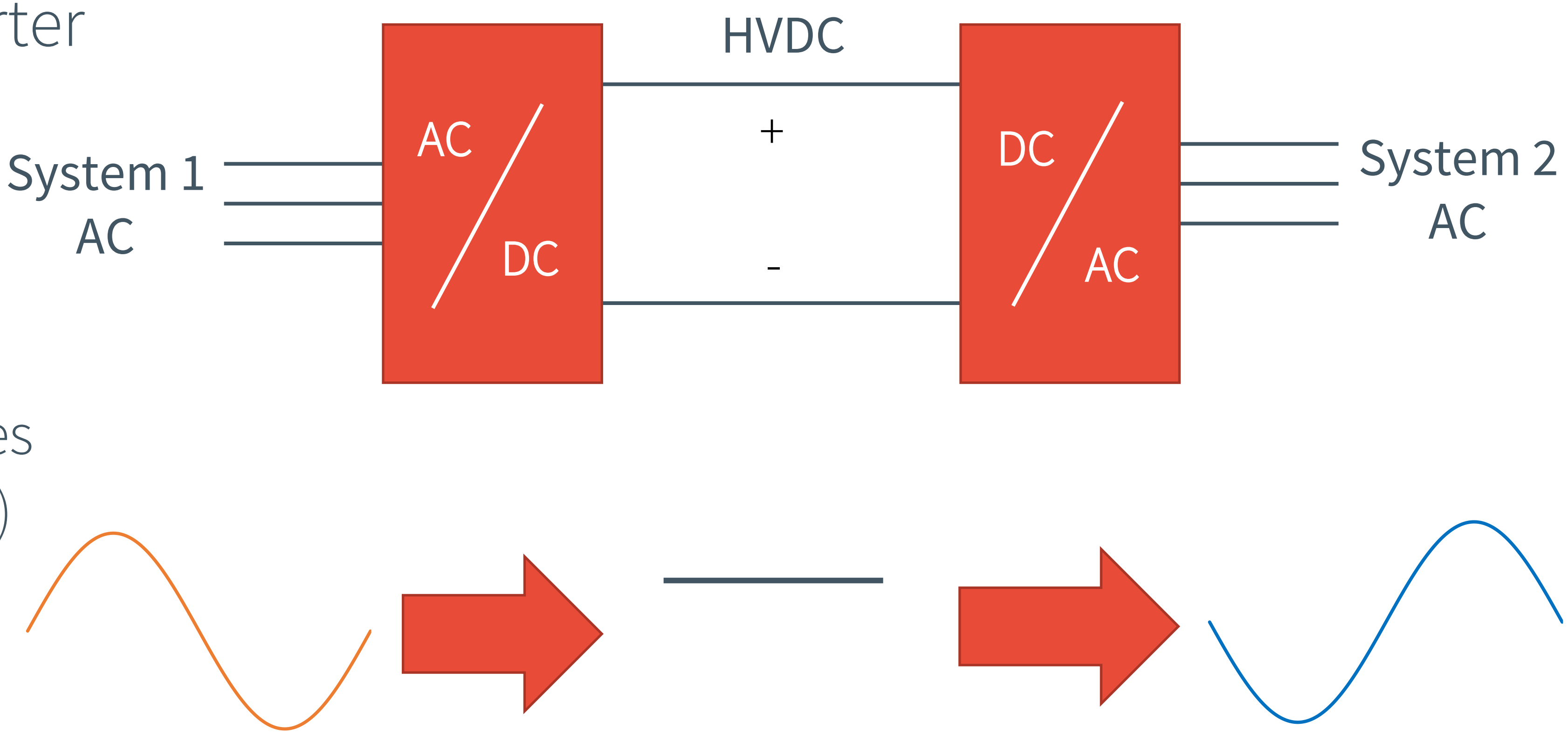
HVDC – off-shore

- Germany is using HVDC to move Wind energy from off-shore
- HVDC to load centres



HVDC Technology
Fundamentals

- Conversion from AC to DC → HVDC Converter
- DC link can be:
  - Overhead lines
  - Cables
  - Mixed Cables / Lines
  - Busbar (back-back)



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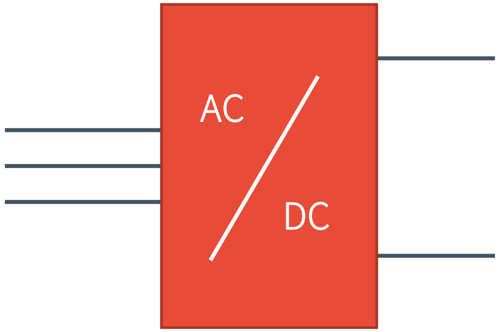
HVDC Technology
Fundamentals

- Two Prominent Technologies:
  - Line Commutated Converters
  - Voltage Sourced Converters

HVDC Technology
Fundamentals



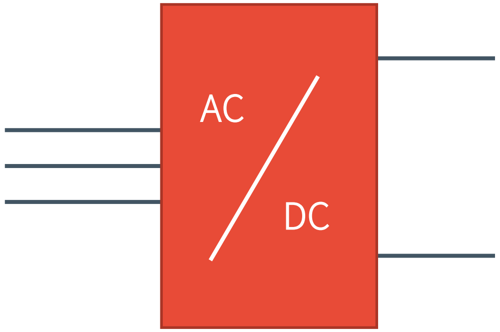
Line Commutated Converter (LCC)

- AC ←→ DC
- Semiconductor: Thyristor
- Active power control
- Large AC filters
- Minimum short circuit ratio required
- DC power flow reversal with momentary interruption

Voltage Source Converter (VSC)

- AC ←→ DC
- Semiconductor: Transistor (IGBT, BIGT)
- Active / Reactive Power Control
- Small (or zero) AC filters
- Very low short circuit ratio (incl. black start capability)
- Fast DC power flow reversal

HVDC Technology
Fundamentals



<u>Line Commutated Converter (LCC)</u>

- Overload capability
- Power up to 12,000MW with +/- 1,100kV
- Losses in range of 0.7%/converter
- Large footprint
- Excellent DC Line Fault Performance

<u>Voltage Source Converter (VSC)</u>

- No inherent overload capability
- Power now in the range of: 3,400MW with +/- 600kV
- Losses now in range of 0.7%/converter
- Compact design
- Excellent DC Line Fault Performance (for a price) or "good" DC Fault Performance

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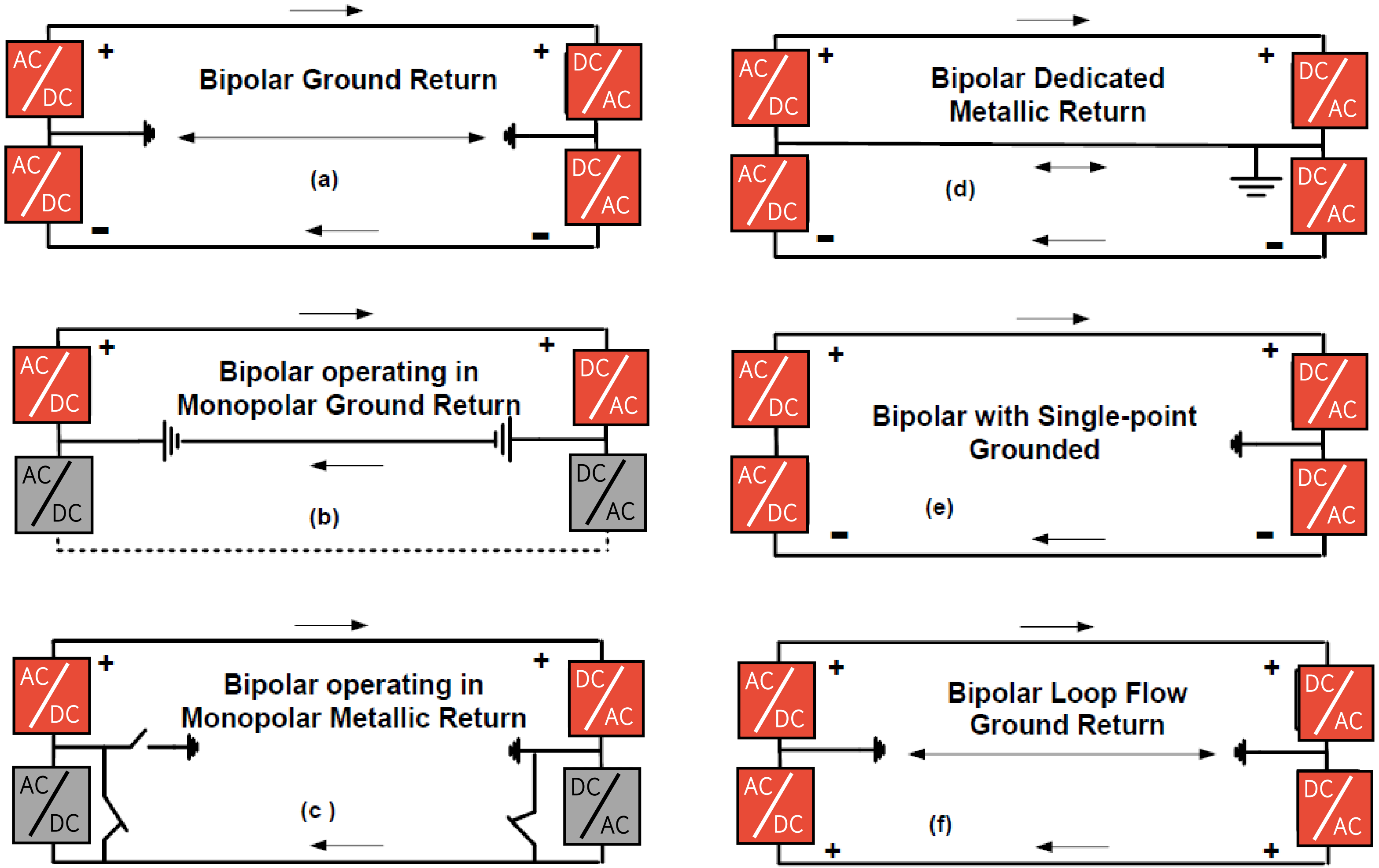
HVDC Technology
Configurations

<u>Bipole</u>

- +/- DC voltage
- Two converters per end



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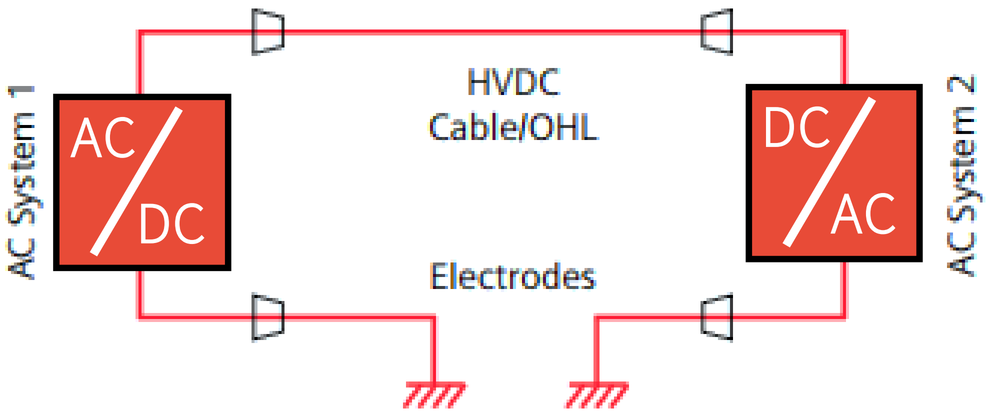
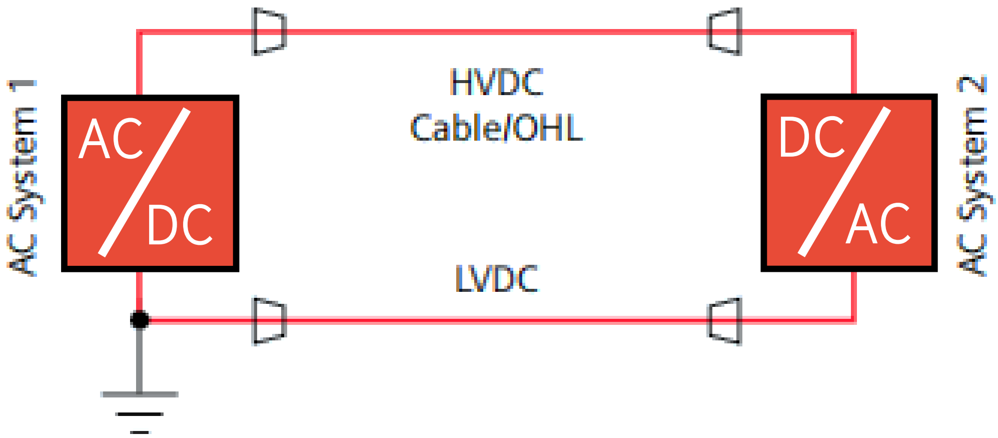
HVDC Technology
Configurations

Monopole

- ➢0/+ DC voltage





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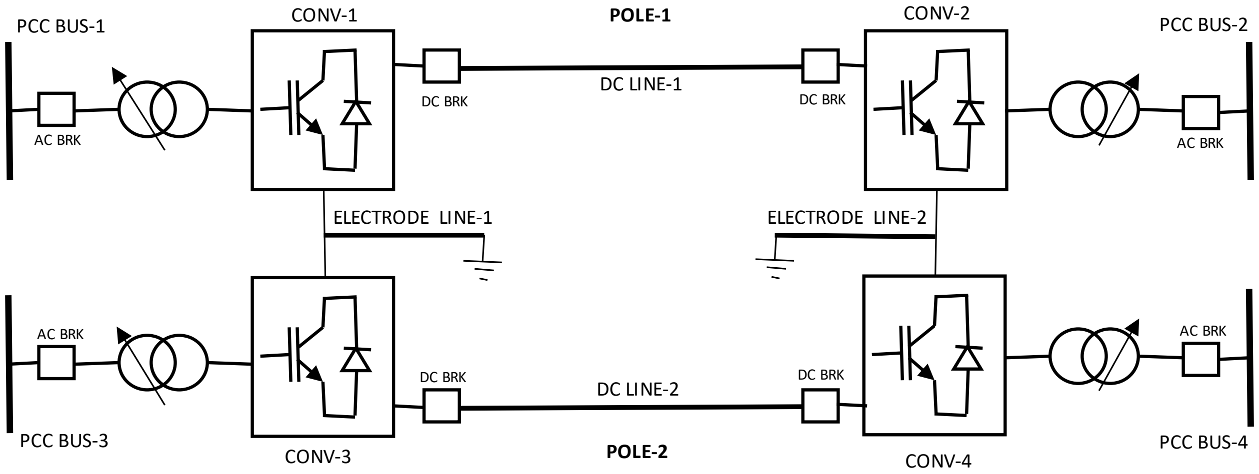
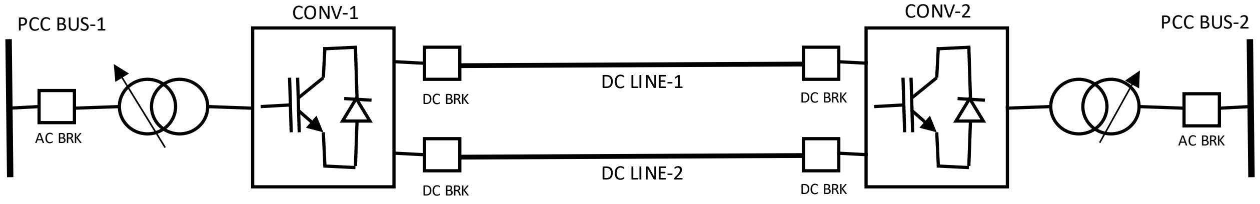
HVDC Technologies



Bipole VSC

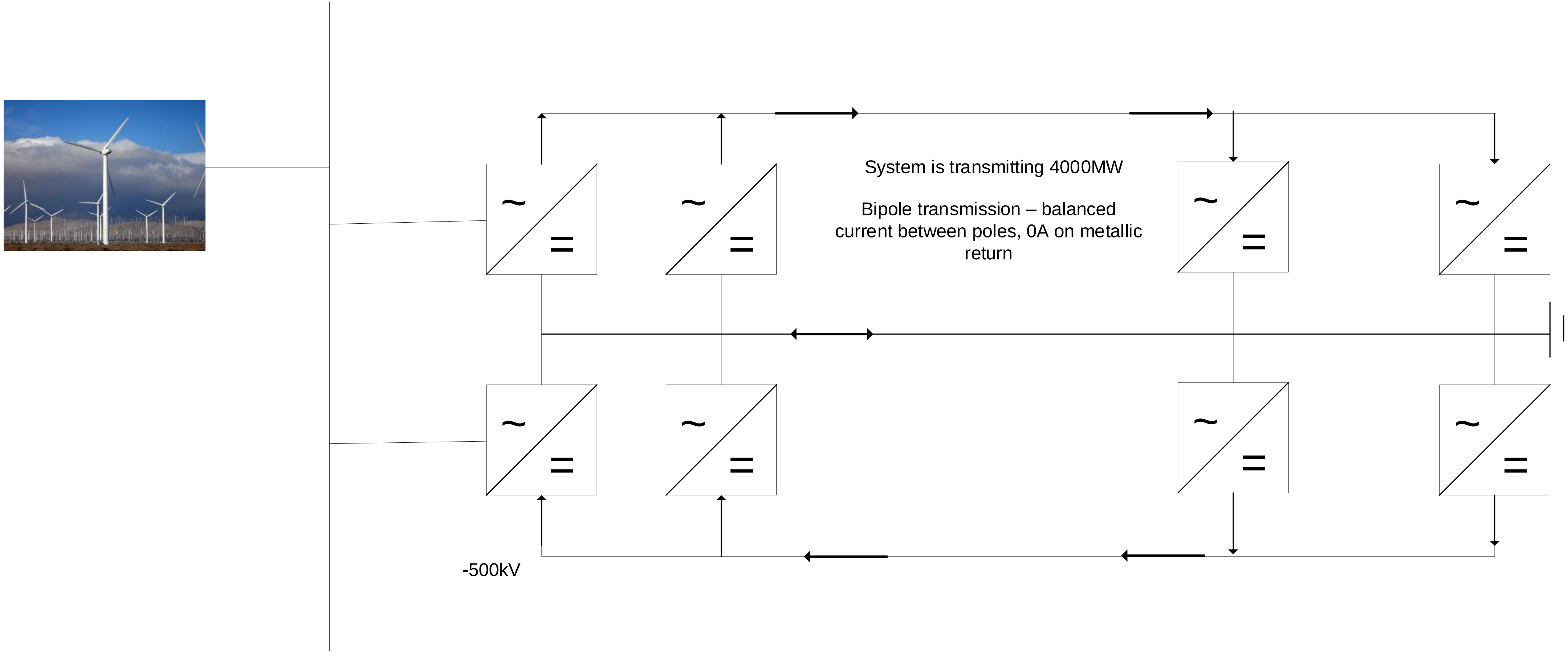


Symmetrical Monopole VSC

MTDC

- Lots of Great Work going regarding MTDC
  - Looking at interoperability of different vendors
  - Integration in weak grids
  - System protections and fault ride through
  - Some jurisdictions are looking into creating a “grid-code” for the MTDC
  - One area that has to be considered in all studies is the additional HVDC nodes terminating in the operating areas

Multi-Terminal HVDC



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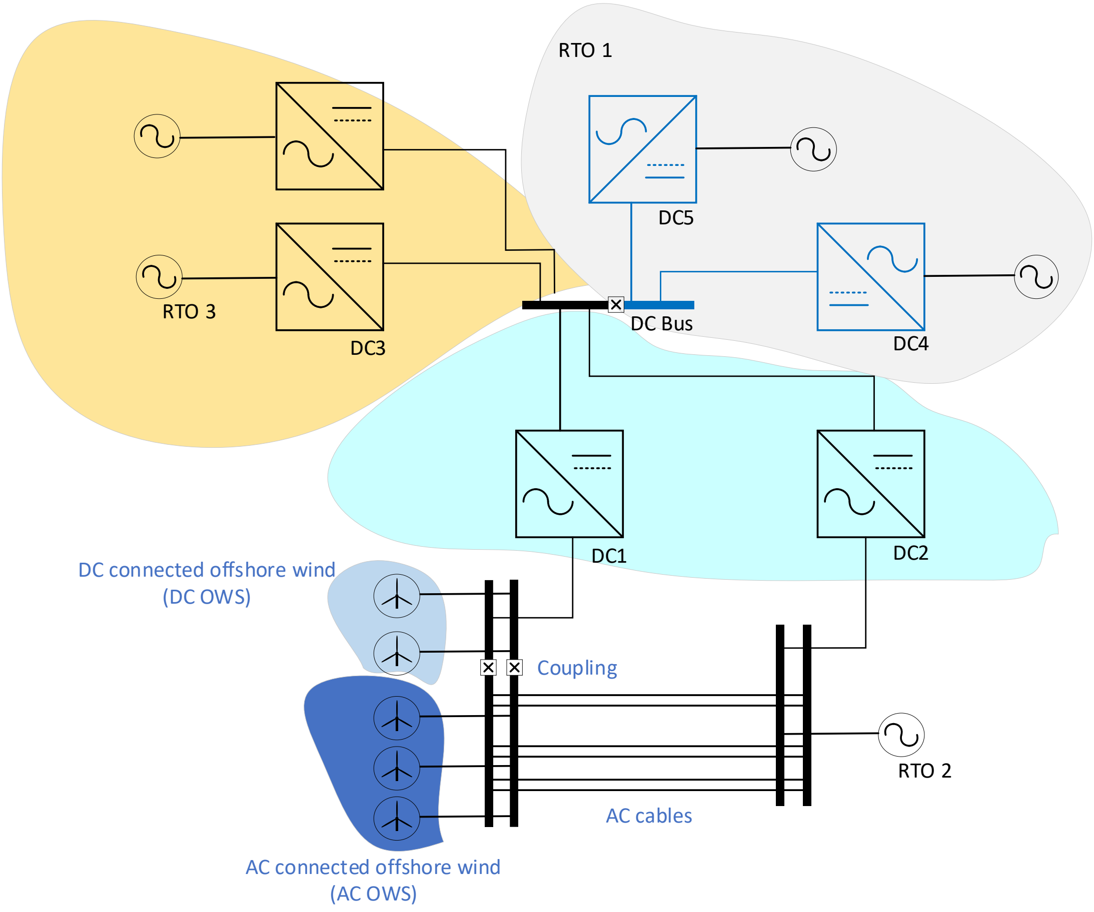
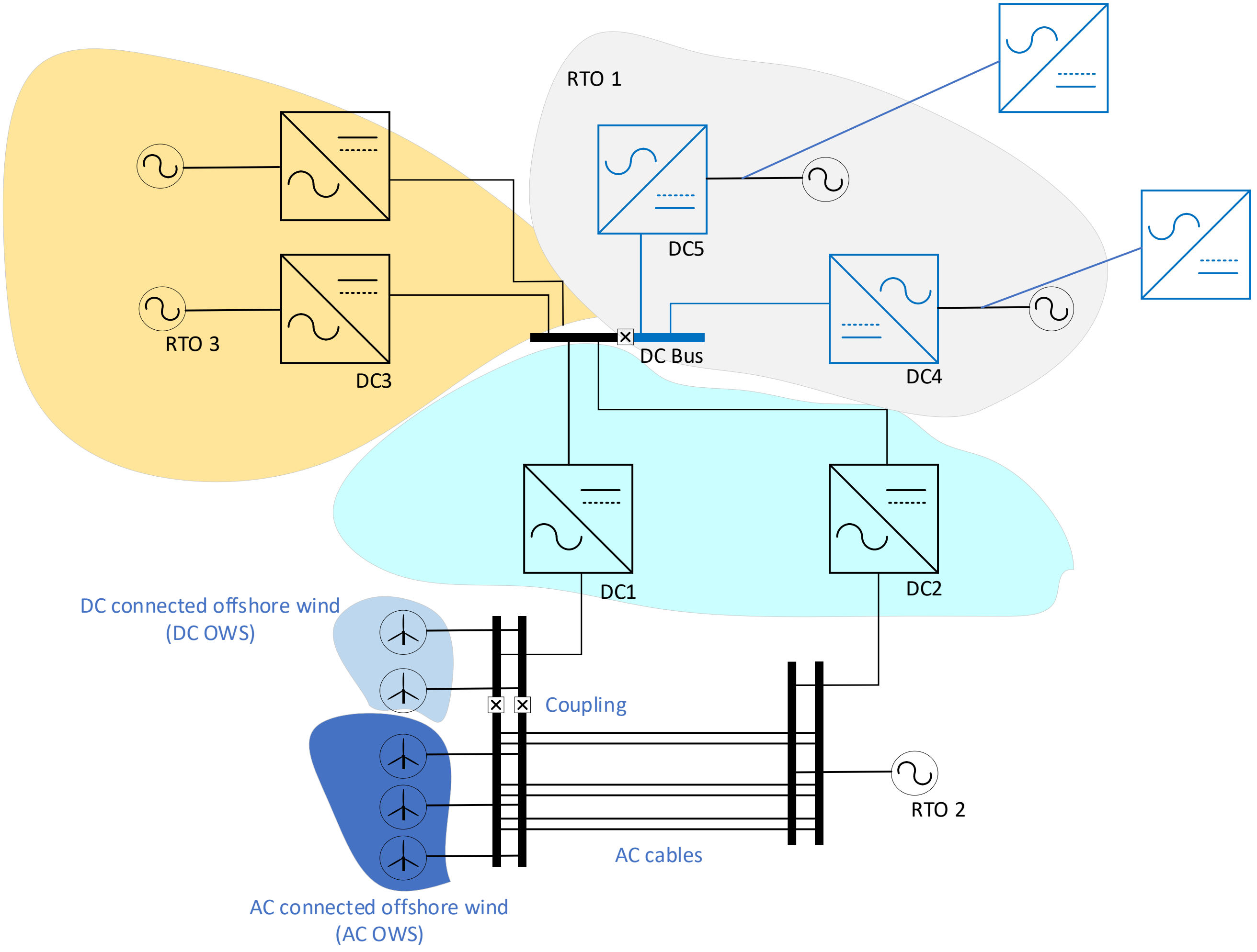
Multi-Infeed

- Consider the Following
  - HVDC Systems connected across multiple RTOs
  - Each RTO will have its own requirement
  - What happens when the next Round of HVDC interconnects



Multi-Infeed

- Each of the new systems are now going to have to be considered by the original HVDC links and as part of their basic design
- Cigre TB 364 provides some guidance for System with multiple DC Infeed – From 2008



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Multi-Infeed

This is already happening in the NE-US

(Source: New York State and Regional Transmission Planning for Offshore Wind Generation (brattle.com))

- The ~30,000 MW of committed off-shore wind development in the Eastern U.S. will require 1,500 to 3,000 miles of offshore transmission plus significant onshore reinforcements
  - In order to integrate 30,000 MW with radial 220kV HVAC gen-ties for every 400 MW of wind generation (up to 30-60 miles offshore) would require about 3000 miles of offshore cables to 75 landing points with associated onshore grid reinforcements
  - Planned off-shore grids for larger wind plants and to optimize onshore grid capabilities—such as used in Germany, the Netherlands, Belgium, and proposed for NJ and MA—would yield scale economies, more resilient meshed grids, and only about 1500 miles of cables with 25 landing points
- Radial connections from the off-shore wind to the on-shore points of interconnection will be based on the VSC HVDC technology as it is required by the PSC Order on Power Grid Study Recommendations issued on January 20, 2022

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Multi-Infeed

Total (MW)	Alt POI	Default POI For Sol #2	Default POI	Alt POI	Default POI For Sol #2	Alt POI	Default POI	Alt POI	Alt POI	Alt POI
	Orchard 500 kV (MW)	Cardiff 230 kV (MW)	Deans 500 kV (MW)	Lighthouse 500 kV (MW)	Smithburg 500 kV (MW)	Atlantic 230 kV (MW)	Larrabee 230 kV (MW)	Oceanview 230 kV (MW)	Sewaren 230 kV (MW)	Werner 230 kV (MW)
6400		1510	2542		1148		1200			
4258		1510			1148		1600			
6258	1148	1510			1200	1200	1200			
6258		2658			1200	1200	1200			
6400		1510	2290				1200		1400	
6310		1510			2400	1200	1200			
6400		2658	3742							
6400		1510		4890						
6400		1510	1890					3000		
6400		1510	2400		1690					800

(Source: https://www.pjm.com/-/media/committees-groups/committees/teac/2022/20220308/20220308-item-08-nj-osw-saa-update-proposal-overview.ashx))

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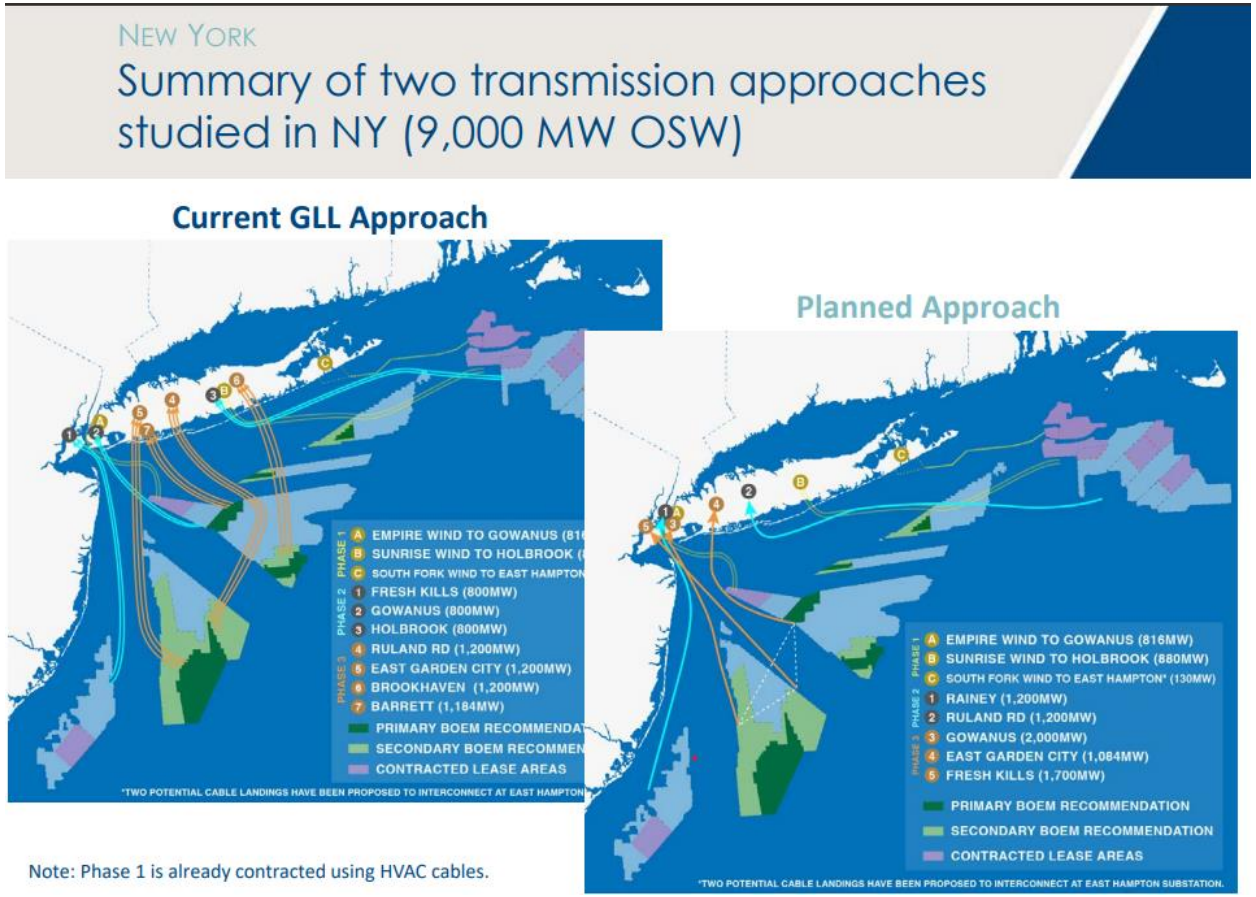
Multi-Infeed



(Source: Offshore Wind Transmission: An Analysis of Planning in New England and New York (brattle.com))

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Multi-Infeed

- What needs to be considered
  - Any impact on Main Circuit Design
    - Short-circuit level
    - Harmonics
    - Dynamic considerations
  - Any impact on control strategies of neighbouring systems
    - Grid-forming/Grid-following
    - Voltage/Reactive Power
    - Any grid stabilizing features
    - SPS
    - Small-signal stability

How to ensure a stable power system of the future

- More discussion
  - Technical working groups
  - Inter-regional studies
- Detailed system studies looking at best guess systems
- Sharing of models
  - Need to develop standardize models that are freely shared and "open"
  - **Simulation is key**
  - Moving towards an EMT based simulation platform

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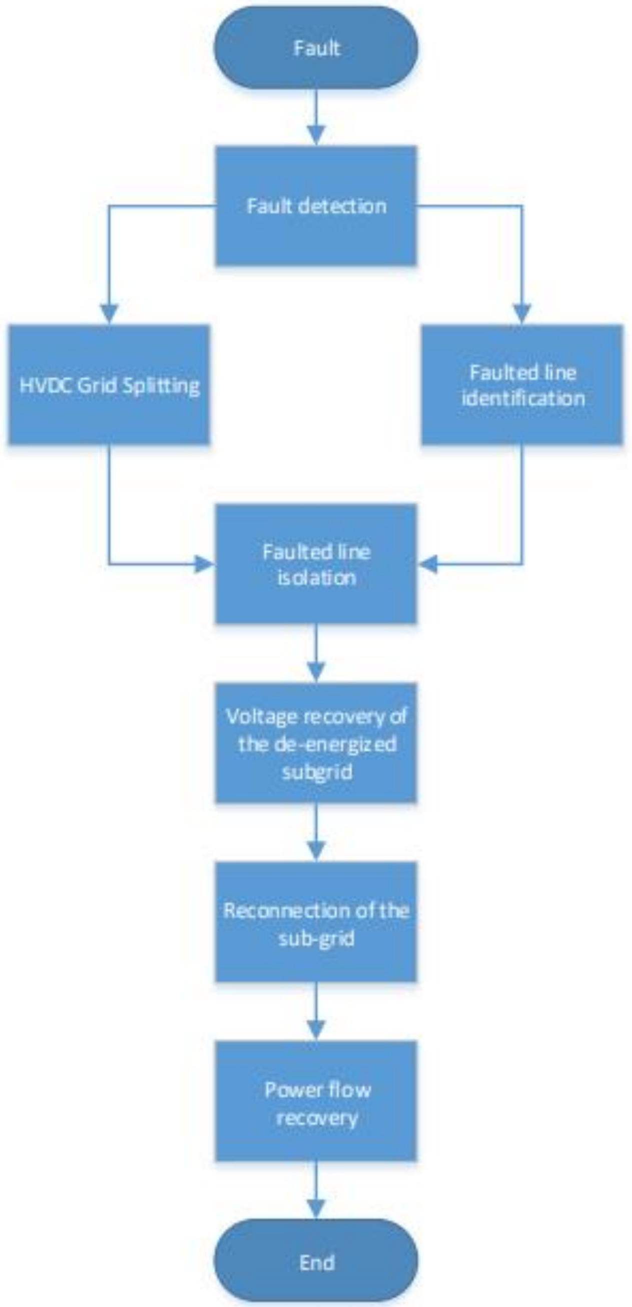
DC Breaker

- Most vendors are offering
- Limited service
- Hitachi Energy Publisher - Basic principles of the Hybrid HVDC Breaker



The Fun Stuff…

Voltage Sourced Converters

Pictures from ABB (ww.abb.com)

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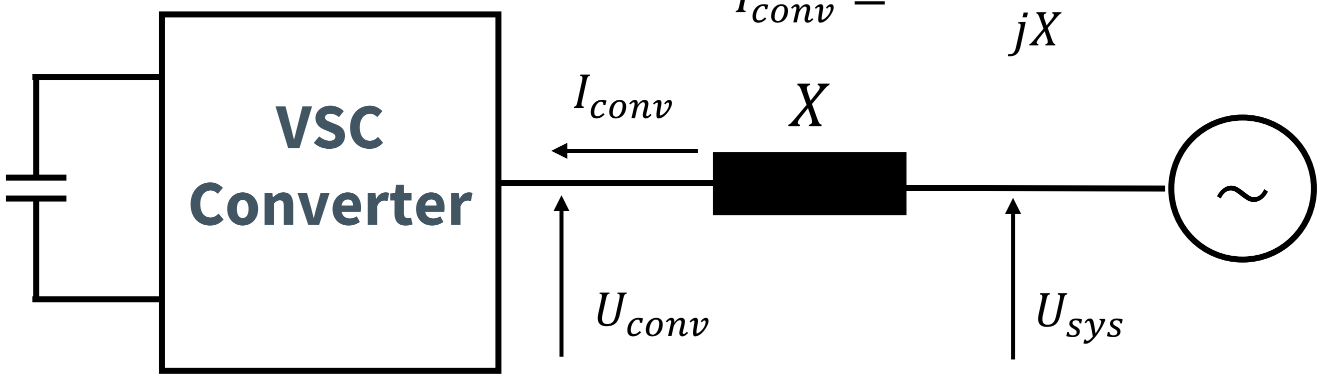
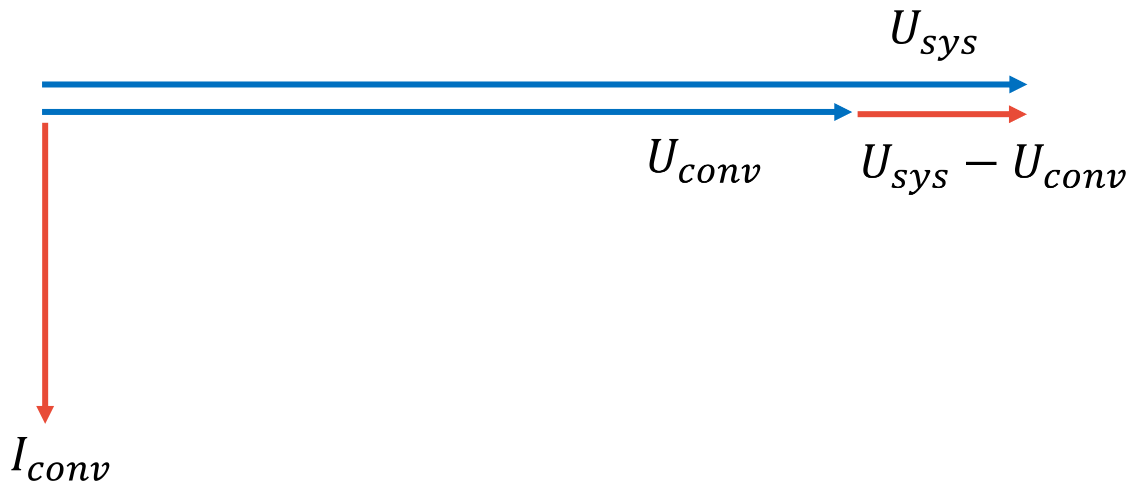
VSC Theory

- VSC operation is very similar to a synchronous machine
- Provides active and reactive power control (4-Quadrant control)
- Can use a cheaper XLPE cable
- Works well in weak, even “dead” systems

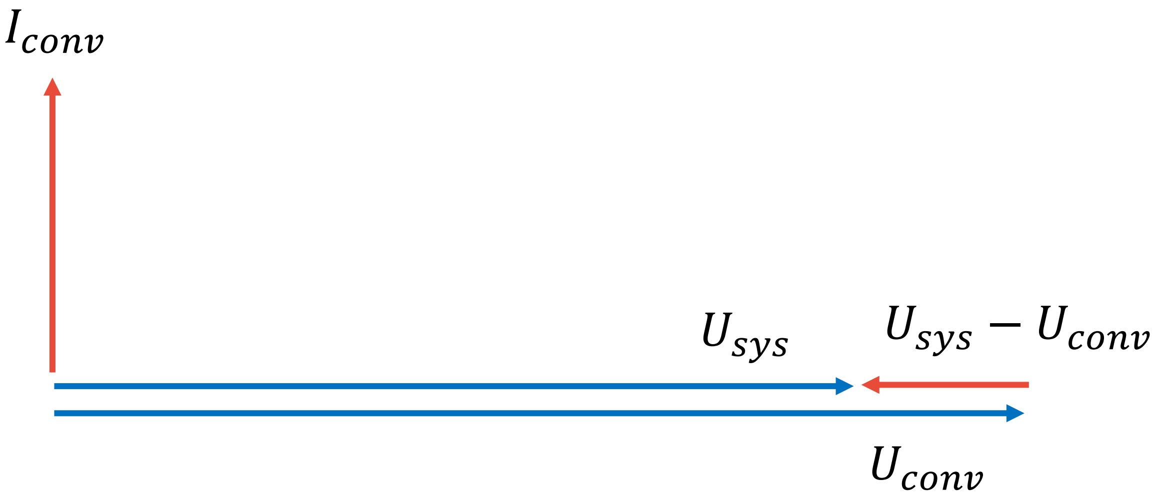
VSC Theory

$$I_{conv} = \frac{U_{sys} - U_{conv}}{jX}$$





Converter absorbing reactive power



Converter producing reactive power

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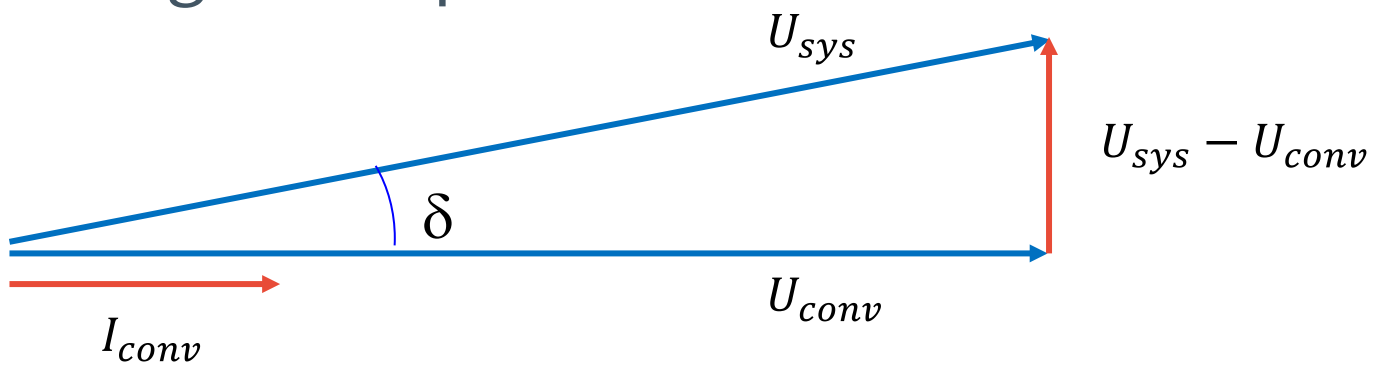
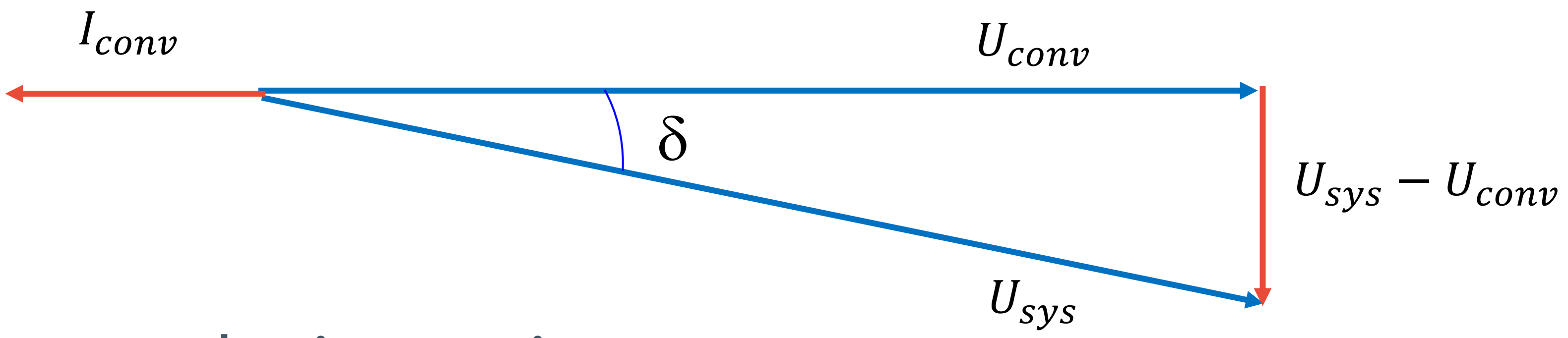
VSC Theory

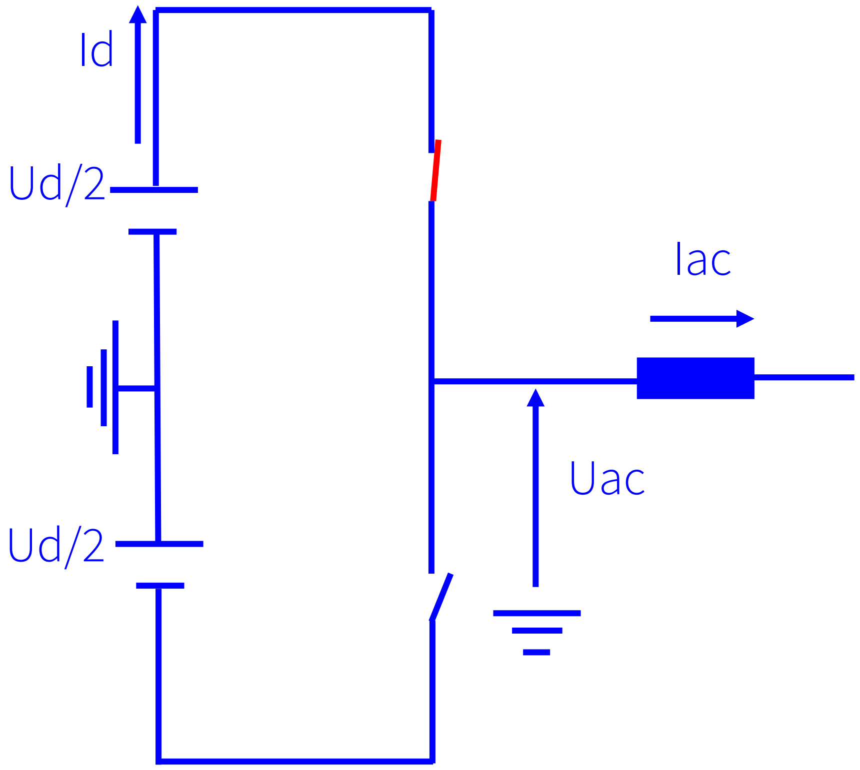
Converter absorbing active power

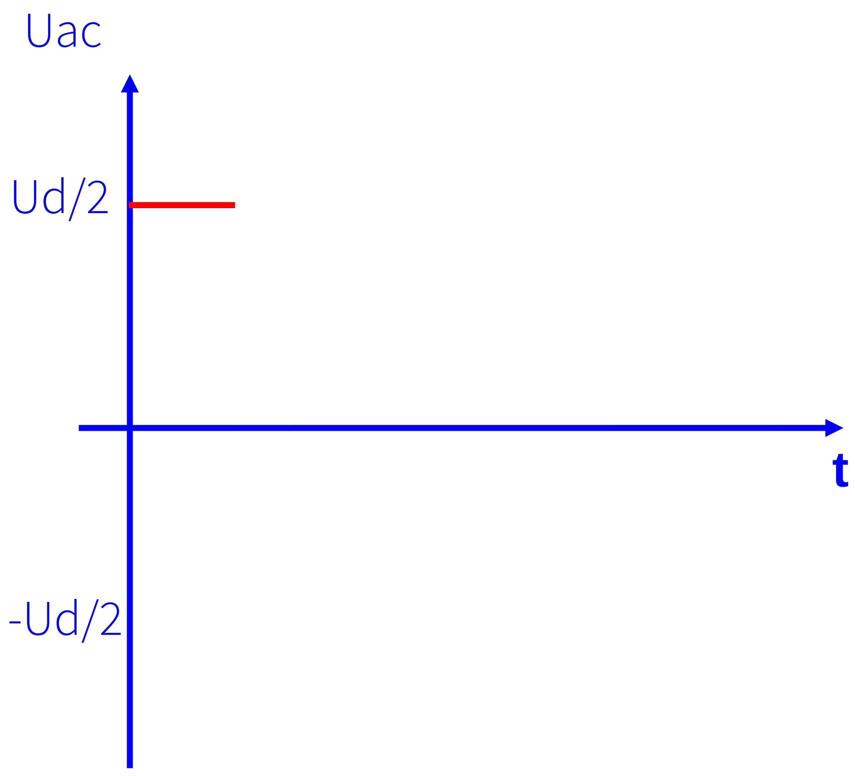




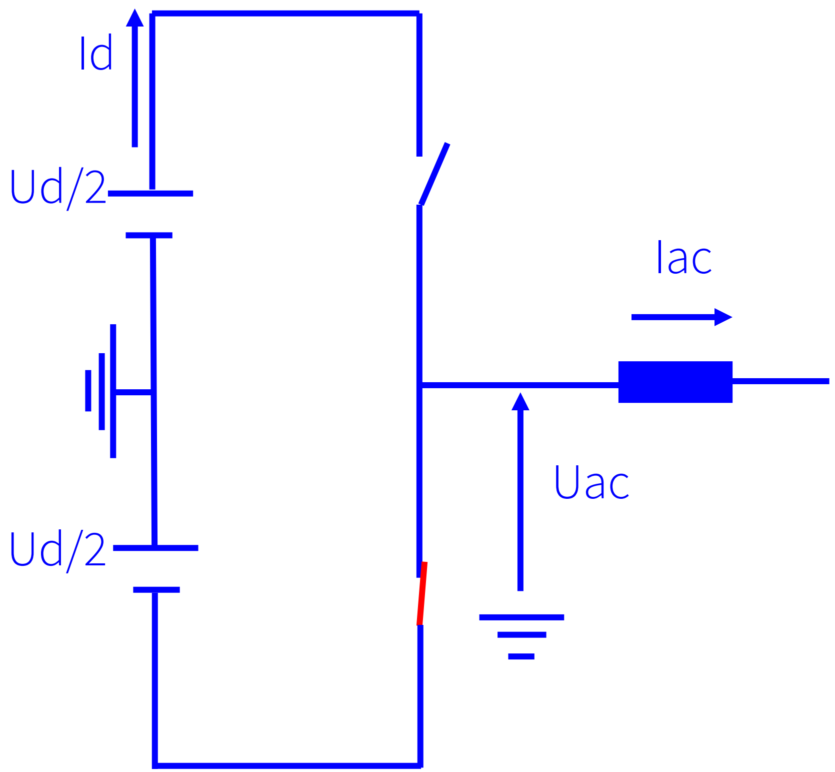
Converter producing active power

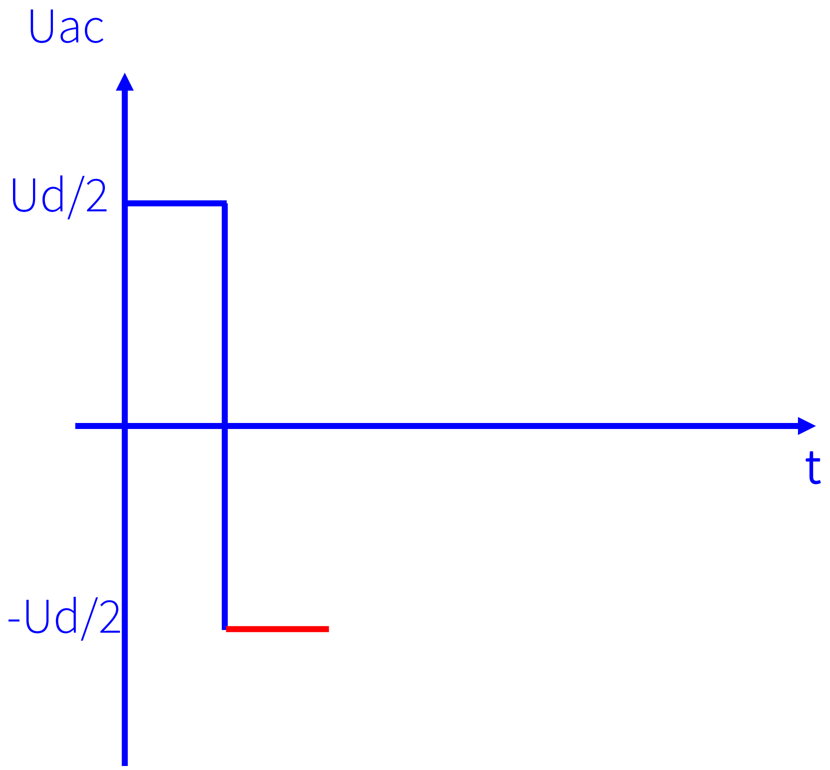
VSC Theory



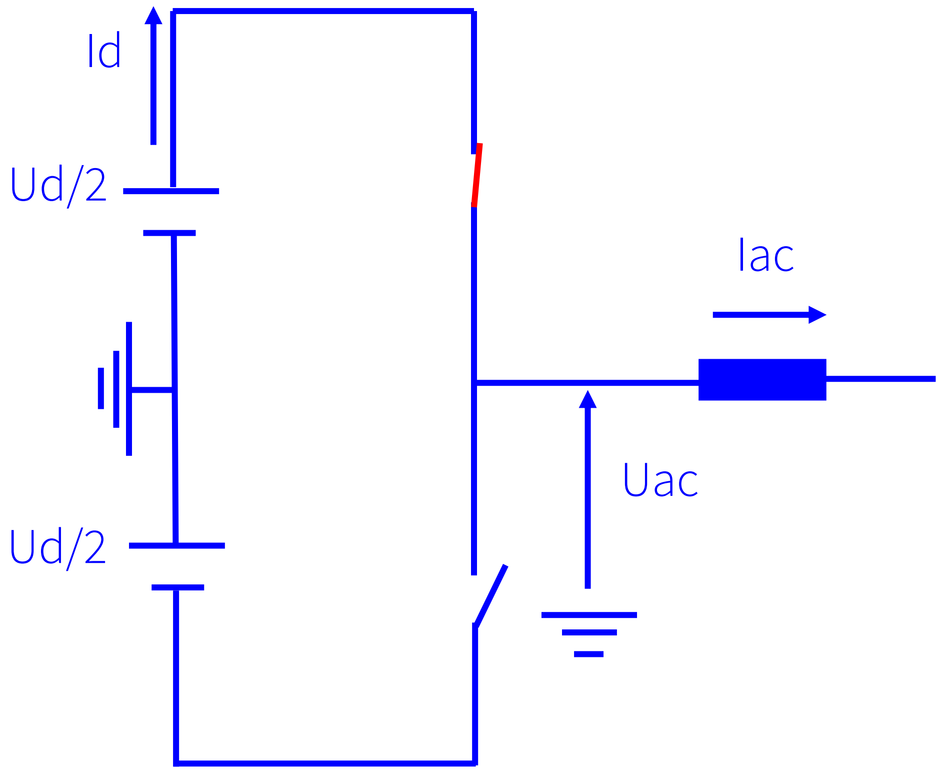


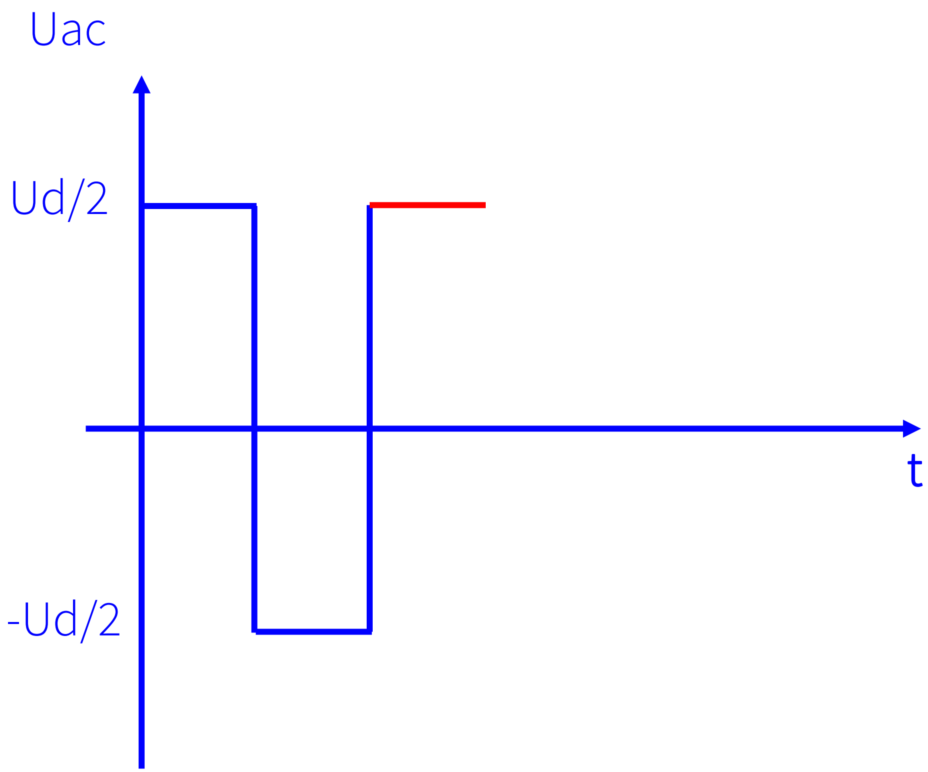
VSC Theory





VSC Theory

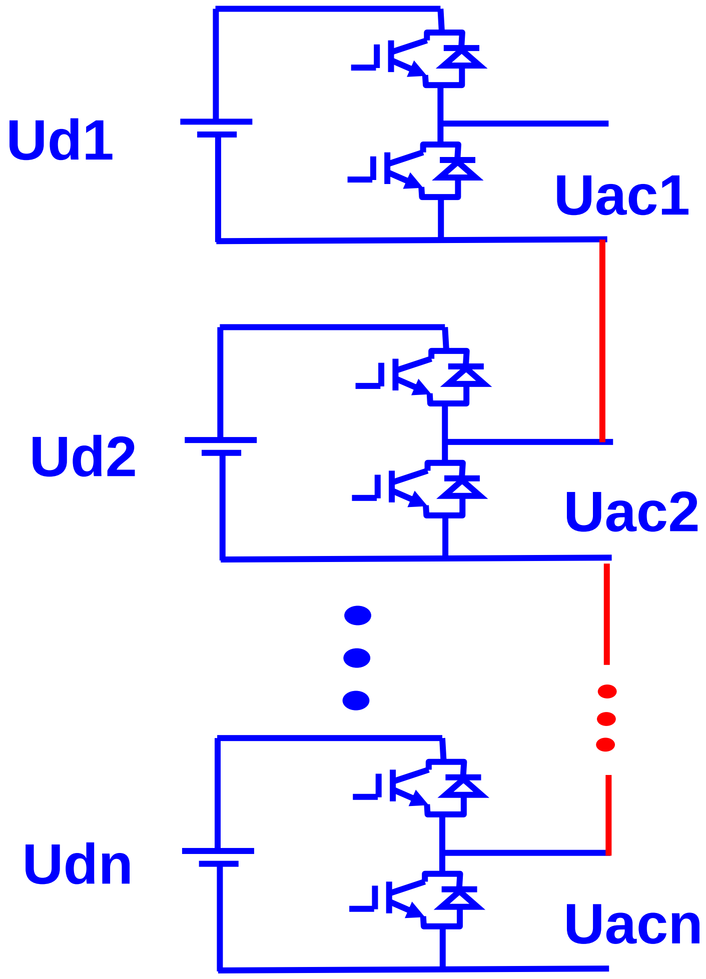


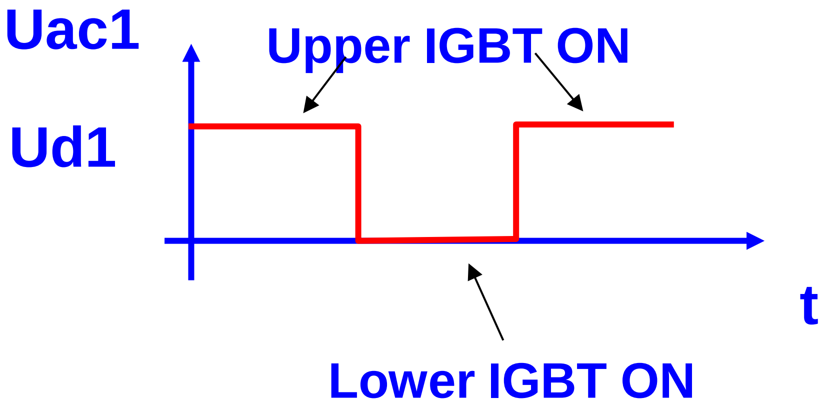


Uac can be set to Ud/2 or –Ud/2 independent of Iac, hence the name Voltage Source

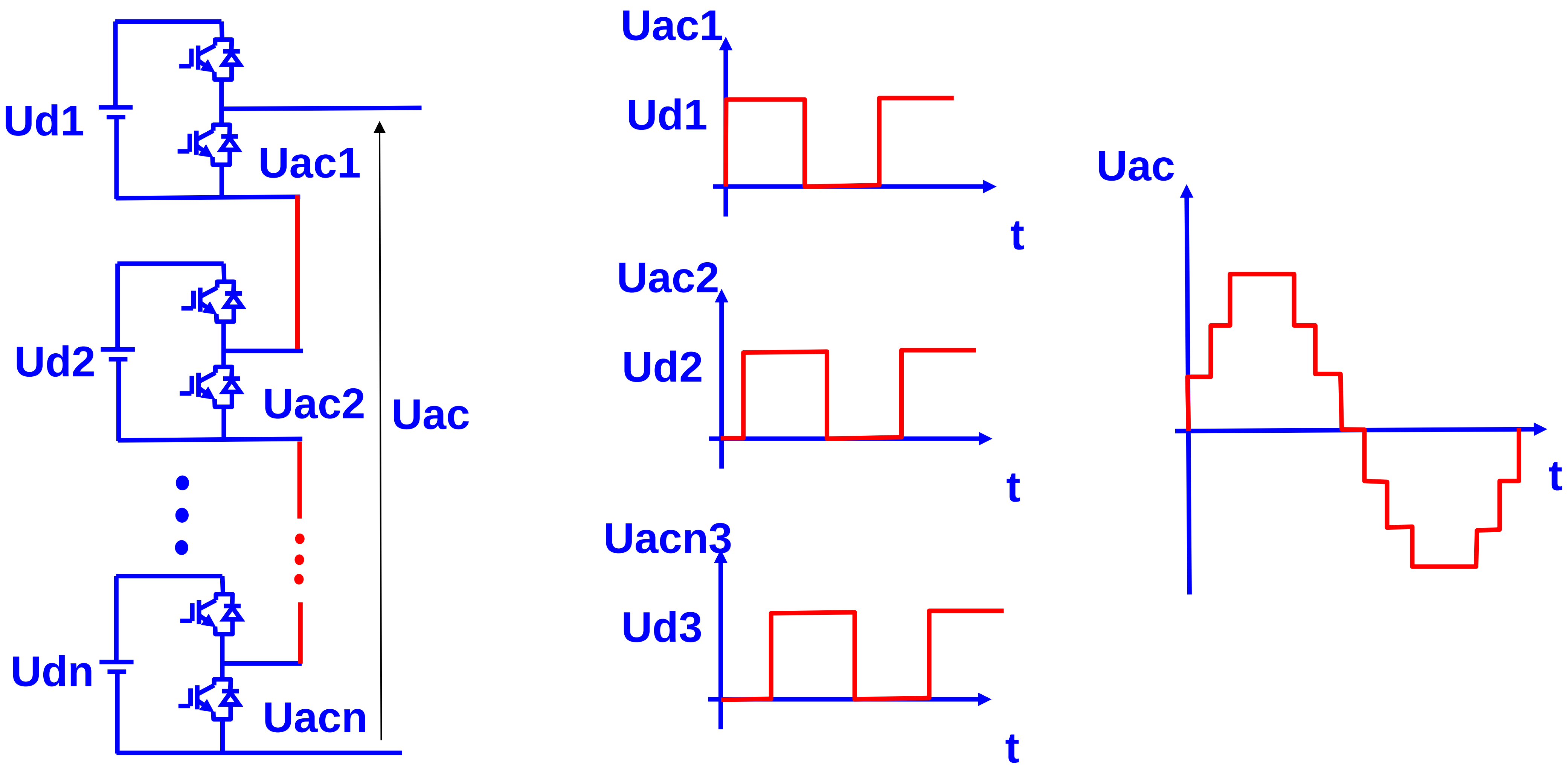
VSC Theory

Multi-level (MMC)





VSC Theory



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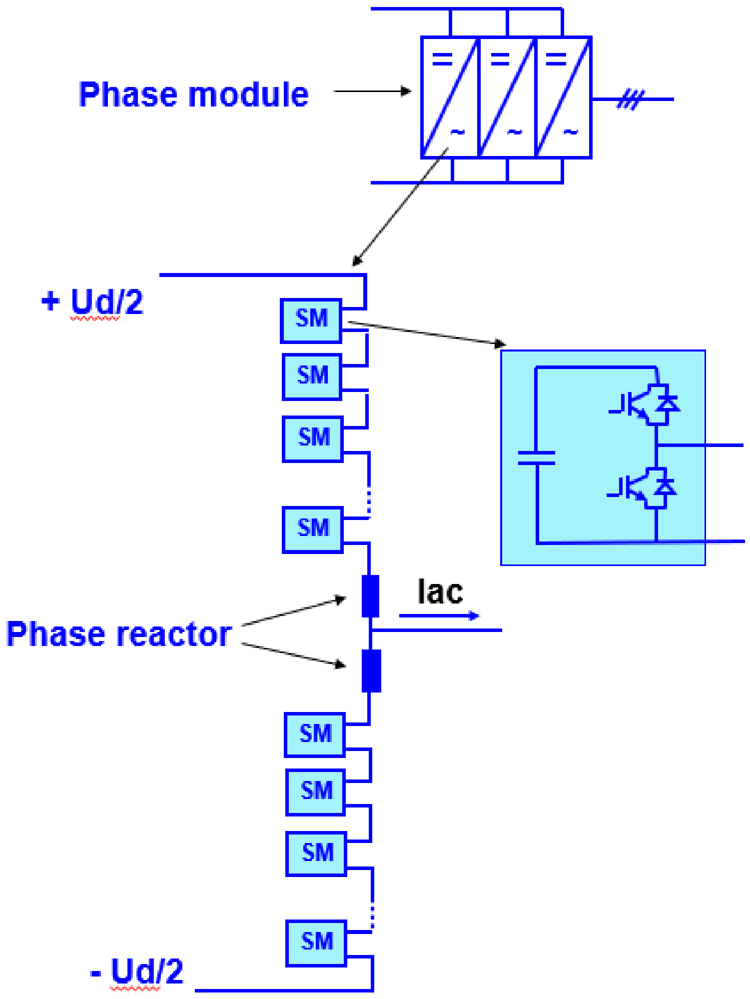
VSC Theory

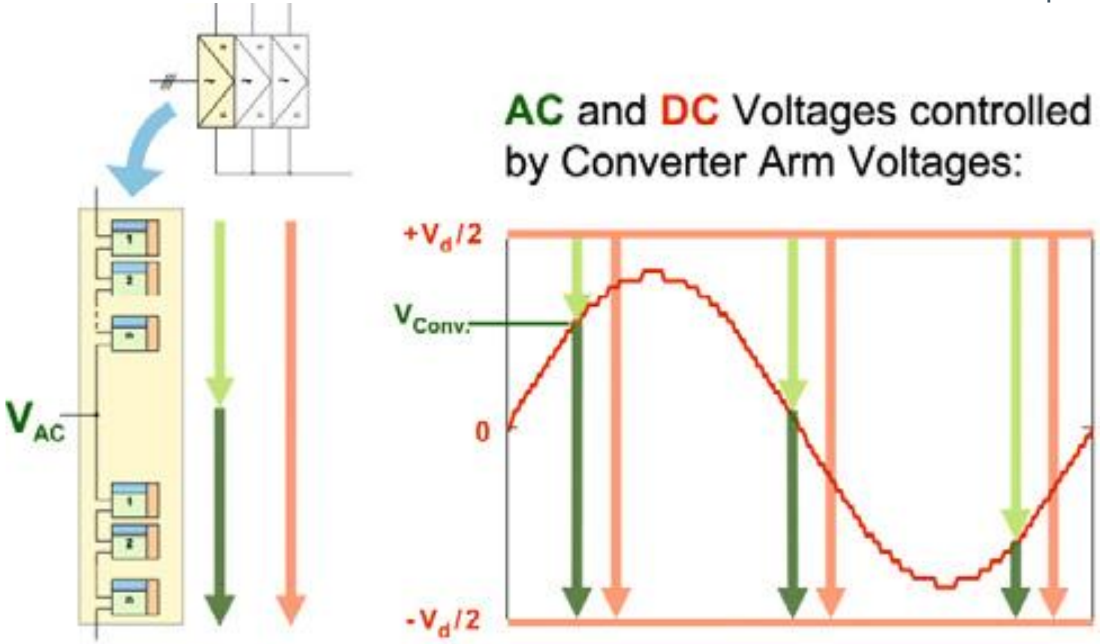


- Each arm contains N submodules
- SM Capacitor voltages are kept almost equal, Uc≈Ud/N
- Each SM can be either OFF or bypassed (lower IGBT triggered, zero voltage at terminals) or ON (upper IGBT triggered, capacitor voltage at terminals)
- $n_u= (N/2)(1-m.\sin(wt))$, $n_L=(N/2)(1+m.\sin(wt))$

  $V_{ac}=(U_d/2).m.\ \sin(wt)$

VSC Theory

- Modulation index m determines the magnitude of the ac voltage
- $V_u = U_c\,(N/2)(1\text{-}m.\sin(wt)) = U_d/2 - V_{ac}$
- $V_L = U_c\,(N/2)(1+m.\sin(wt)) = V_{ac} - U_d/2$
- At each moment total of N submodules are ON in each phase



Courtesy of GE

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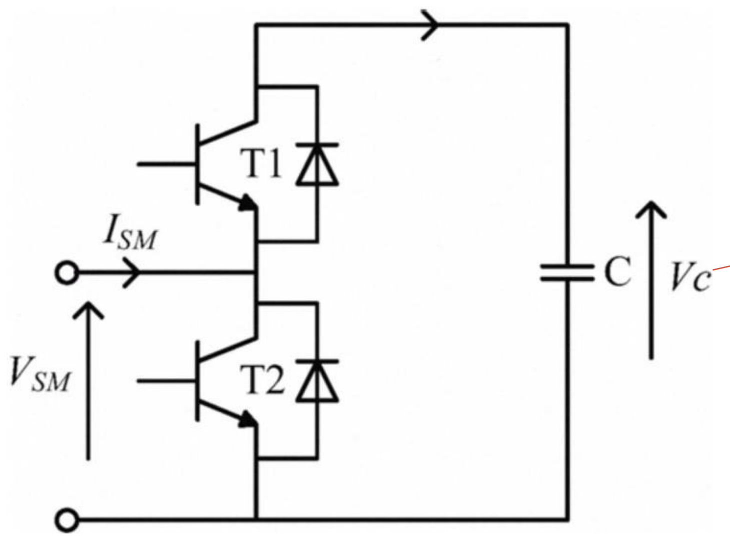
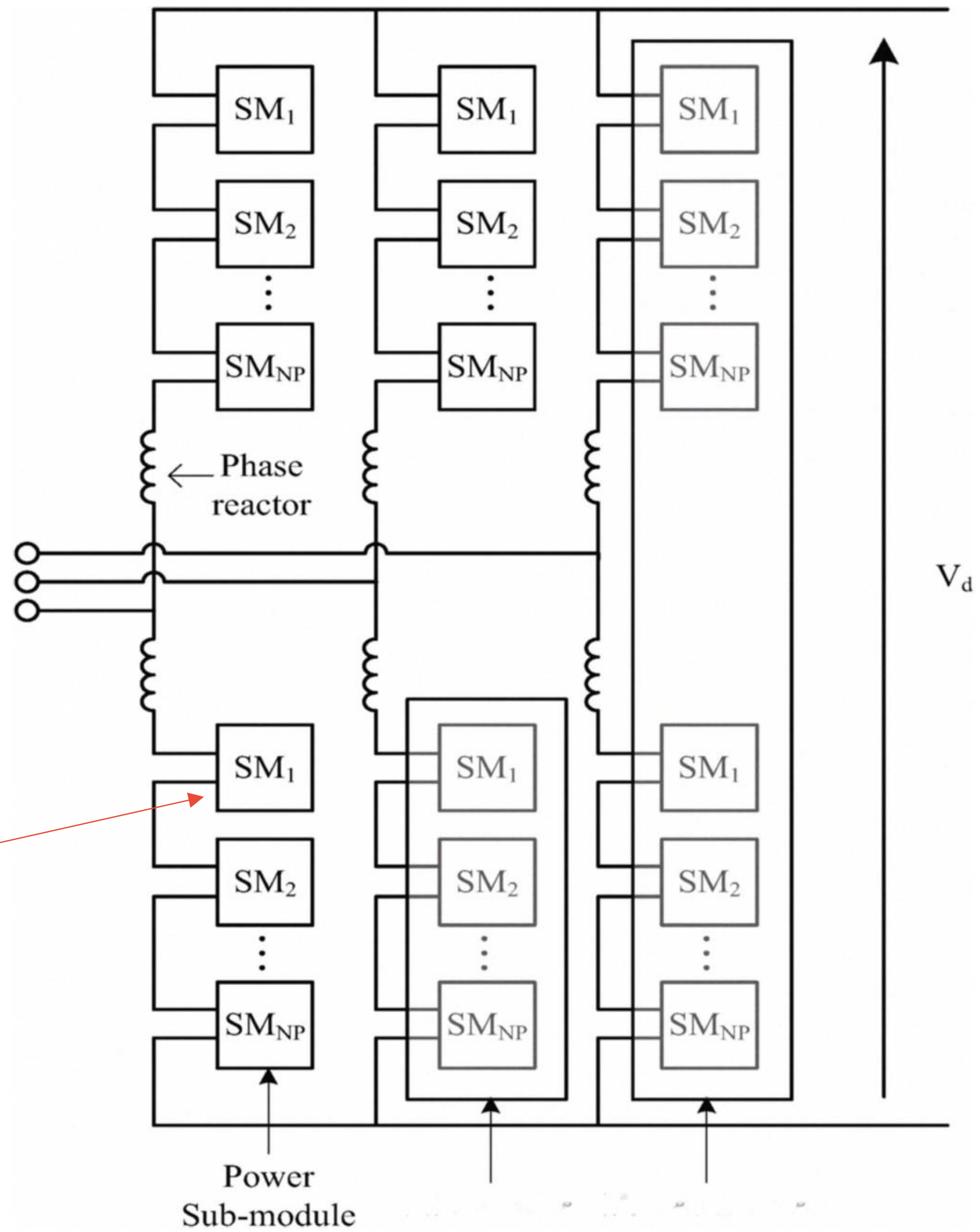
VSC Theory

- $V_{SM} = V_C$ if T1 is on and T2 is off
- $V_{SM} = 0$ if T1 is off and T2 is on





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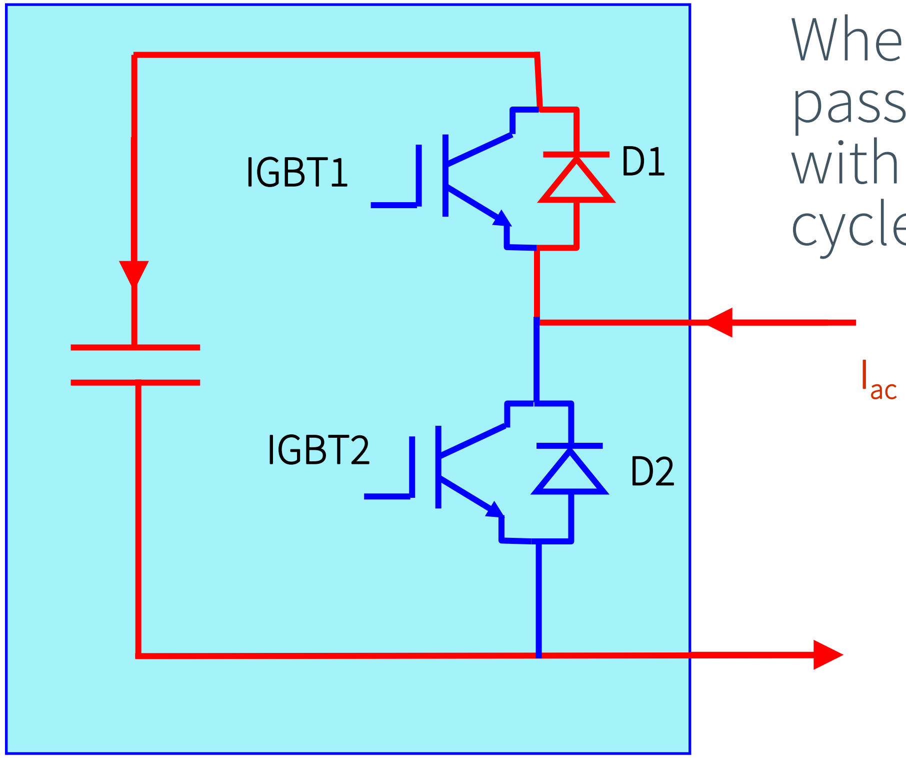
VSC Theory



When both IGBTs 1 and 2 are off the current Iac passes through the diode D1 to charge the capacitor with positive polarity during the positive half cycle cycle.

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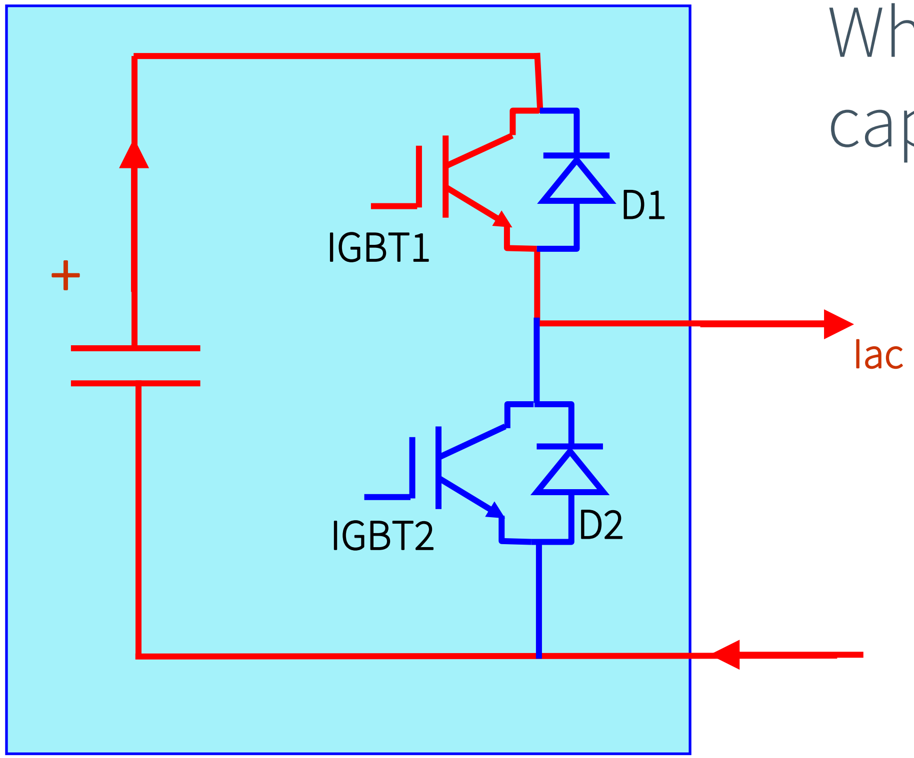
VSC Theory



When IGBT 1 is on and IGBT 2 is off the capacitor will discharge.

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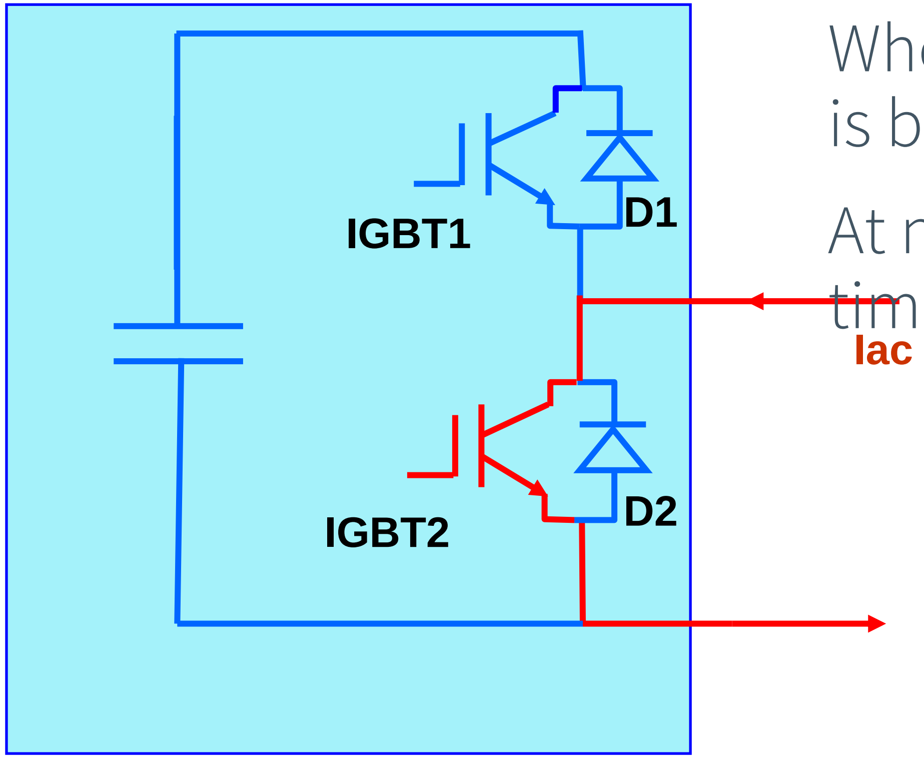
VSC Theory



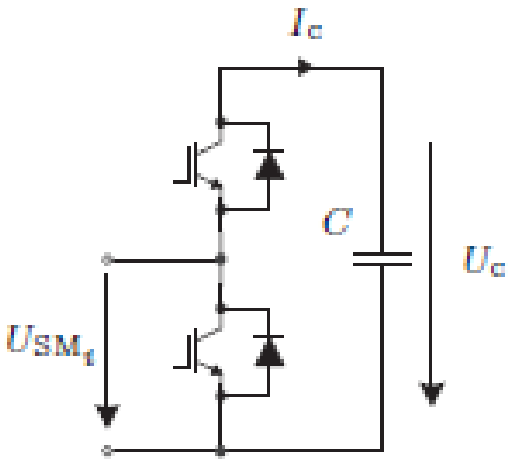
When IGBT 1 is off and IGBT 2 is on the module is bypassed.

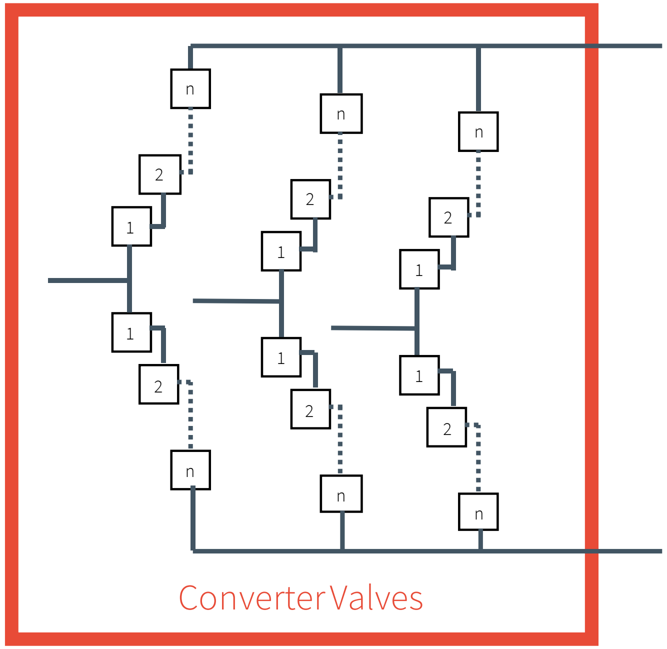
At no time IGBTs 1 and 2 are on at the same time.

HVDC Technology
Valve Cell

Half-Bridge

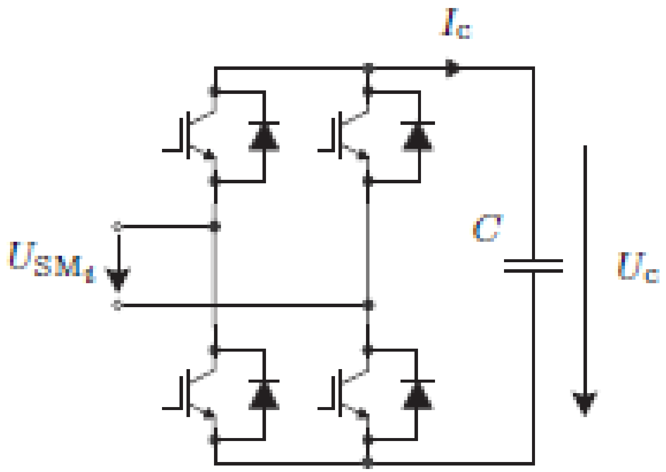
- Less power components



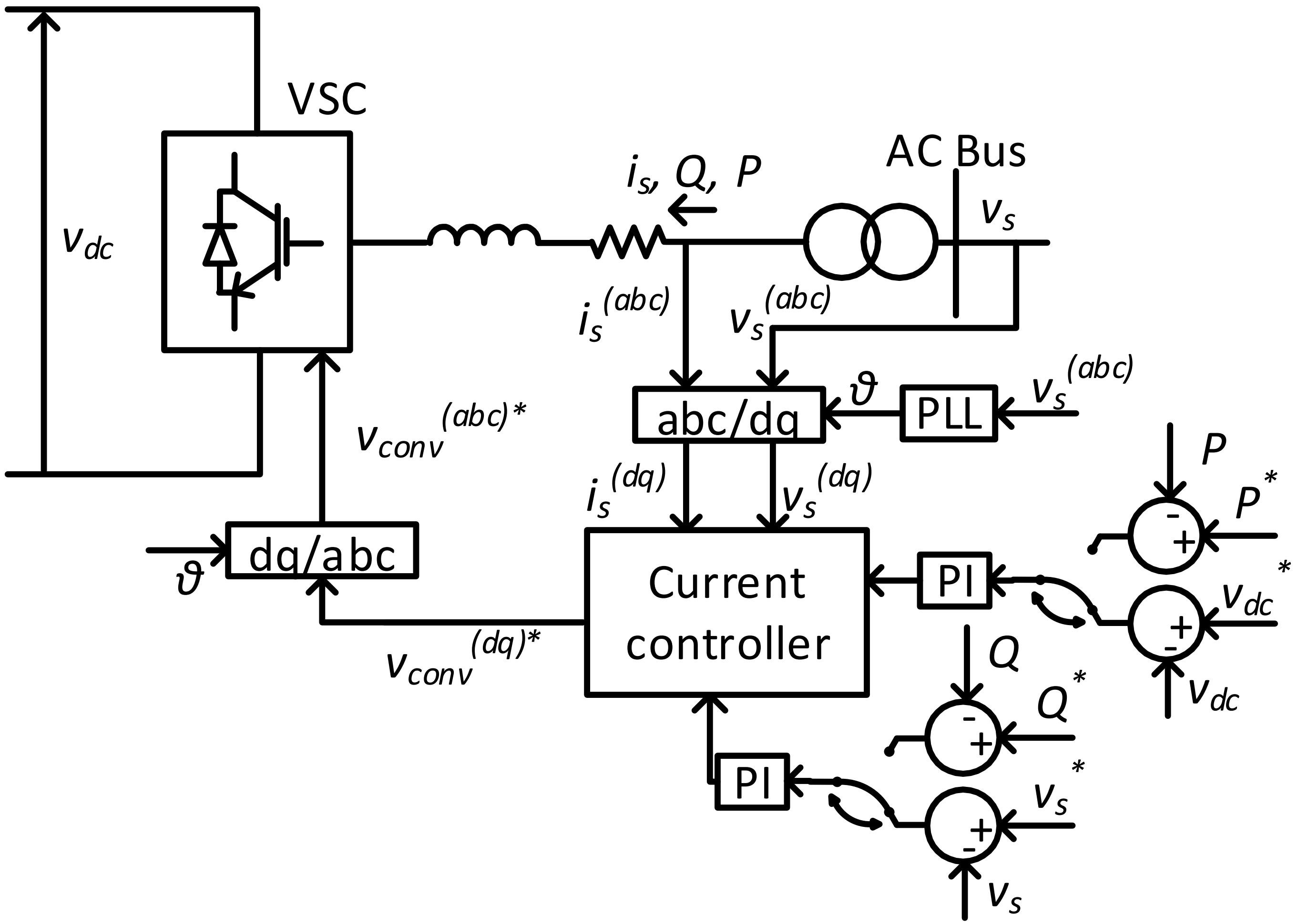


Full Bridge

- Excellent dc fault handling



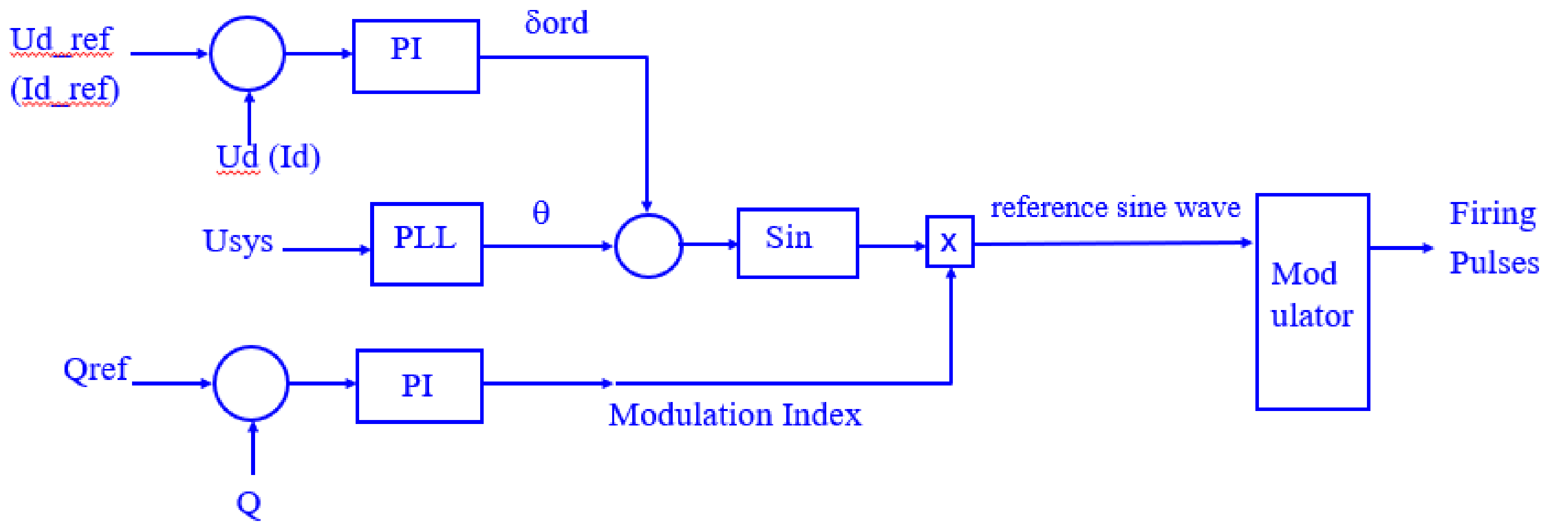
VSC Theory



VSC
AC Bus
v_{dc}
i_s, Q, P
v_s
$i_s^{(abc)}$
$v_s^{(abc)}$
abc/dq
ϑ
PLL
$v_s^{(abc)}$
$v_{conv}^{(abc)*}$
$i_s^{(dq)}$
$v_s^{(dq)}$
P
P^*
dq/abc
ϑ
Current controller
PI
v_{dc}^*
v_{dc}
$v_{conv}^{(dq)*}$
Q
Q^*
PI
v_s^*
v_s

VSC Theory - Controls

- Conventional control
  - Based on steady state phasor relations
  - Active and reactive power controls affect each other



VSC Theory - Controls

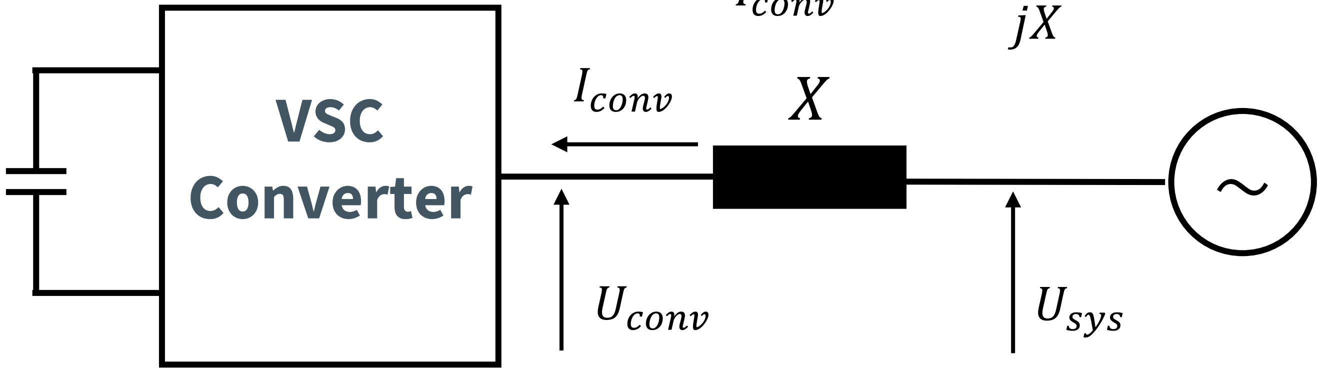
- Decoupled control
  - Based on steady state phasor relations
  - Active and reactive power controls affect each other

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R + L_s.\frac{d}{dt} & 0 & 0 \\ 0 & R + L_s.\frac{d}{dt} & 0 \\ 0 & 0 & R + L_s.\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = (2/3) \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

VSC Theory - Controls

$$I_{conv} = \frac{U_{sys} - U_{conv}}{jX}$$



$$\begin{bmatrix} U_{sysa} \\ U_{sysb} \\ U_{sysc} \end{bmatrix} = \begin{bmatrix} R + L_s.\frac{d}{dt} & 0 & 0 \\ 0 & R + L_s.\frac{d}{dt} & 0 \\ 0 & 0 & R + L_s.\frac{d}{dt} \end{bmatrix} \begin{bmatrix} i_{conva} \\ i_{convb} \\ i_{convc} \end{bmatrix} + \begin{bmatrix} U_{conva} \\ U_{convb} \\ U_{convc} \end{bmatrix}$$

VSC Theory - Controls

- Equations in dq frame:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -R/L_s & \omega \\ -\omega & -R/L_s \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} e_d - |V| \\ e_q \end{bmatrix}$$

- These equations suggest the d and q axis controls can be separated if the following values are used for e_d and e_q

ed= |V| - LS.w.iq+ud

eq= LS.w.id+uq

- Substituting these equations, we have:

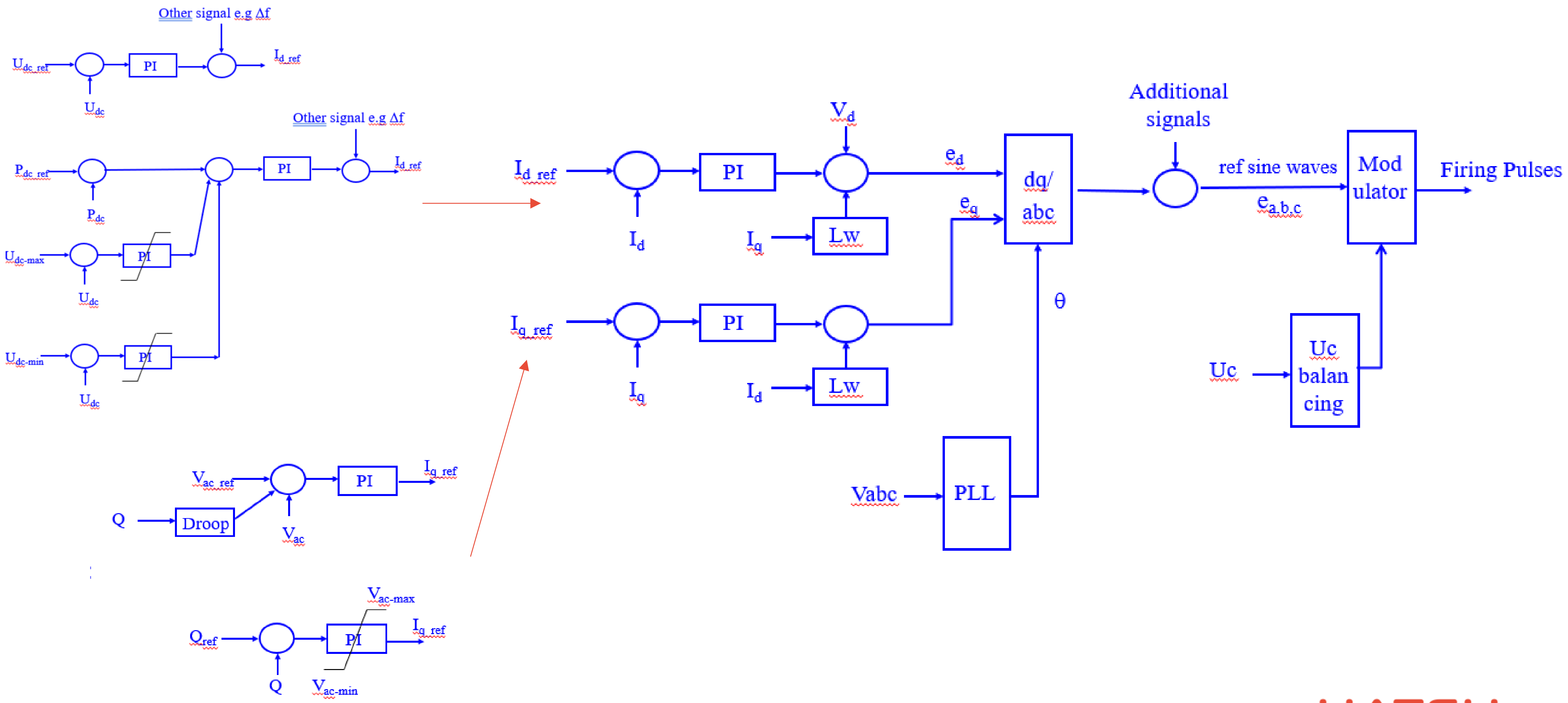
$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -R/L_s & 0 \\ 0 & -R/L_s \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} u_d \\ u_q \end{bmatrix}$$

VSC Theory - Controls

- Decoupled Control
  - D-axis
    - One station controls DC Voltage
    - One station controls DC Power
  - Q-axis
    - AC voltage control
    - Q Control

HATCH

VSC Theory - Controls



VSC Theory - Controls

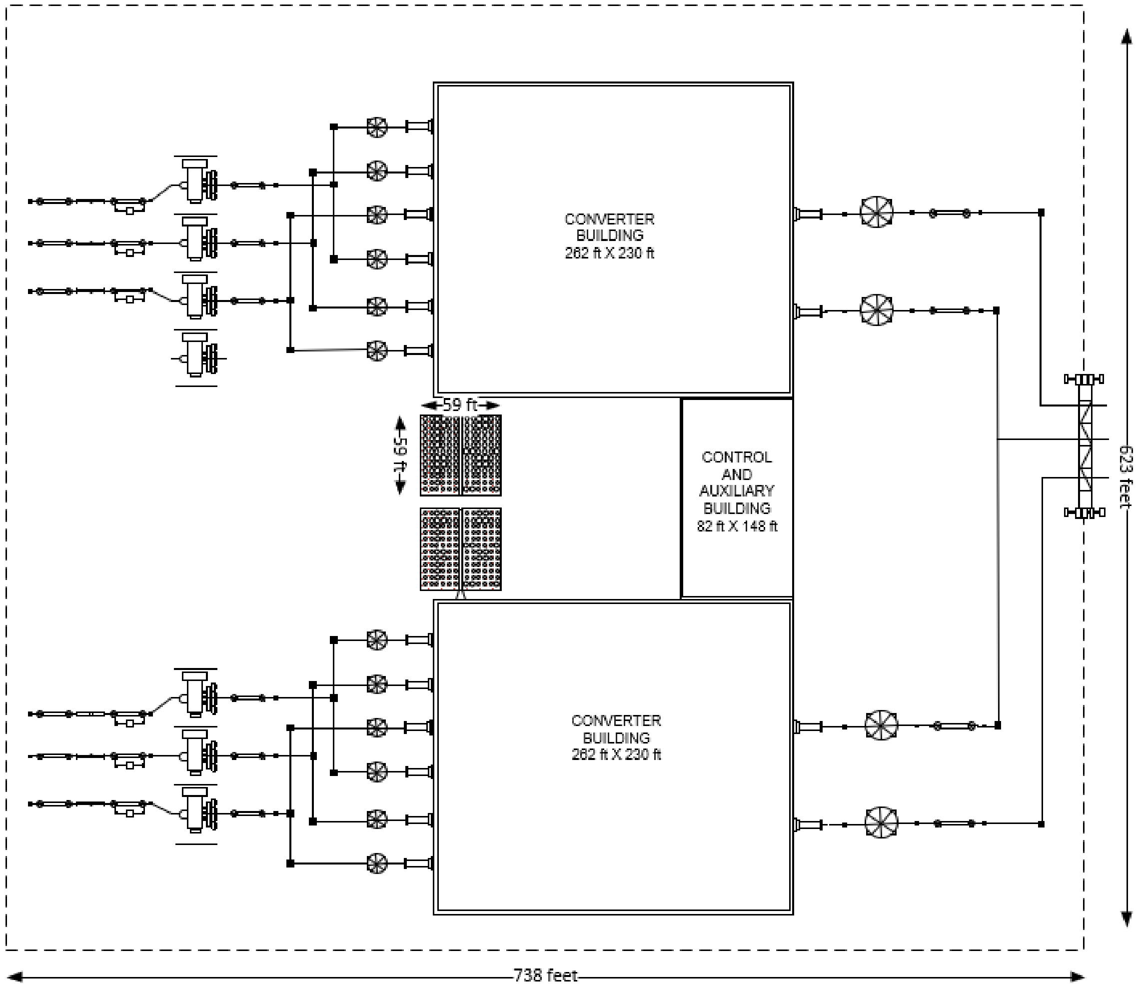
- Other Control modes
  - Negative sequence control
  - Circulating current
  - Capacitor voltage balancing

HVDC Station Overview

HVDC Technology

HVDC VSC Station Overview

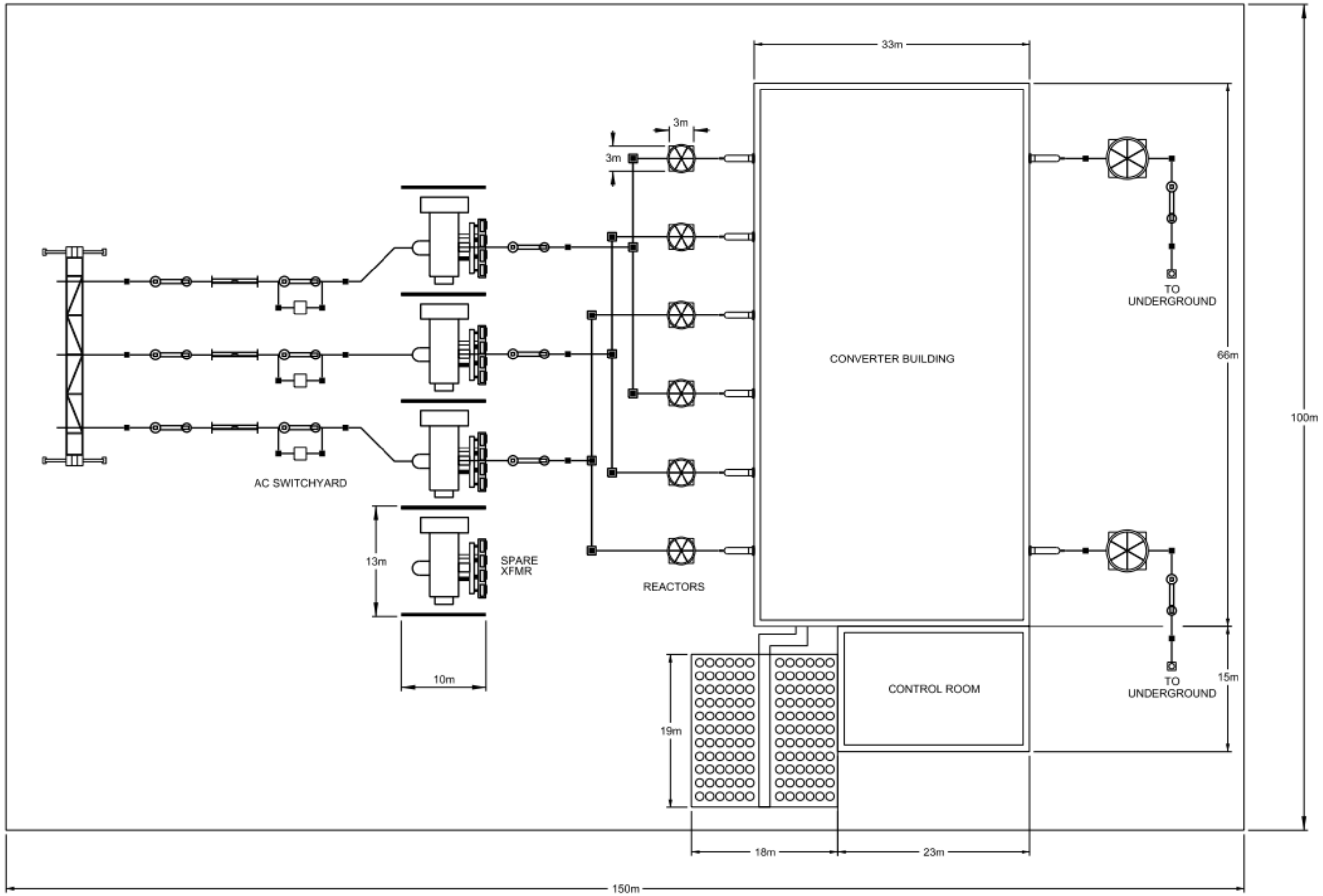
- VSC 2000MW +/- 525kV
- Footprint: 625ft x 740ft
  - 10-11 acres
- Layout optimization possible



HVDC Technology

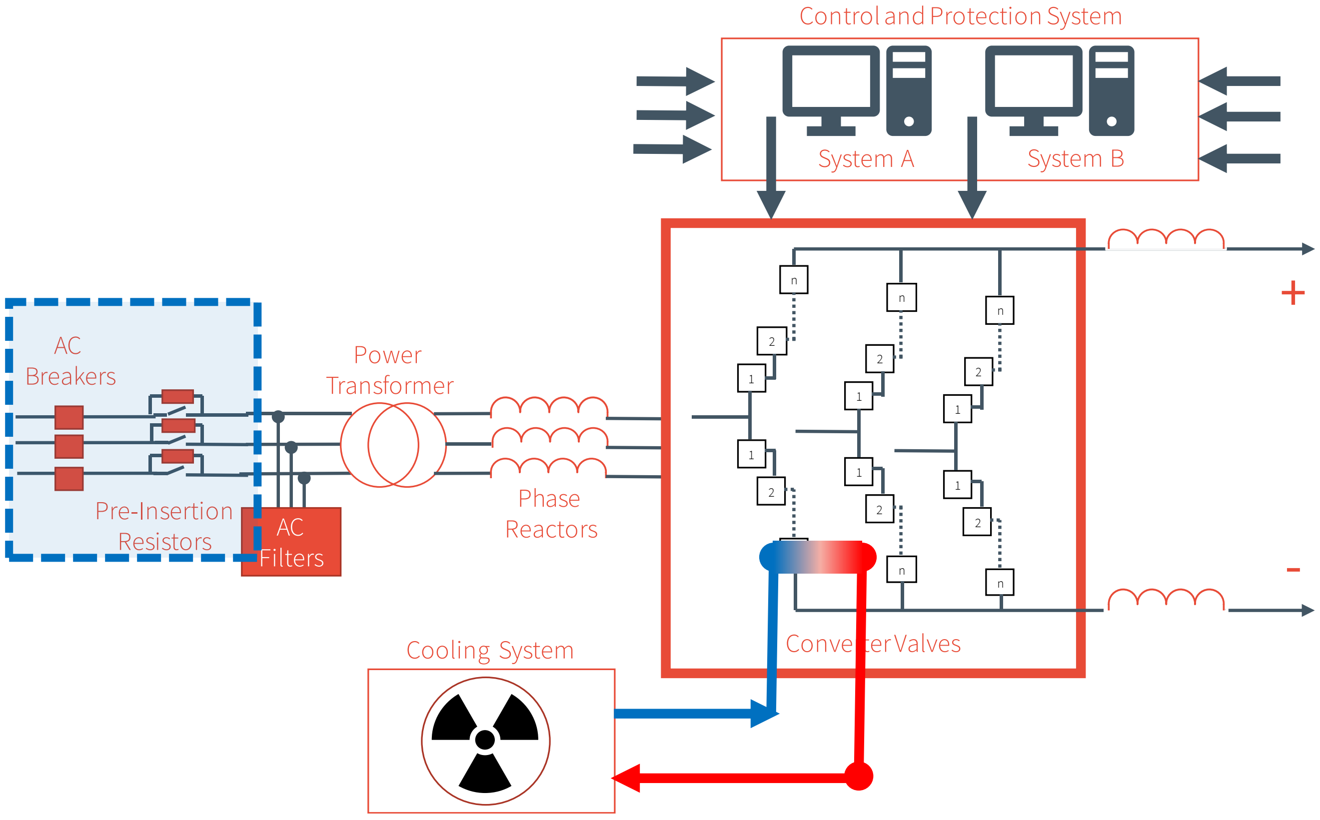
HVDC VSC Station Overview

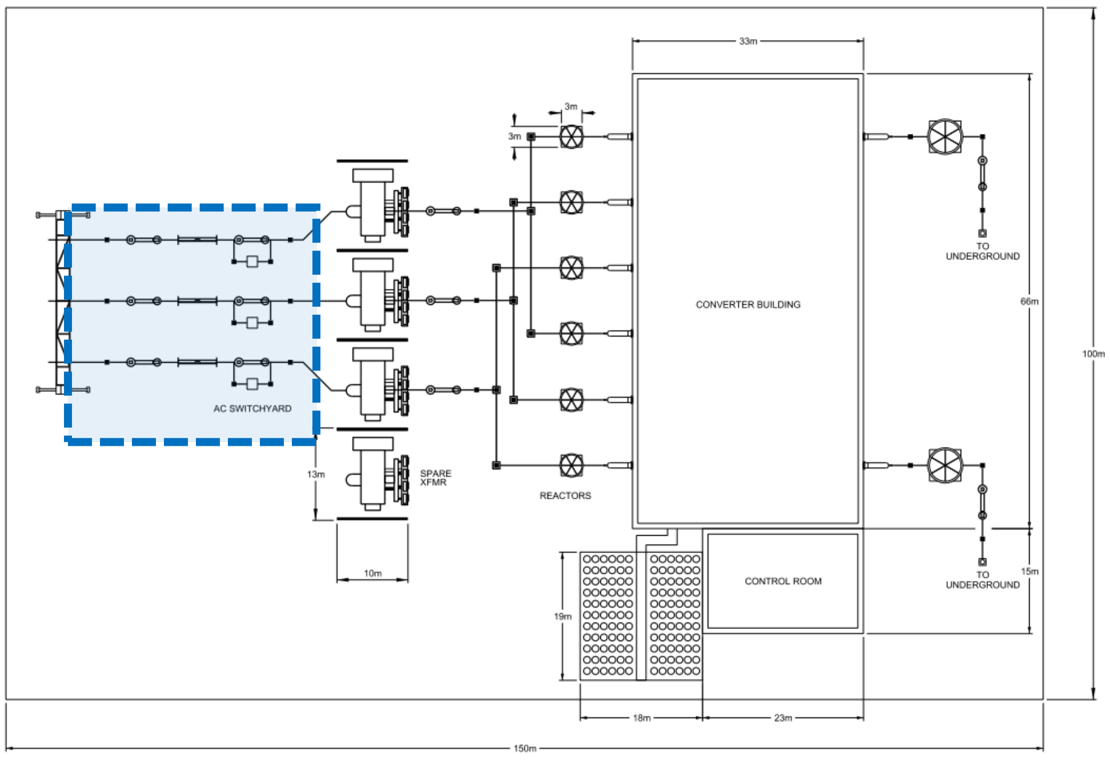
- VSC 500MW +/- 200kV
- Footprint: 325ft x 400ft
- Layout optimization possible



HVDC Technology

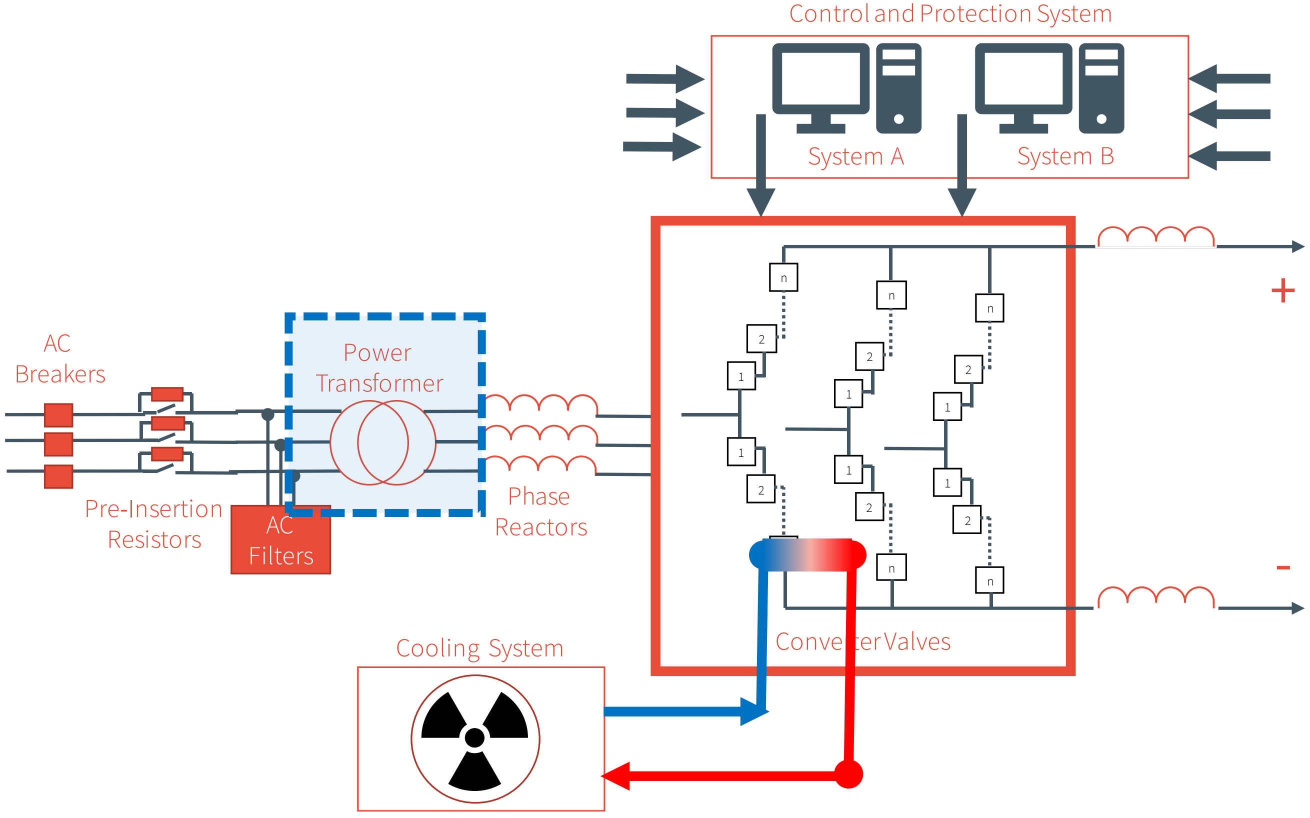
HVDC Station Overview

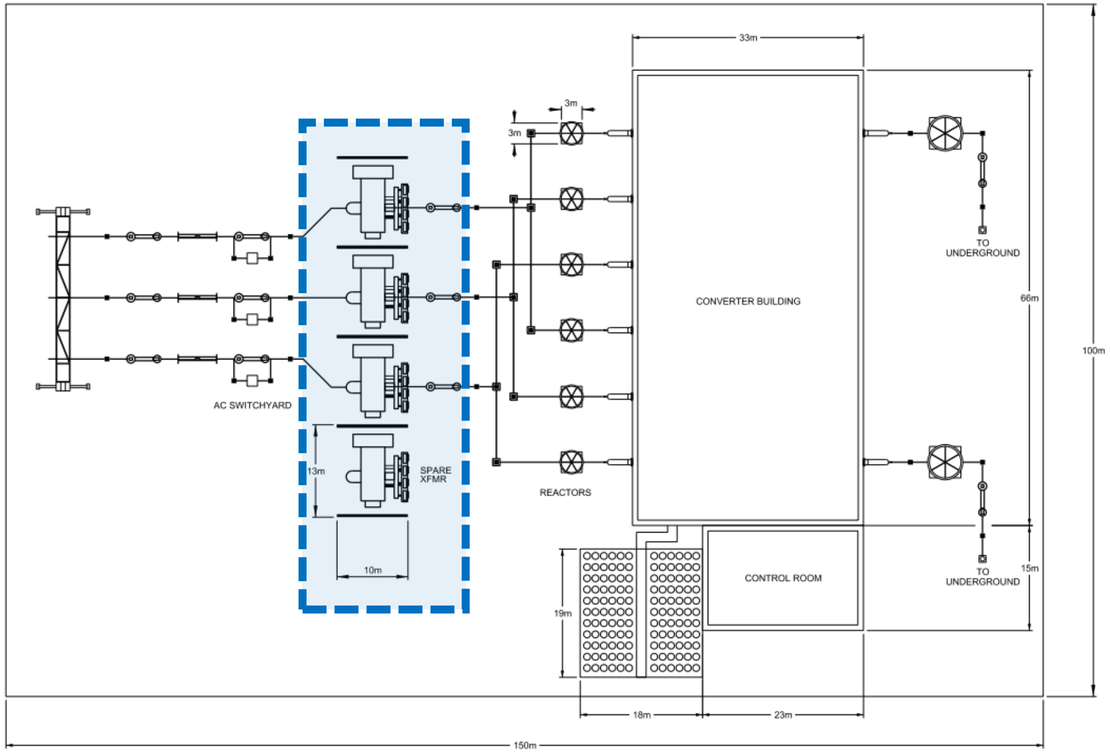




HVDC Technology

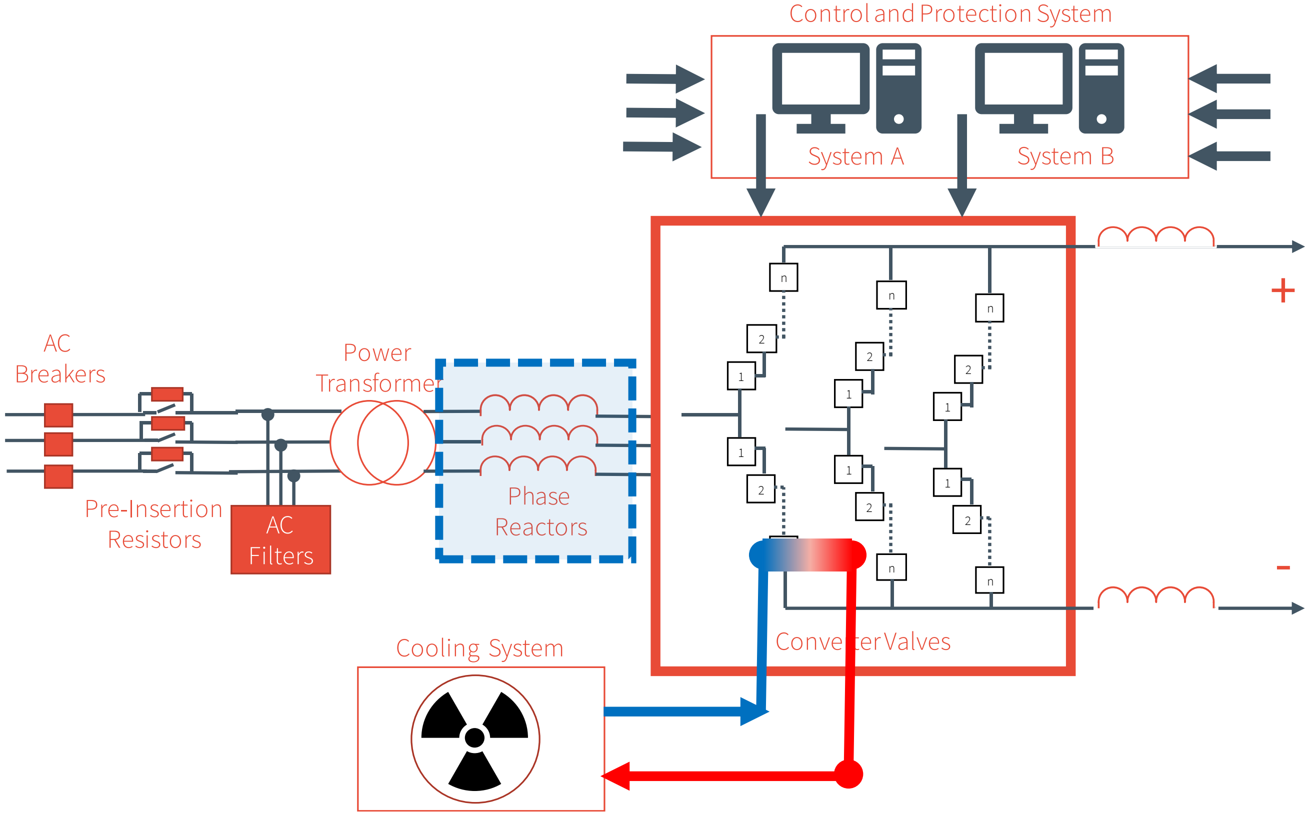
HVDC Station Overview

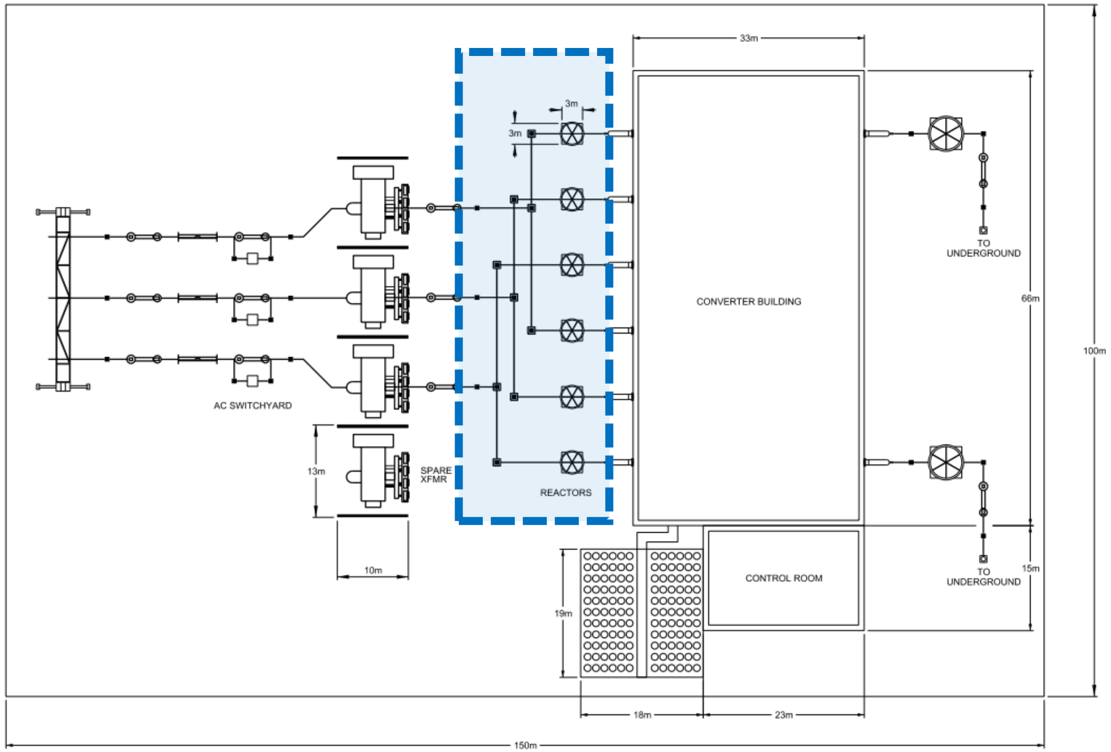




HVDC Technology

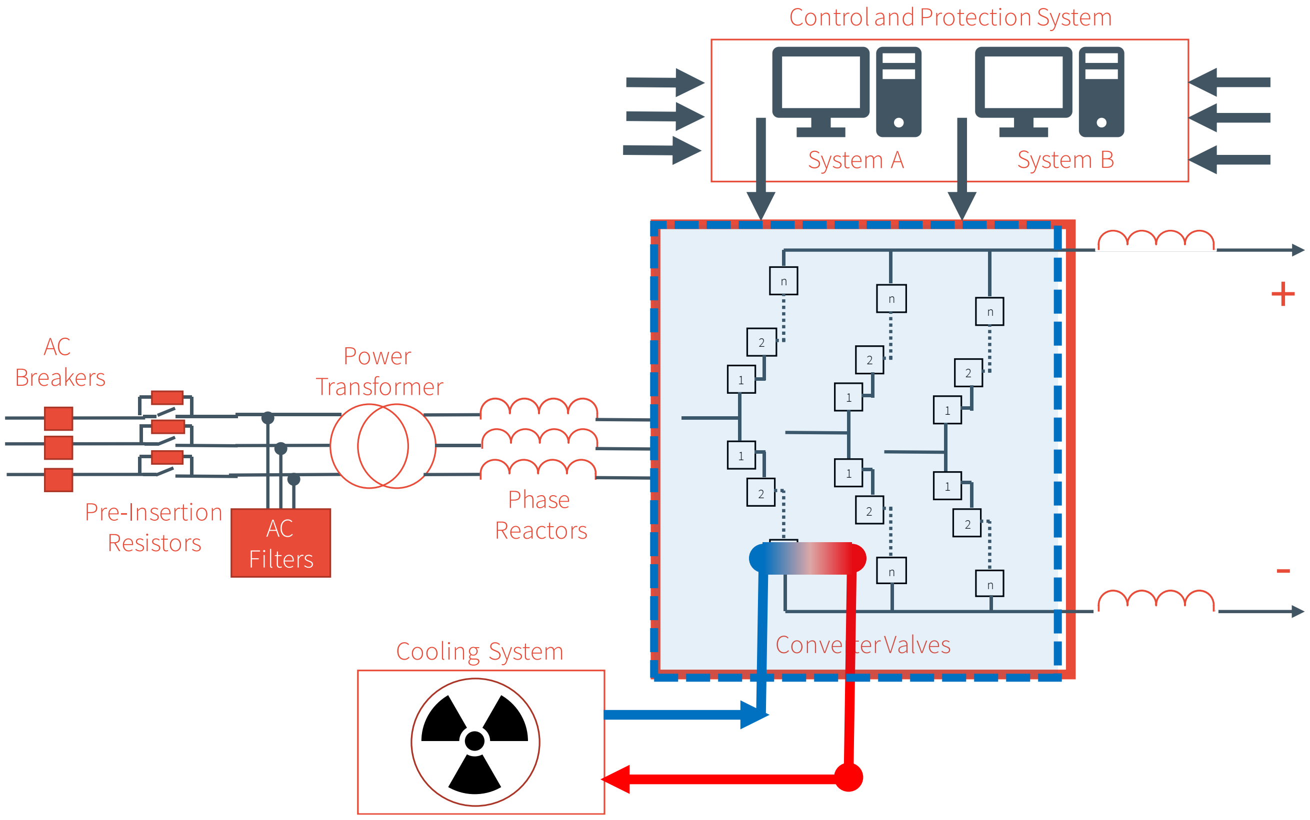
HVDC Station Overview

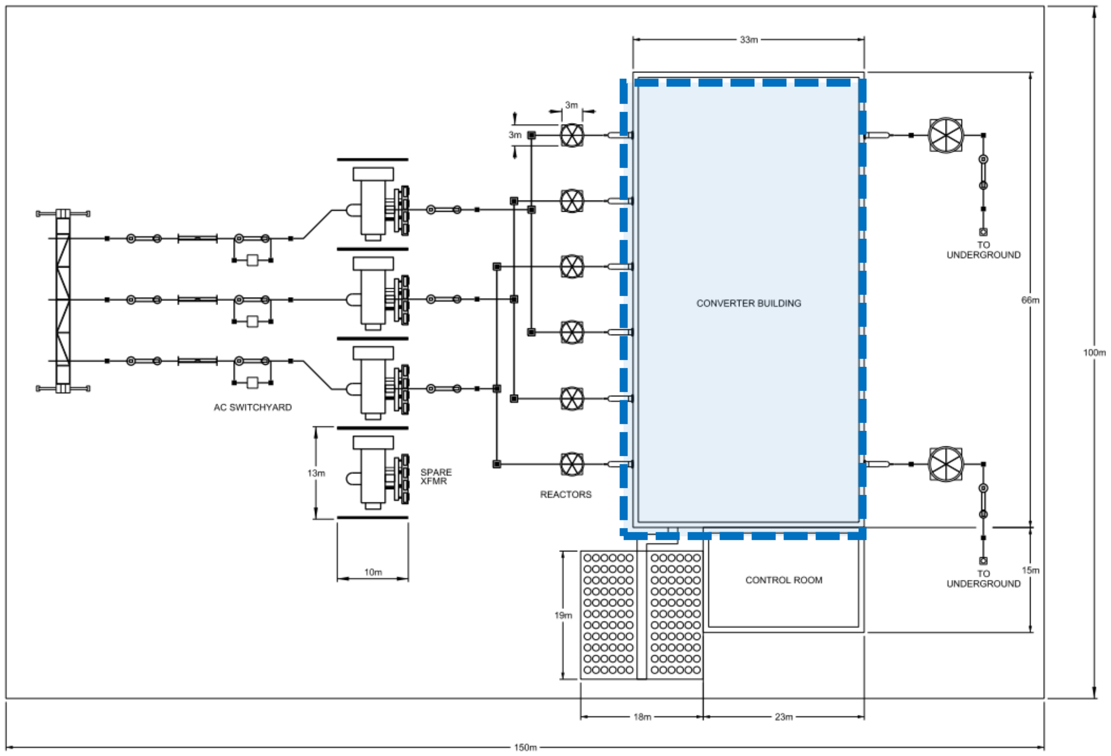




HVDC Technology

HVDC Station Overview

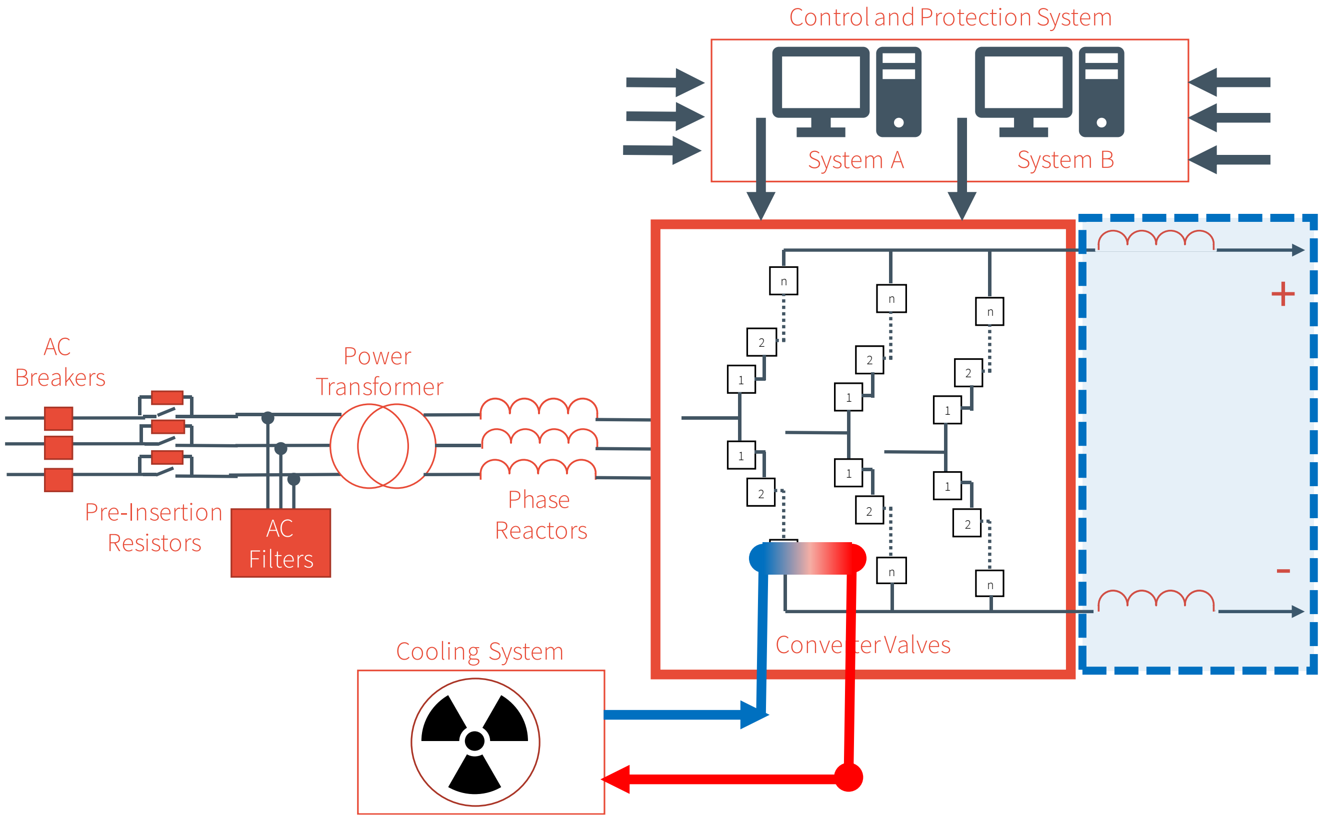


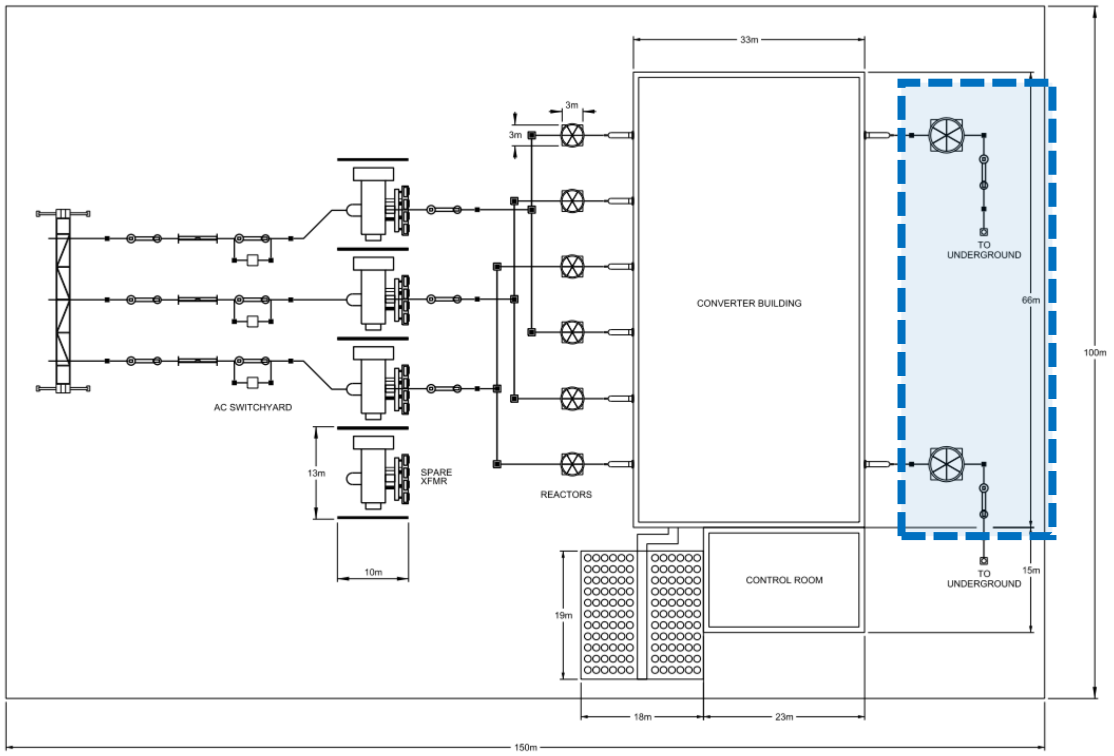


HATCH

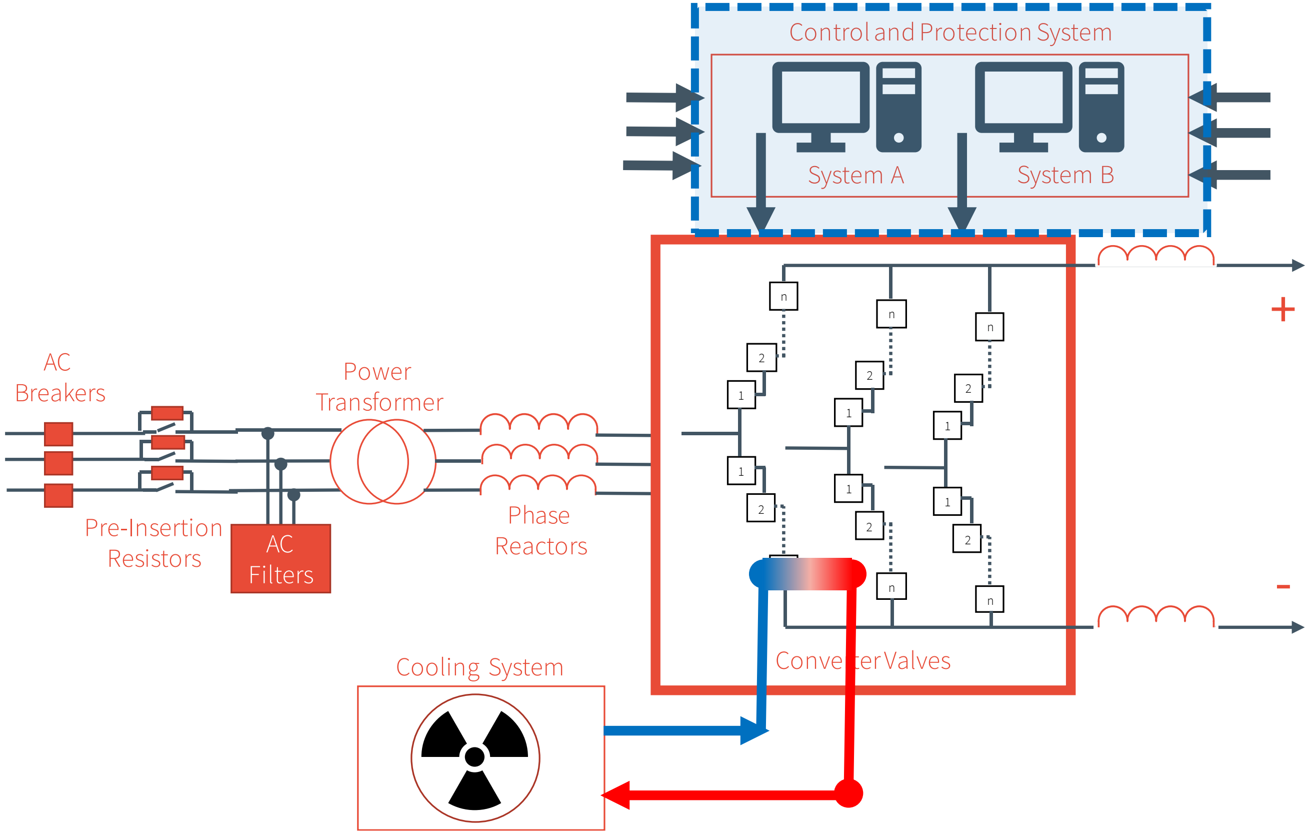
HVDC Technology

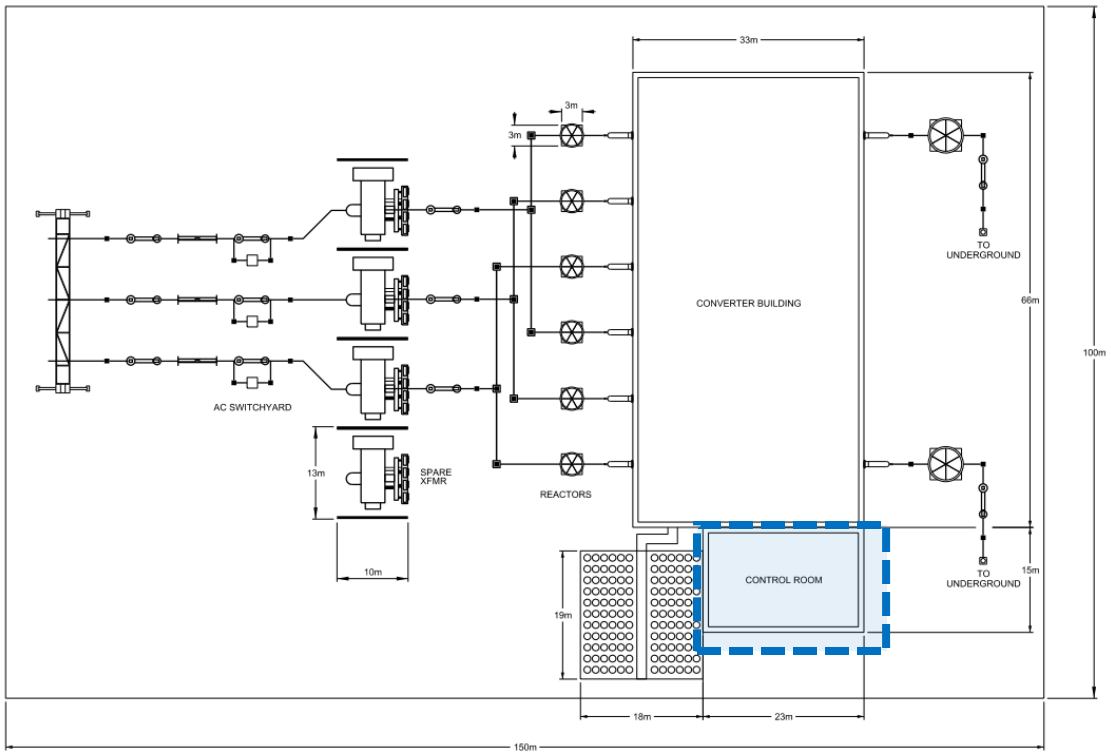
HVDC Station Overview





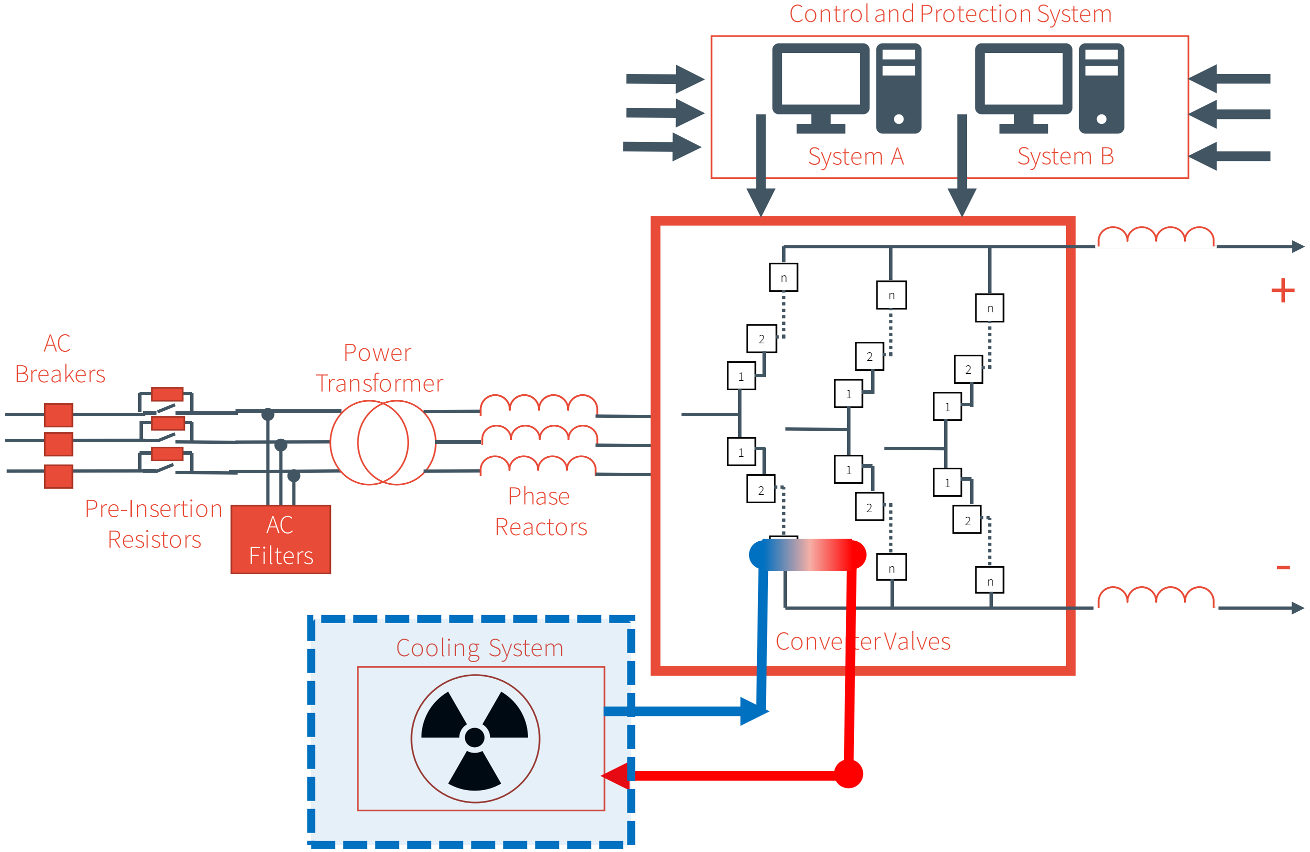
HVDC Technology
HVDC Station Overview

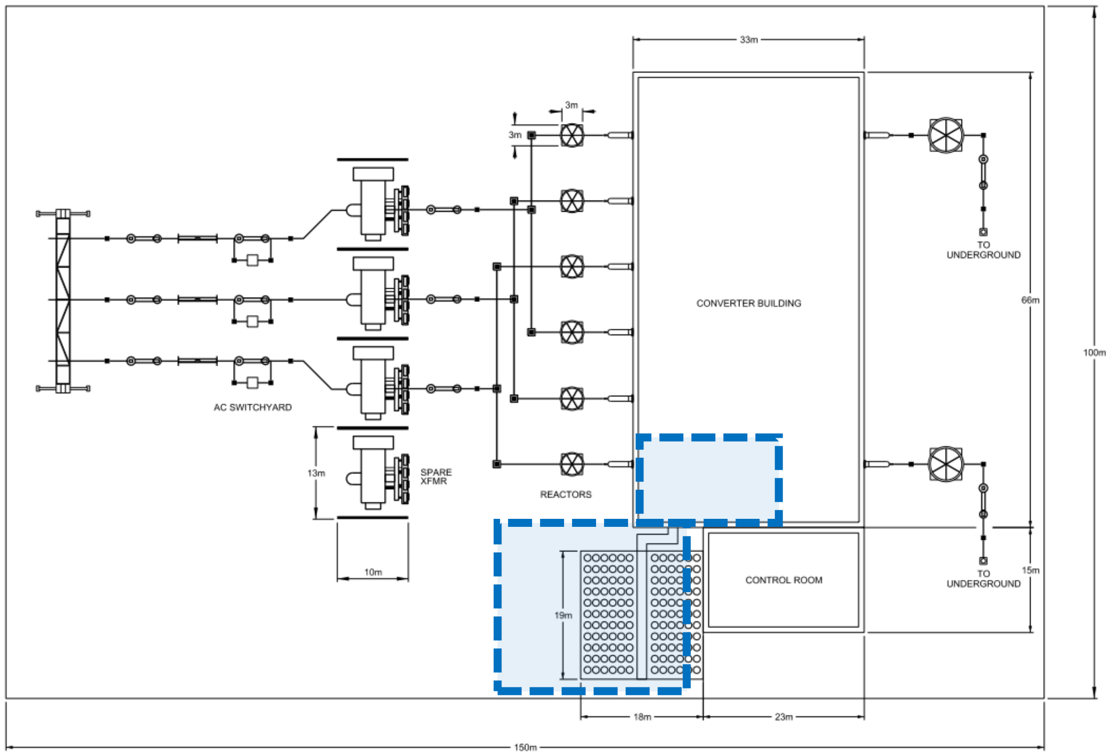




HVDC Technology

HVDC Station Overview





System Studies and Planning

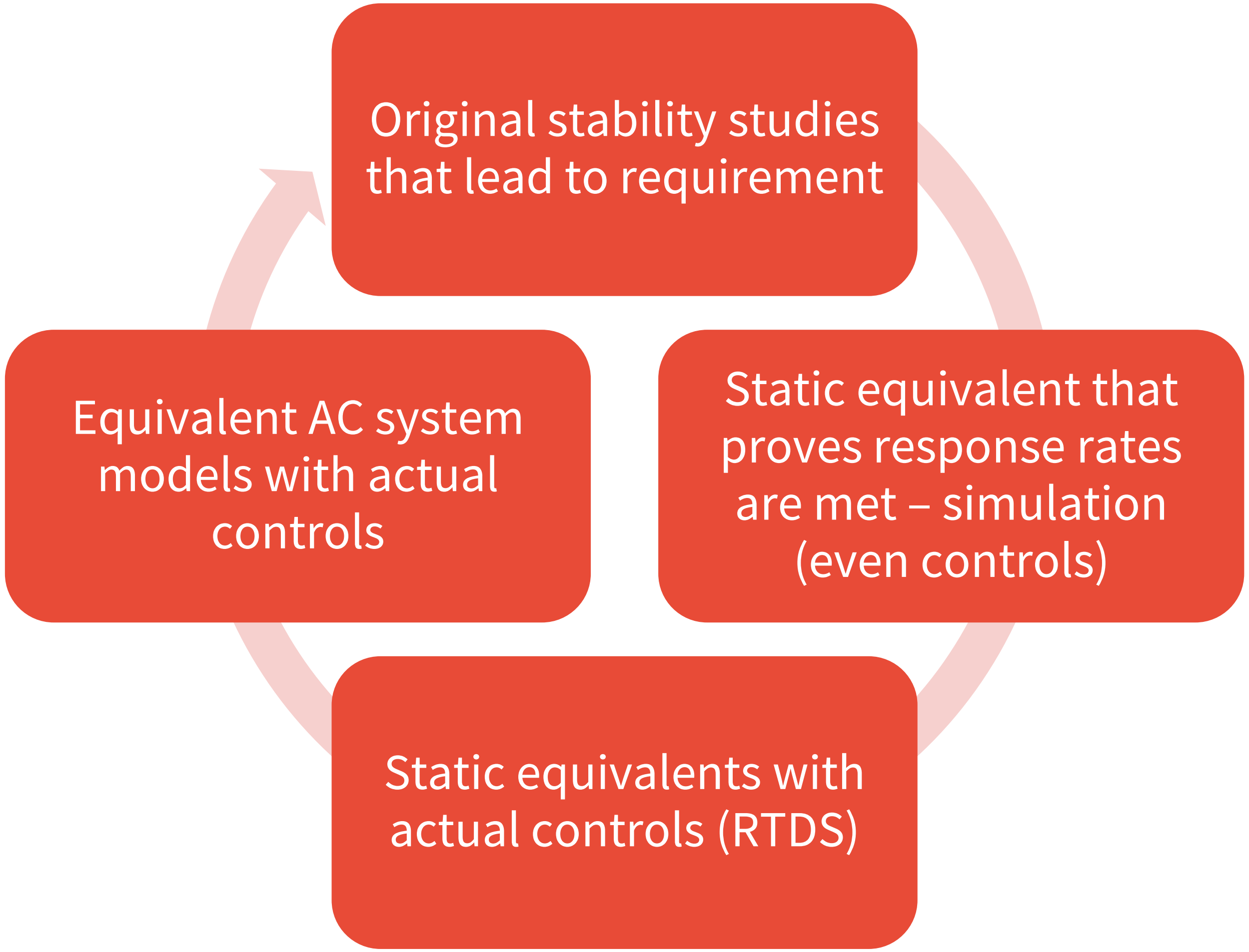
HVDC Technology

System Studies – In preparation

Steady-State Analysis	Short Circuit Analysis	Stability Analysis	Harmonic Analysis	Specialized
Voltage limit for intact case (N-0) and during contingencies Thermal limit Reactive power Various network conditions	Maximum current for equipment ratings	Transient stability Dynamic stability Transient recovery requirements for various contingencies	Harmonic impedance sectors for design Existing background harmonics	Sub-synchronous Control interaction Noise level RTDS
PSSE	**PSSE, ASPEN, eTAP**	**PSSE/PSCAD**	**PSSE, ASPEN, Etran, in-house**	**PSCAD, RSCAD/RTDS**

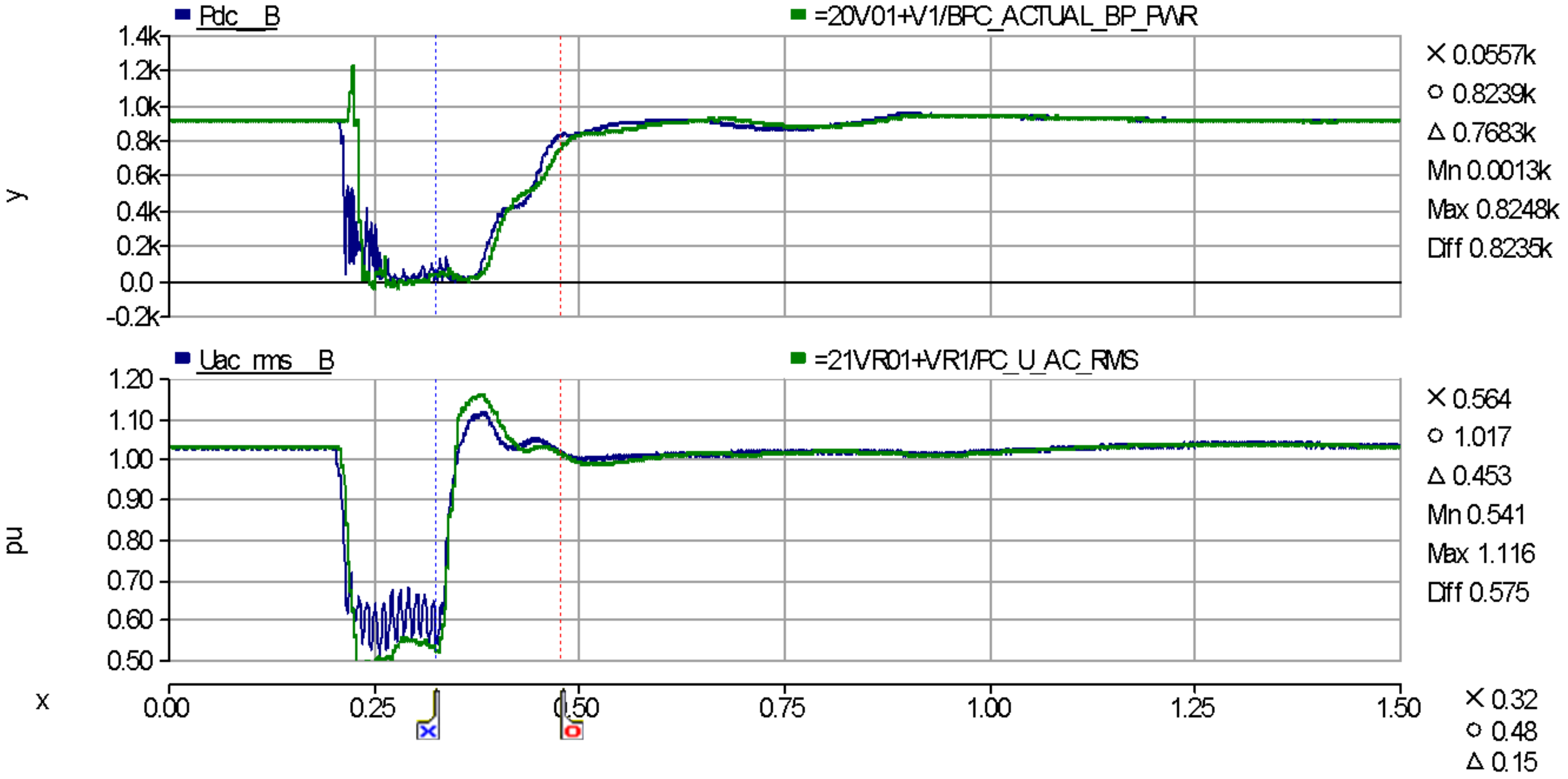
HATCH

Cycle of Life…For a System Study



Case Study

- Comparison of PSCAD model vs. RTDS with actual controls



HVDC Technology

System Studies – During Execution

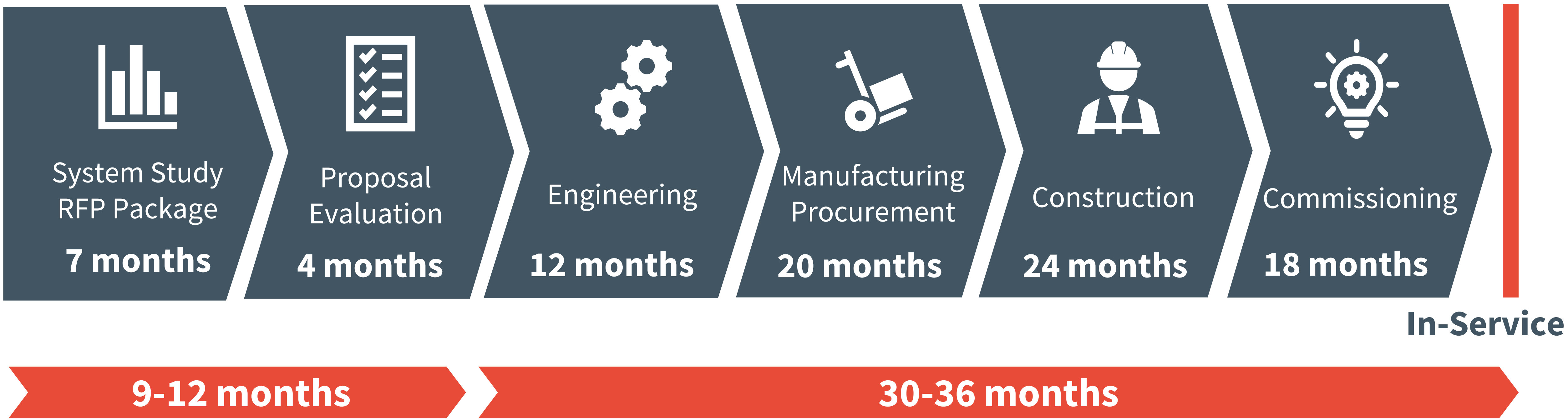
From HVDC vendors (not limited to):

- Dynamic Performance Study
- AC Overvoltage
- DC transient over-voltages
- Transient currents
- Load flow
- Reactive power control
- Sub-Synchronous Resonance
- Control Interaction
- Main circuit parameters
- Insulation coordination
- Grounding
- Noise Level Study
- Reliability, availability and maintainability
- Harmonic Performance

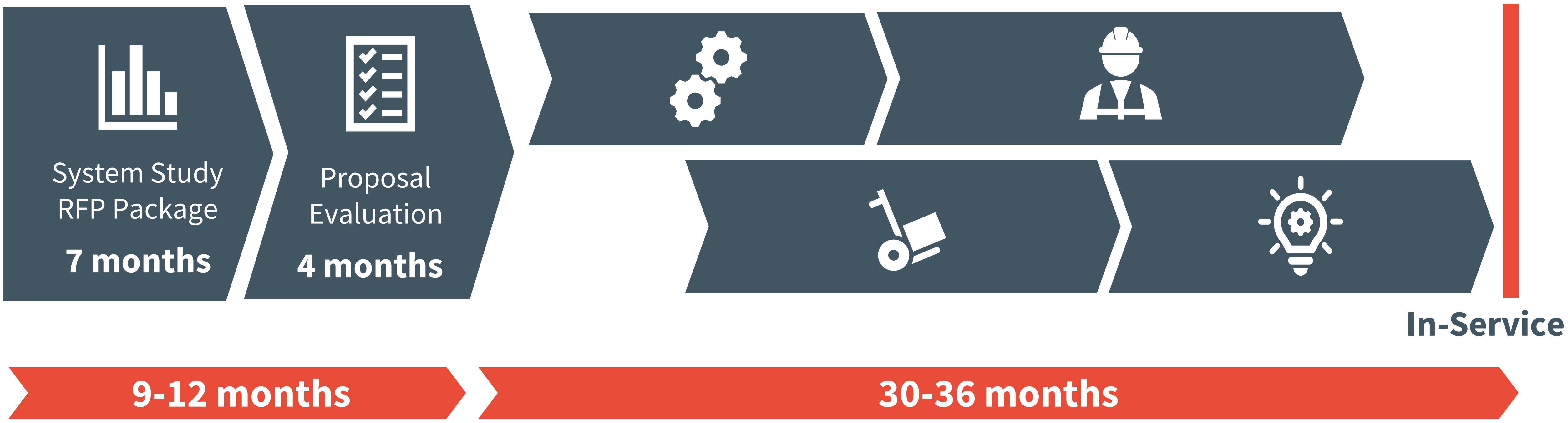
HATCH

Typical Project Phases

HVDC Technology
Typical Project Phases

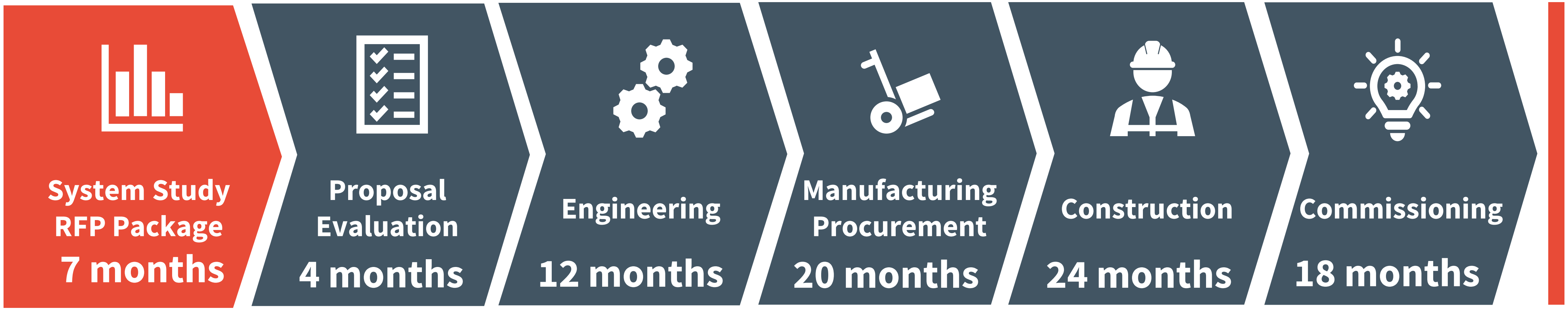


HVDC Technology
Typical Project Phases



HATCH

HVDC Technology
Typical Project Phases



System study which includes:

- Converter ratings
- Network data
- Operating conditions
- Technical requirements
- Technical Specifications preparation
- Commercial clauses
- Evaluation criteria

HATCH

HVDC Technology
Typical Project Phases

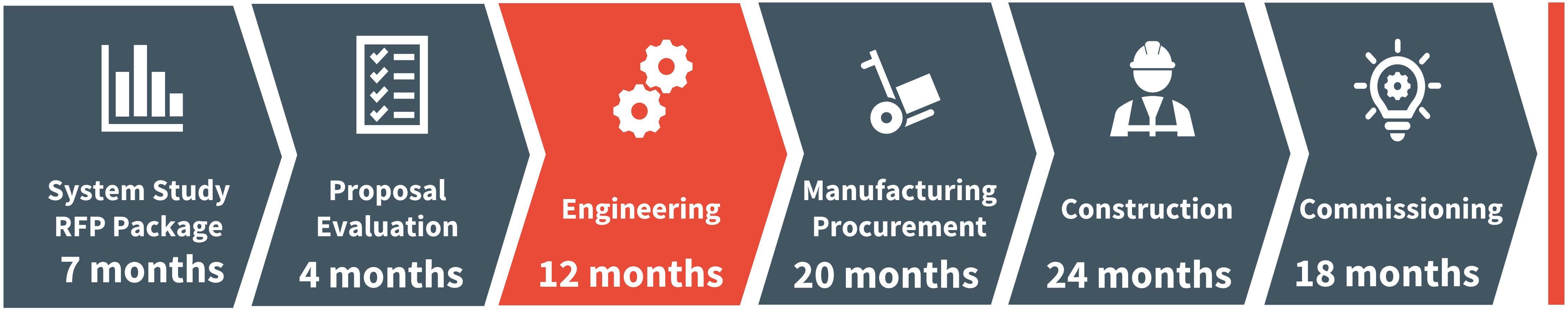
- System Study RFP Package — 7 months
- Proposal Evaluation — 4 months
- Engineering — 12 months
- Manufacturing Procurement — 20 months
- Construction — 24 months
- Commissioning — 18 months

- HVDC vendors : 6 to 10 weeks
- Analysis and clarification: 4 to 6 weeks
- Final negotiation and contract: 2 to 4 weeks

Good level of pre-engineering is required to specify equipment ratings + converter building requirements.
Then, they can go and get firm prices from suppliers.

HATCH

HVDC Technology
Typical Project Phases

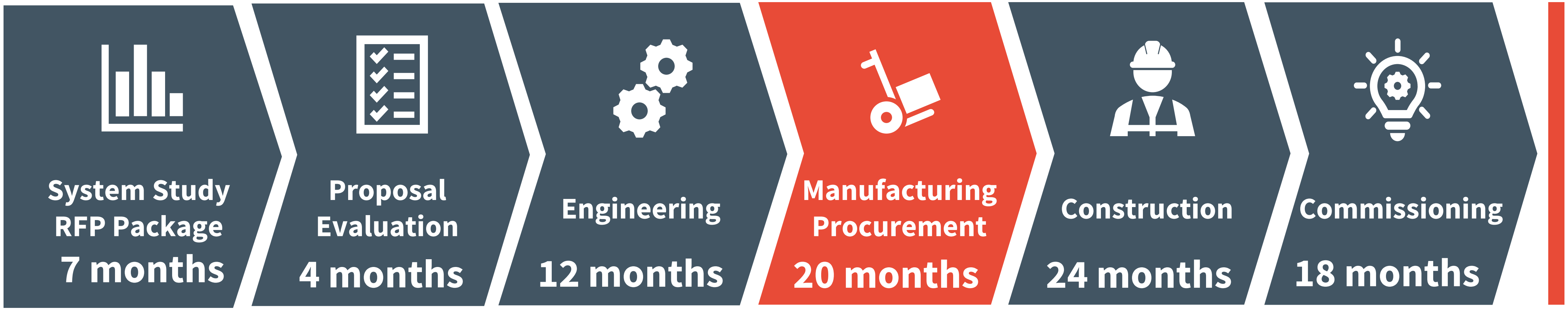


Design
- System Design
- Equipment requirement specifications
- Control Strategy
- Dynamic performance

Detailed engineering
- Layout, civil, foundation, structure
- Electrical arrangement
- Building
- Cable connections

HATCH

HVDC Technology
Typical Project Phases



Long lead items:

- Power transformers
- Converter valves
- Control and Protection System
- Building*
- Shipping consideration
- Type test requirements
- Factory Acceptance Tests (FAT)

HATCH

HVDC Technology
Typical Project Phases

System Study RFP Package — **7 months**

Proposal Evaluation — **4 months**

Engineering — **12 months**

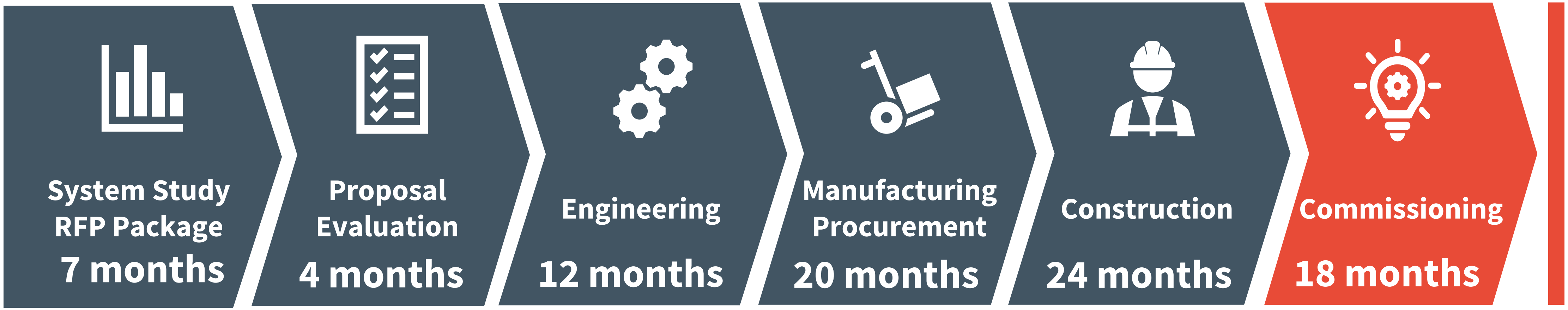
Manufacturing Procurement — **20 months**

Construction — **24 months**

Commissioning — **18 months**

- 24 months includes site preparation
- Construction sequence and areas
- Construction partner
- Local regulation and permits

HVDC Technology
Typical Project Phases



- Pre-Commissioning / ITP: 12 months
- Pre-Energization Commissioning: 3 months
- Energization Commissioning: 3 months
- Trial Operation 1 to 3 months

HATCH

FACTS

Transmission Planning

Transmission System Requirements

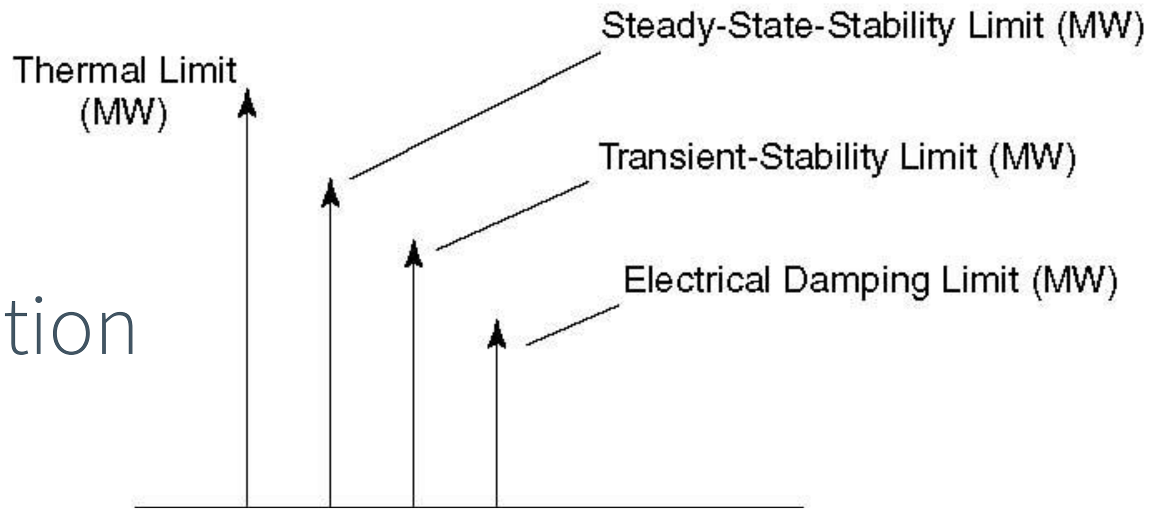
- Serve load while controlling voltage and frequency
- Maximize transmission capacity
- Maintain steady-state and transient stability
- Provide ancillary services
  - Limit harmonic distortion
  - Damp inter-area power oscillations
  - Inject fault current (system strength)
  - Regulate frequency (inertial response)
  - Black start and/or islanding

HATCH

Transmission Planning

Transmission System Limitations

- Thermal level (line ampacity)
- Line impedance unbalance (natural power flow)
- System stability (transient and dynamic)
- Power oscillation damping
- Available fault current
- Rate of change of frequency
- Control stability and coordination



Transmission Planning

Benefits of Shunt Compensation

- Regulate steady state voltage
- Balance powerflow
- Extend power transfer limit
- Reduce line losses
- Enhance transient stability
- Increase system damping
- Provide short circuit current
- Augment system strength
- Control frequency

HATCH

Transmission Planning
Specification Considerations

- Fixed shunt compensation (MSC/MSCDN/MSR)
- Synchronous condensers (synchronous machine)
- Static var compensators (SVC)
- Static synchronous compensator (STATCOM)
- Hybrid compensators – combinations STATCOM, thyristor switched capacitors or reactors and MSC/MSCDN/MSR at the HV side
- Enhanced STATCOM with energy storage

OPTIMAL SOLUTION DEPENDS ON THE FUNCTIONAL REQUIREMENTS!

HATCH

Transmission Planning
Specification Considerations

- STATCOM solutions have advanced significantly in the last few years
- Models are becoming available for STATCOMs with grid forming control and energy storage capabilities
- Equipment limitations and control capabilities differ between vendors
- Any Request for Proposal should require preliminary dynamic simulations demonstrating the expected performance

HATCH

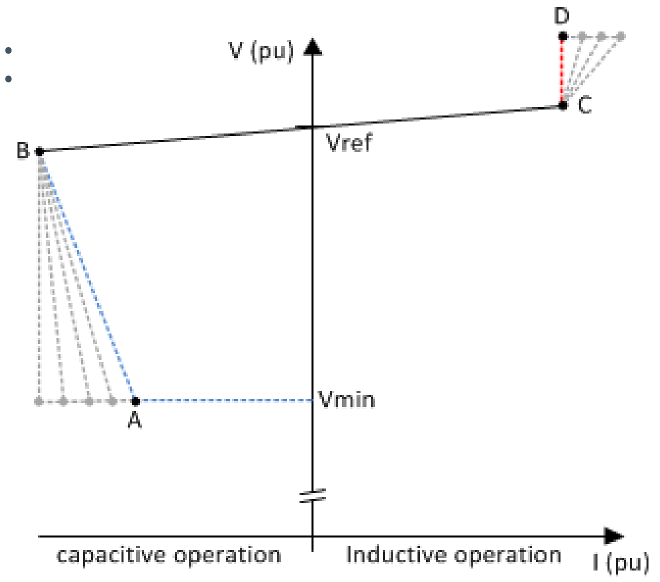
Transmission Planning
Specification Considerations

1) Recognize the need for shunt compensation and energy storage
   - One or more system limitation identified

2) Placement and rating of shunt compensation device
   - Steady-state and transient studies

For dynamic shunt compensation define VI curve points:

- A: Mvar and MW output at Vmin (time dependent)
- - System strength, fault current, inertia, islanding
- B: Maximum capacitive Mvar output (continuous)
- C: Maximum inductive Mvar output (continuous)
- D: Overvoltage Mvar output requirement (time dependent)

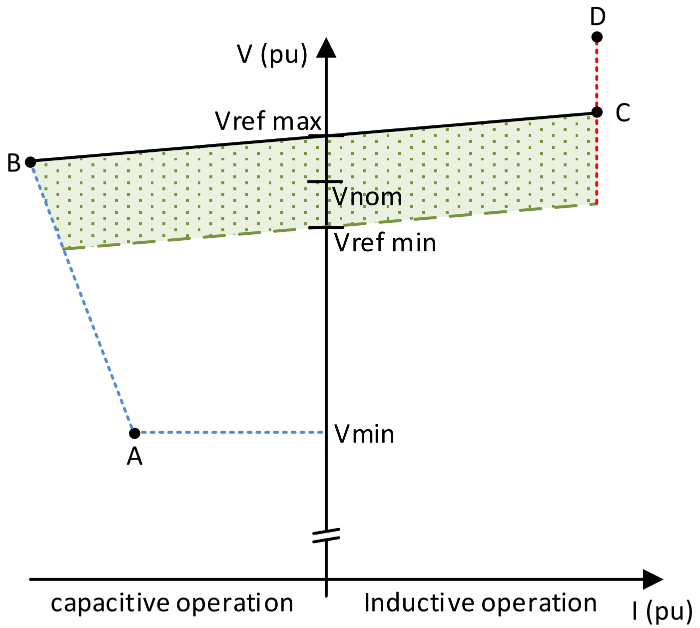


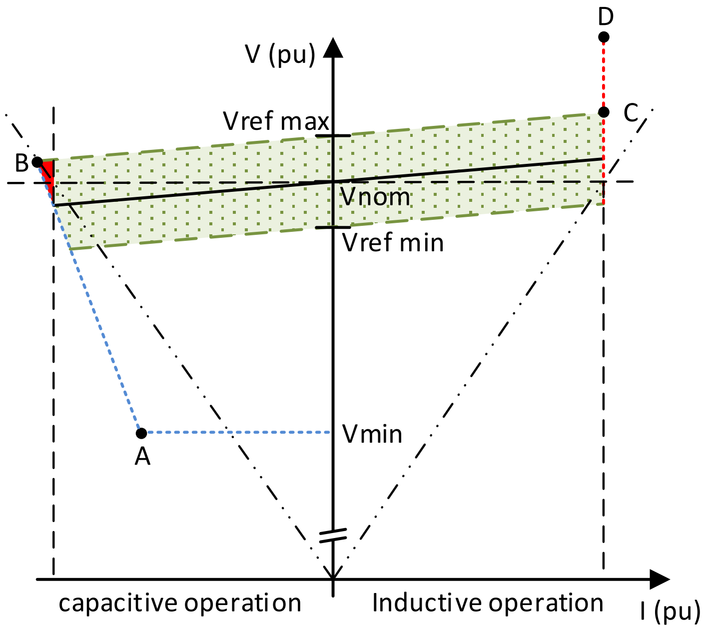
HATCH

Transmission Planning
Specification Considerations

3) Define the steady-state operating characteristic

- Vref max: maximum reference voltage
- Vref min: minimum reference voltage

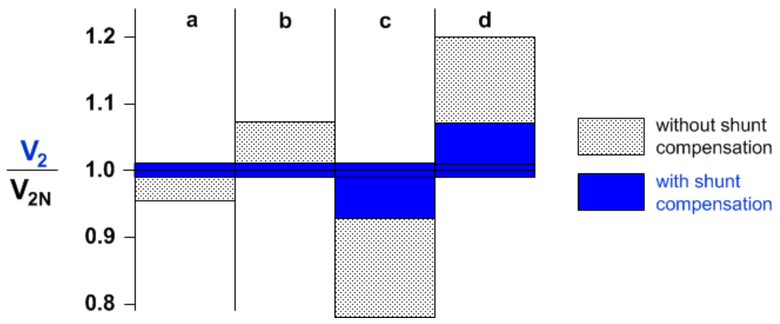


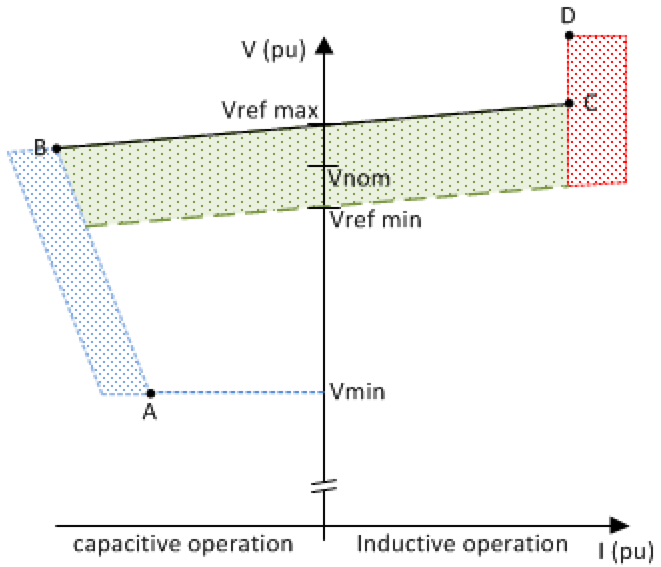


Transmission Planning
Specification Considerations

4) Define the dynamic functional requirements

- Primary function of shunt compensation
- Time-dependent Mvar and MW ratings for
  - Voltage control
  - Fault current contribution
  - System strength
  - Inertia support



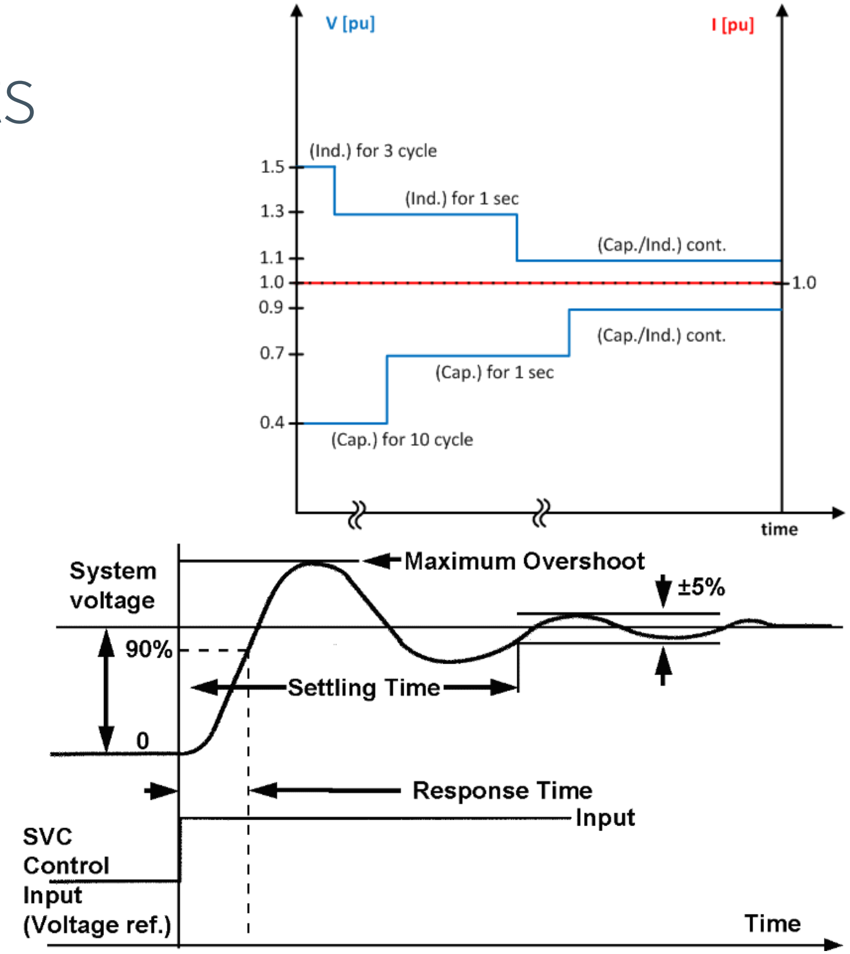


Transmission Planning

Specification Considerations

5) Define the performance requirements

- Fault response requirements
  - Short circuit current contribution
  - inertia equivalent
- Fault recovery requirements
  - Step response
  - Overvoltage



(Ref: IEEE Std 1031 and 1052)

Transmission Planning
Specification Considerations

6) Other functional requirements

- Harmonic performance
- Audible noise
- Radio interference
- Power oscillation damping
- Negative sequence control
- Active filtering
- Black start capability
- Slow VAR control / coordination of external shunt devices
- Possibility of reconfiguration
- Modularity and possibility of relocation to congested corridors

Transmission Planning

Specification Considerations

7) Define the external network

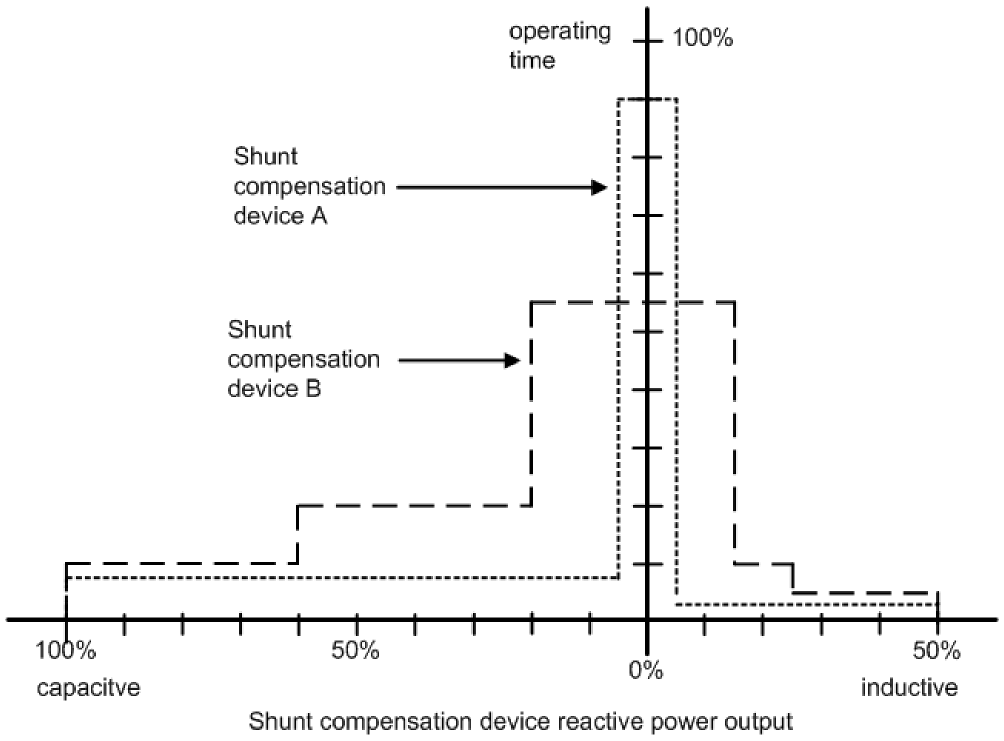
- Short circuit strength at the PCC (minimum and maximum)
- Operating voltage range (minimum and maximum)
- Existing harmonic voltage distortion
- Network harmonic impedances
- Other system specific conditions (SSR, GIC, etc.)

Transmission Planning

Specification Considerations

8) Define the operating range for loss calculation

- operating cost – no load losses vs full load losses



HATCH

Transmission Planning
Specification Considerations

9) Reliability, Availability, Maintainability

- Reliability: Number of forced outages per year
- Availability: Total percentage of the time that the device is available to perform its function
- Maintainability:
    - Number and duration of scheduled outages per year
    - Crew size requirement
    - Level of difficulty of maintenance procedures

Transmission Planning
Specification Considerations

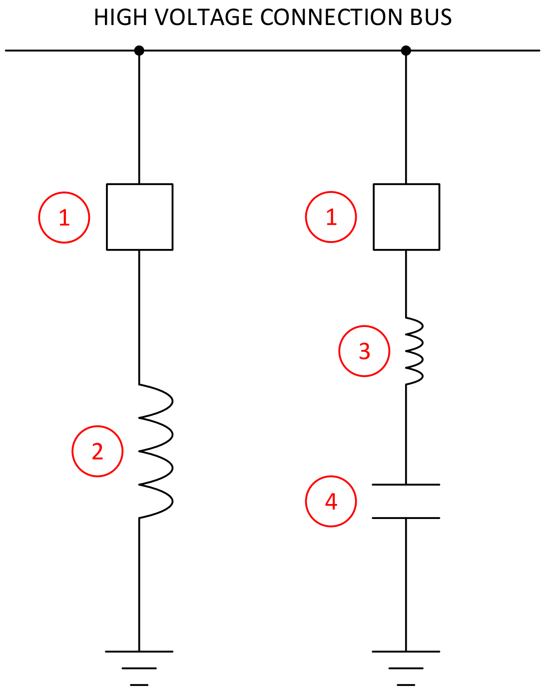
10) Other influential factors

- Footprint
- Expected life cycle
- Cost comparison
- Noise requirements

Mechanically switched devices

Basic Information

- MSR : Mechanically-Switched Reactors
- MSC : Mechanically-Switched Capacitors
- MSCDN : Mechanically-Switched Capacitive Damping Network
- Mechanical switching is typically accomplished by a Circuit Breaker or a Circuit Switcher
- MSRs, MSCs and MSCDNs can complement dynamic voltage control installations (e.g., SVC & STATCOM) to provide:
  - Supplementary reactive power
  - Preservation of dynamic capacity
- Typical Response Time: 5-8 cycles (0.1 s)
- MSRs, MSCs and MSCDNs are normally used for steady-state voltage control requirements
  based on daily, weekly, monthly or seasonal load variation and compensation
- MSRs, MSCs and MSCDNs are sometimes used for dynamic switching control in some applications



1 CIRCUIT BREAKER / CIRCUIT SWITCHER

2 REACTOR (SHUNT)

3 REACTOR (CURRENT LIMITING/TUNING)

4 CAPACITOR (SHUNT)

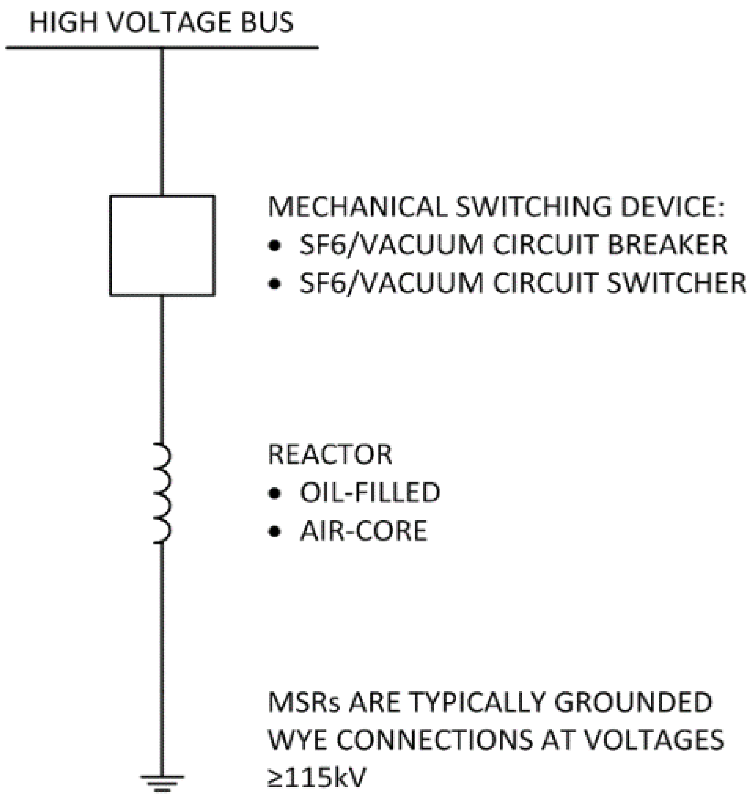
HATCH

Application guidelines

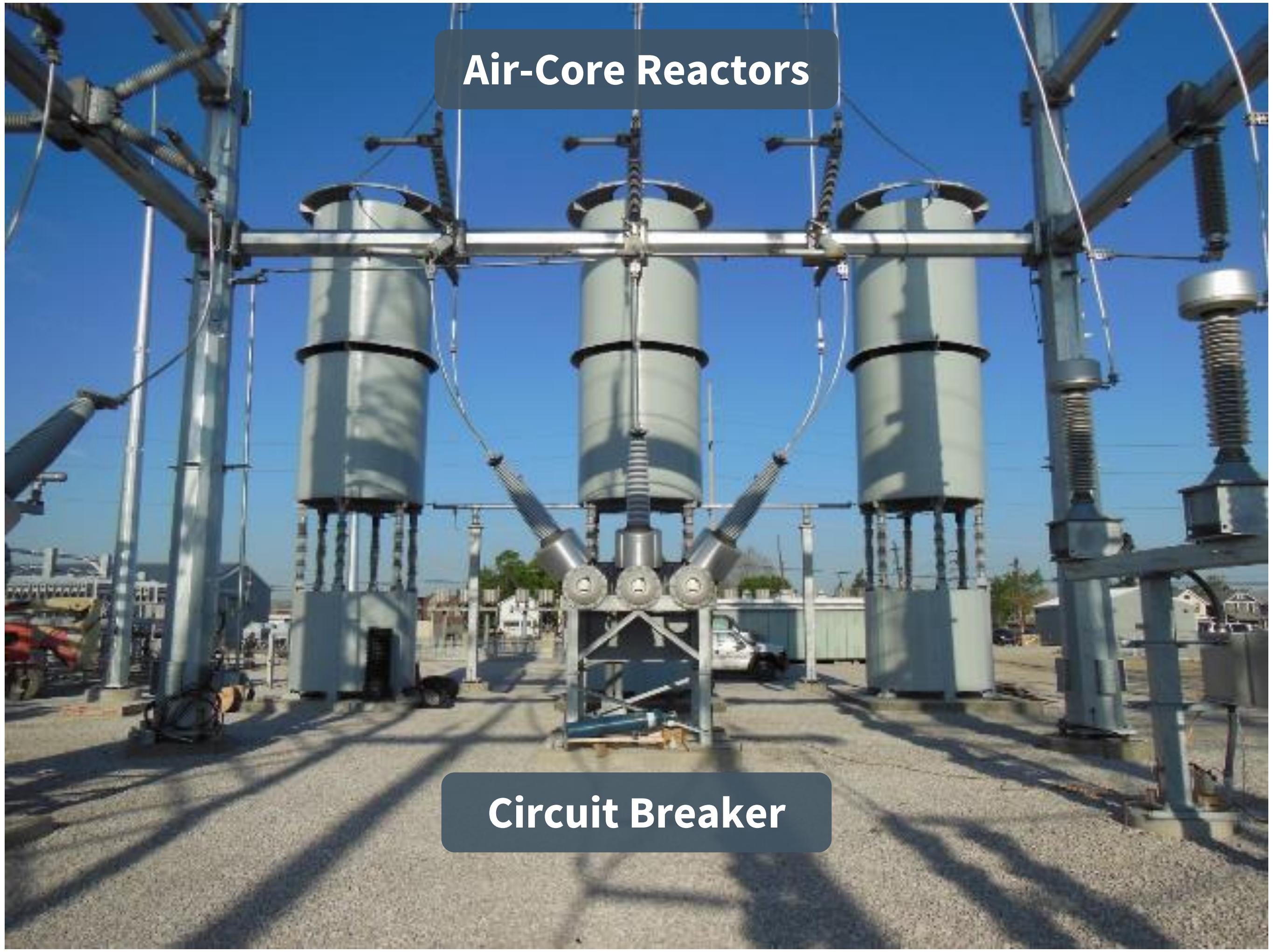
- MSRs are typically applied for inductive reactive power compensation (i.e. voltage support during periods of light load)
- MSCs are typically applied for capacitive reactive power compensation (i.e. voltage support during periods of heavy load)
- MSCDNs are typically applied for capacitive reactive power compensation with the additional benefit of wide range harmonic damping (avoidance of system resonances)

MSR configuration & application notes

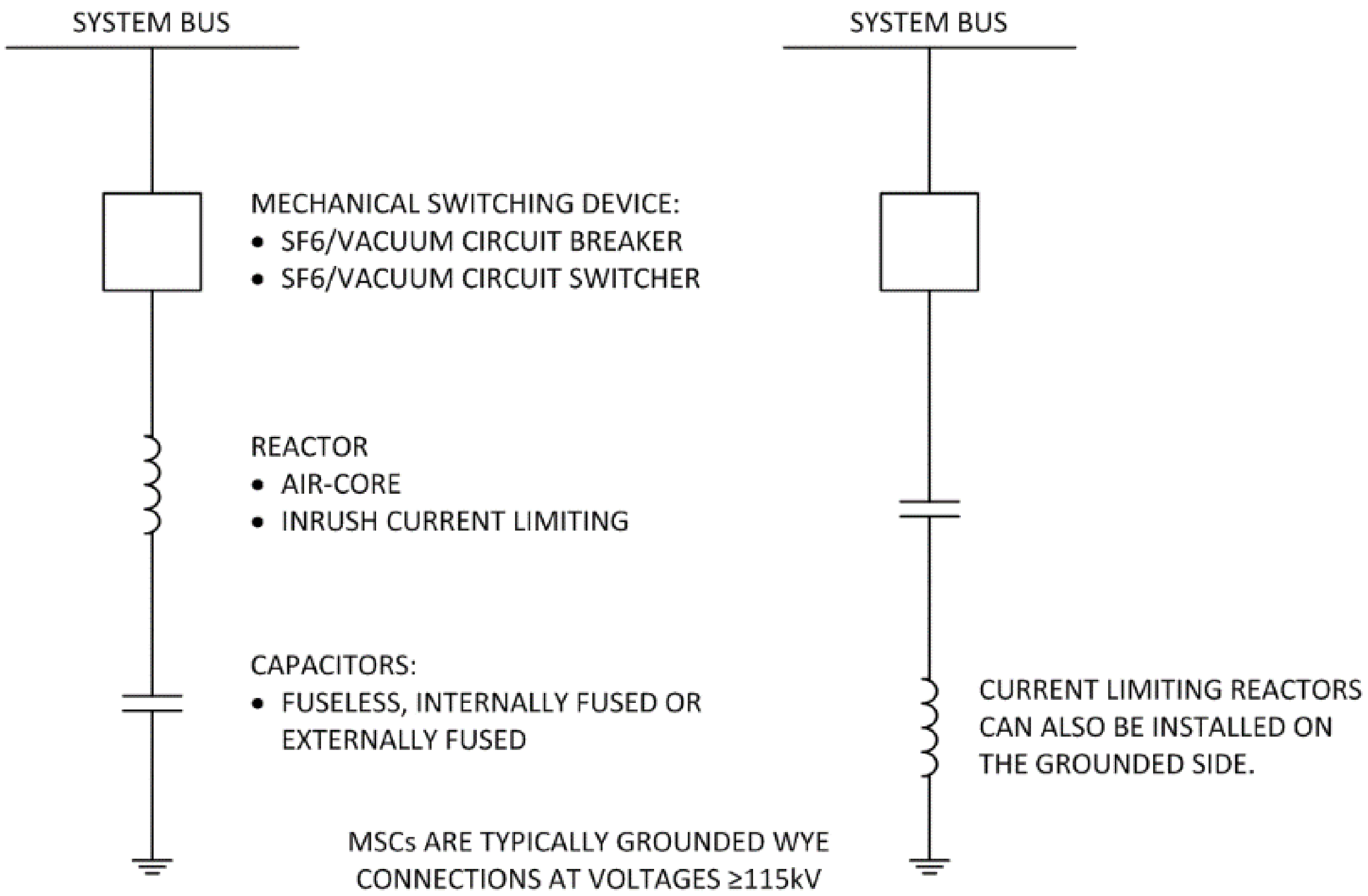
- MSRs are applied to regulate the balance of reactive power in the transmission system by compensating for surplus vars generated by:
  - Generators
  - Underground cable systems
  - High-voltage transmission lines
- Voltage rise on transmission lines and cables is normally caused by Ferranti rise and capacitive rise during conditions of light loading. Consequently, MSRs are typically direct-connected to transmission lines rather than at substation buses
- Transient Design Consideration 1: Energization of the reactor may lead to a significant inrush current due to the magnetic characteristics of the reactor
- Transient Design Consideration 2: De-energization of the reactor may lead to a significant overvoltage transient due to the characteristics of the circuit breaker/switcher (e.g., normal current chopping, virtual current chopping, re-ignitions and pre-ignitions). This can be mitigated with grading capacitors and multi-sectional surge arresters



MSR installation



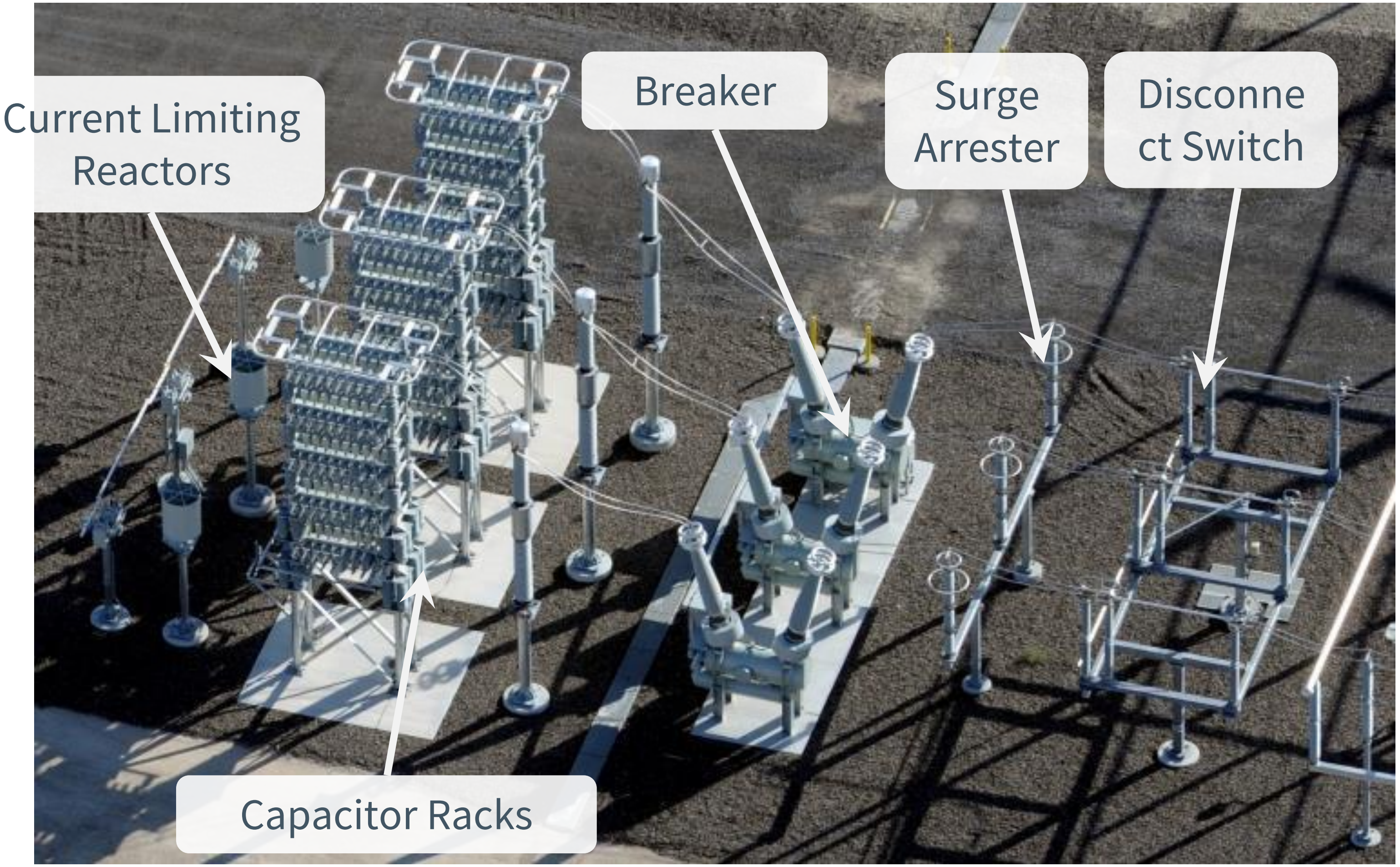
MSC configuration



MSC application notes

- MSCs are applied to regulate the balance of reactive power in the transmission system by supplying additional vars absorbed by:
  - Load centers
  - High-voltage transmission lines
- MSCs can be direct-connected to transmission lines but are typically connected at substation buses
- Design Consideration 1: Energization of the capacitor may lead to a significant inrush currents. Multiple MSCs are sometimes connected at the same bus for step-wise addition of vars. Back-to-Back switching requires consideration of inrush and outrush currents
- Design Consideration 2: De-energization of the MSC may lead to a significant overvoltage transient due to the characteristics of the circuit breaker/switcher
- Design Consideration 3: The inductance (L) and capacitance (C) of a MSC results in a natural sink for harmonic current. The tuning of this circuit (shunt-connected) must be coordinated to avoid possible resonance with the power system connection

MSC installation



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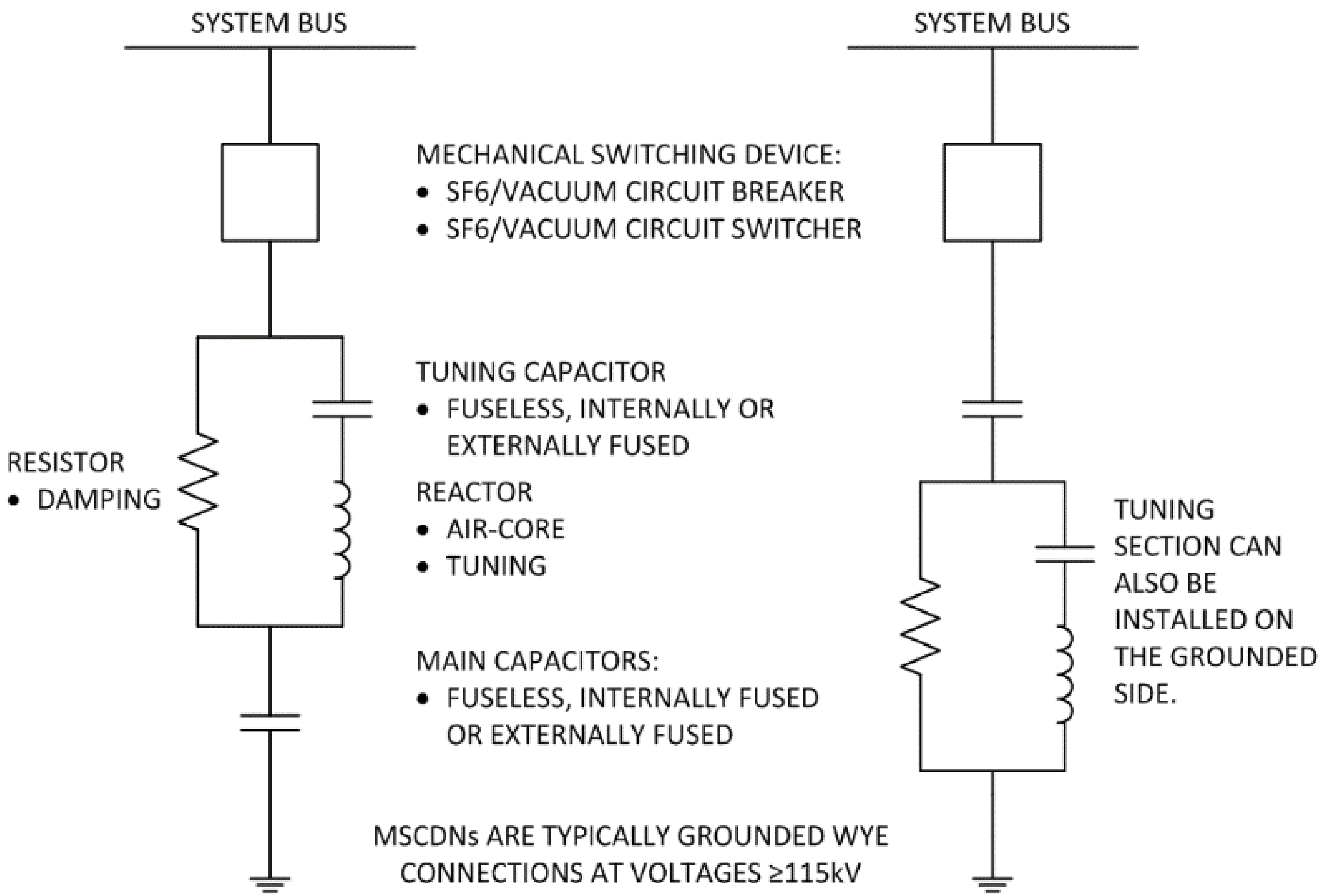
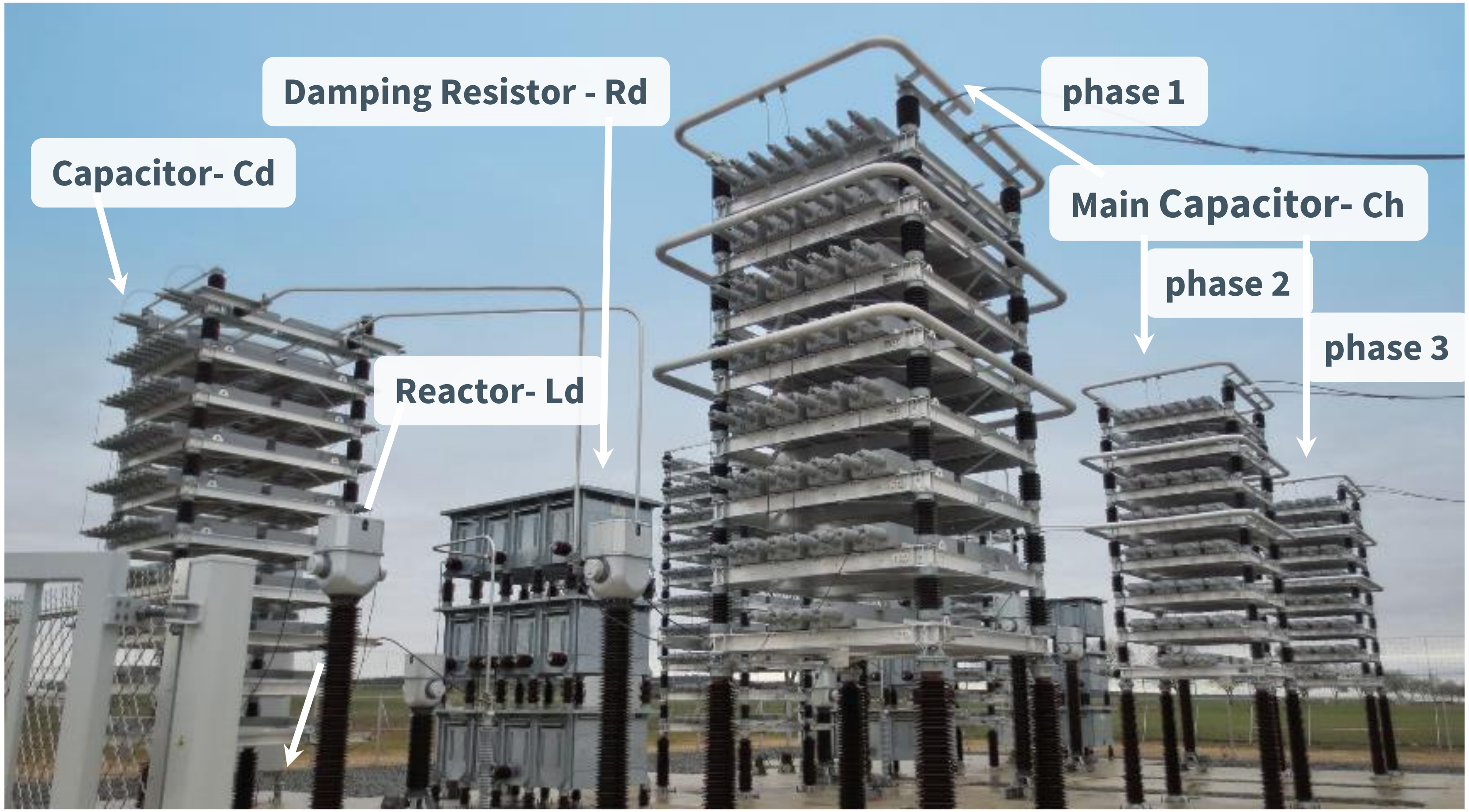
MSCDN configuration

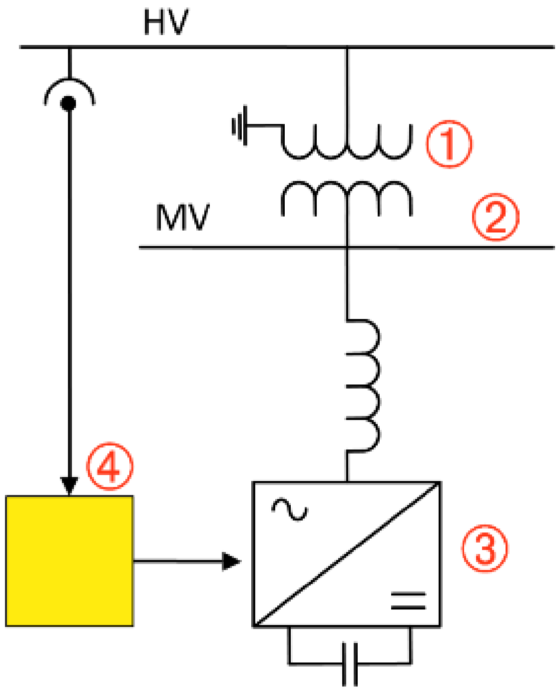


MSCDN installation



Statcom

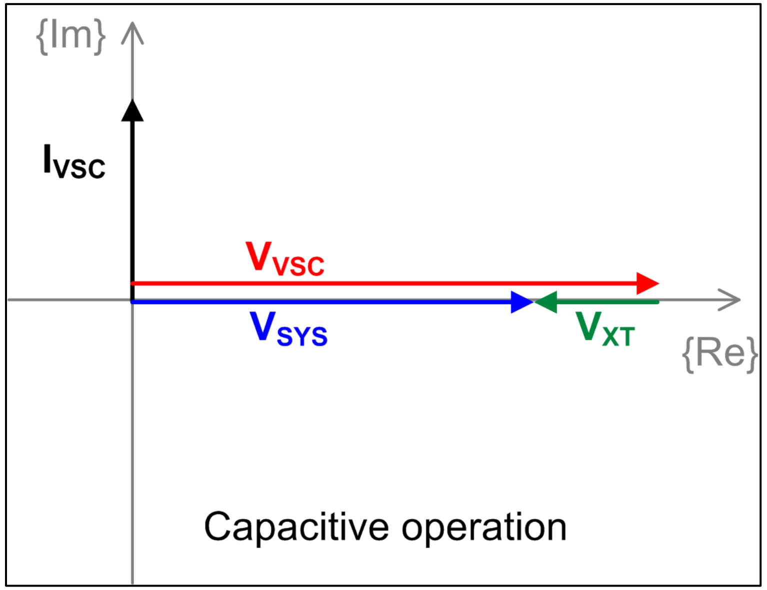
Configuration & Principle of Operation

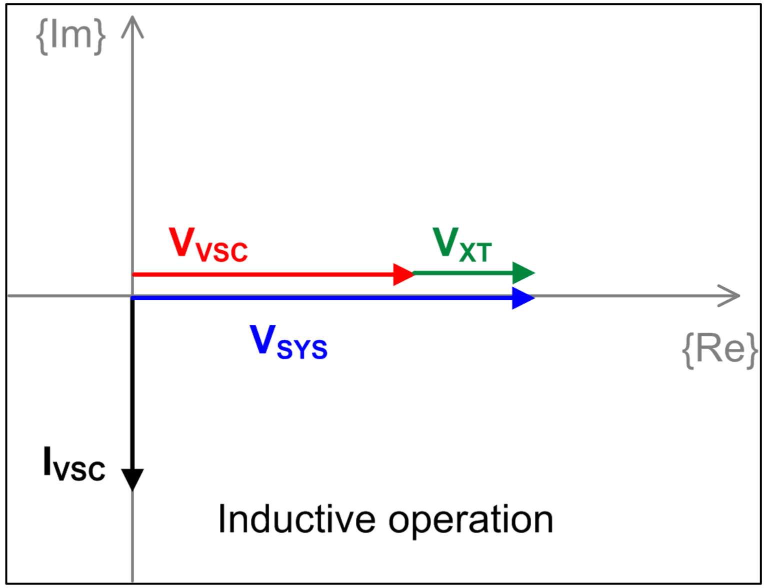


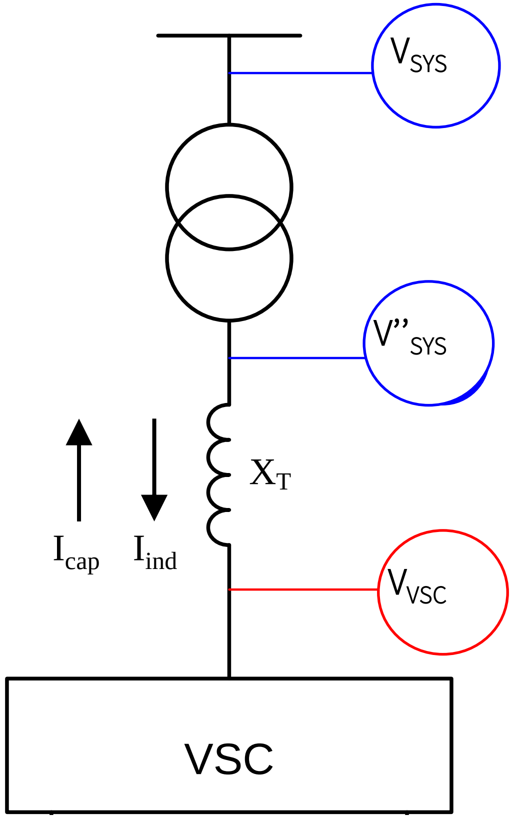
1 Step – down transformer
2 MV bus bar
3 VSC
4 Control

- VSC
  - IGBT modules
  - DC-capacitors
  - Line reactors (if applicable)
- Self commutated – does not rely on the ac grid for operation, suitable for weak ac systems
- Presence of a dc voltage bus – can be used to connect storage devices, generating virtual inertia
- Switching frequency can be higher than grid frequency
- Black-start capability, if sufficient energy (dc bus) is present

Principles of Operation
VSC

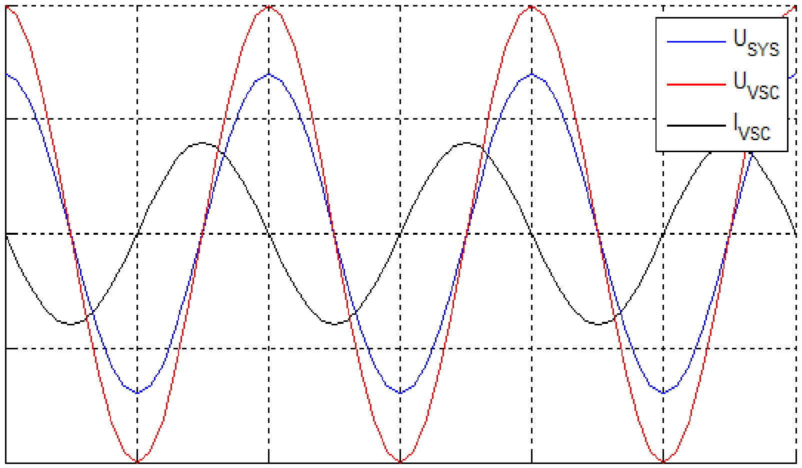




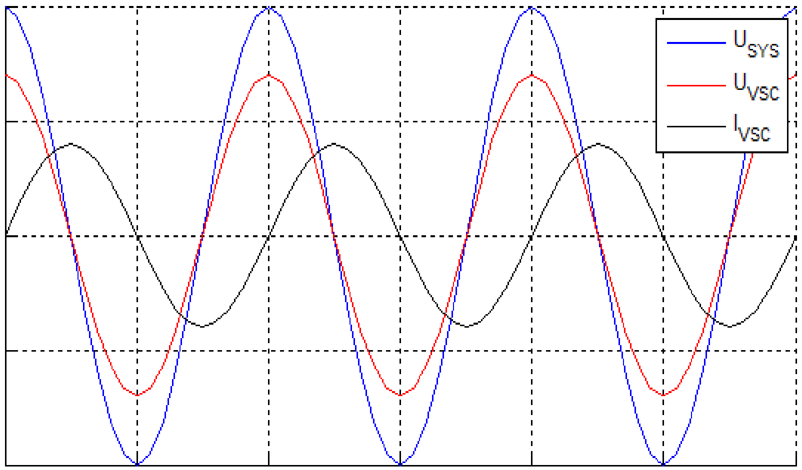


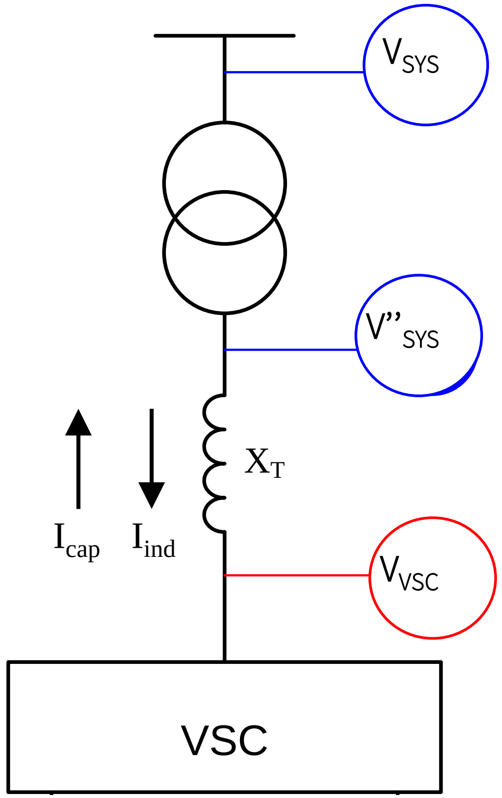
Principles of Operation
VSC

Capacitive operation

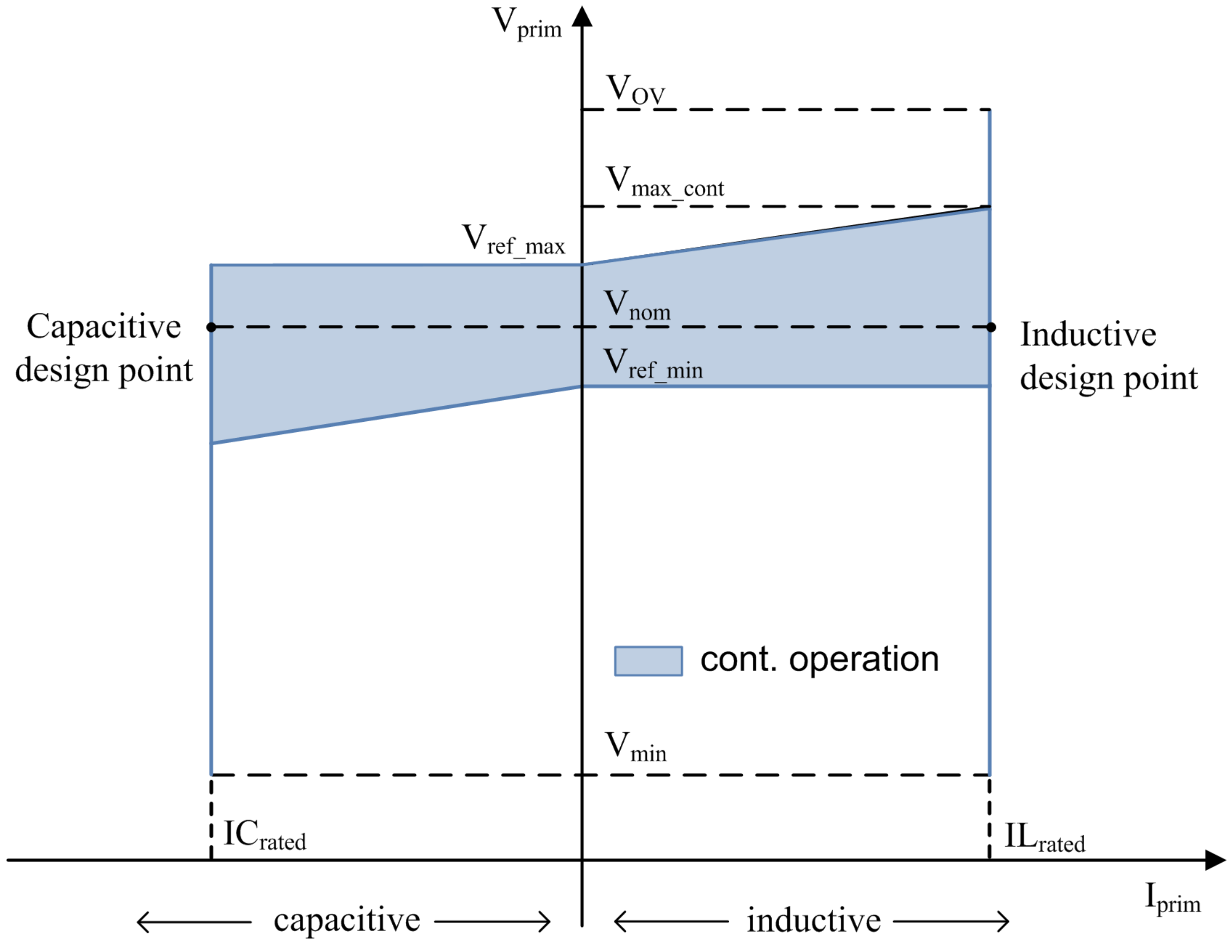


Inductive operation

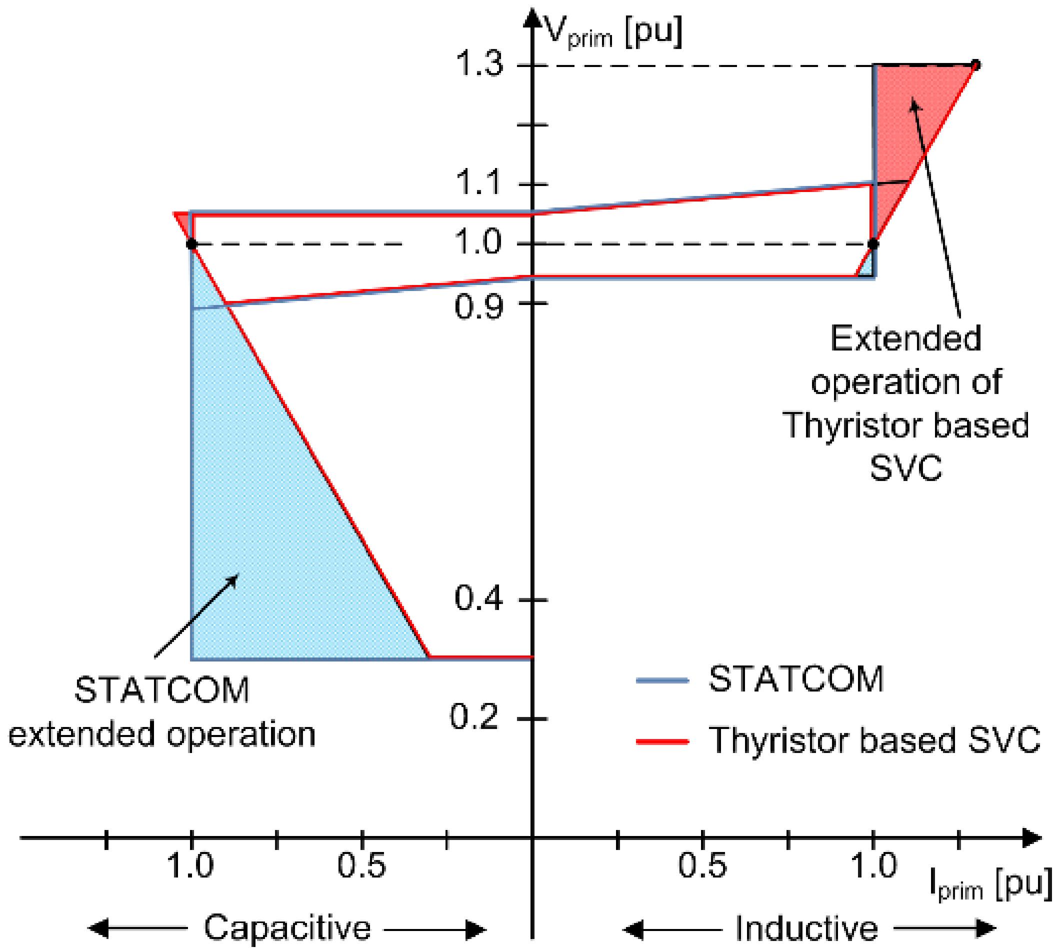




Principles of Operation
VI Characteristic



Principles of Operation
VI Characteristic Comparison

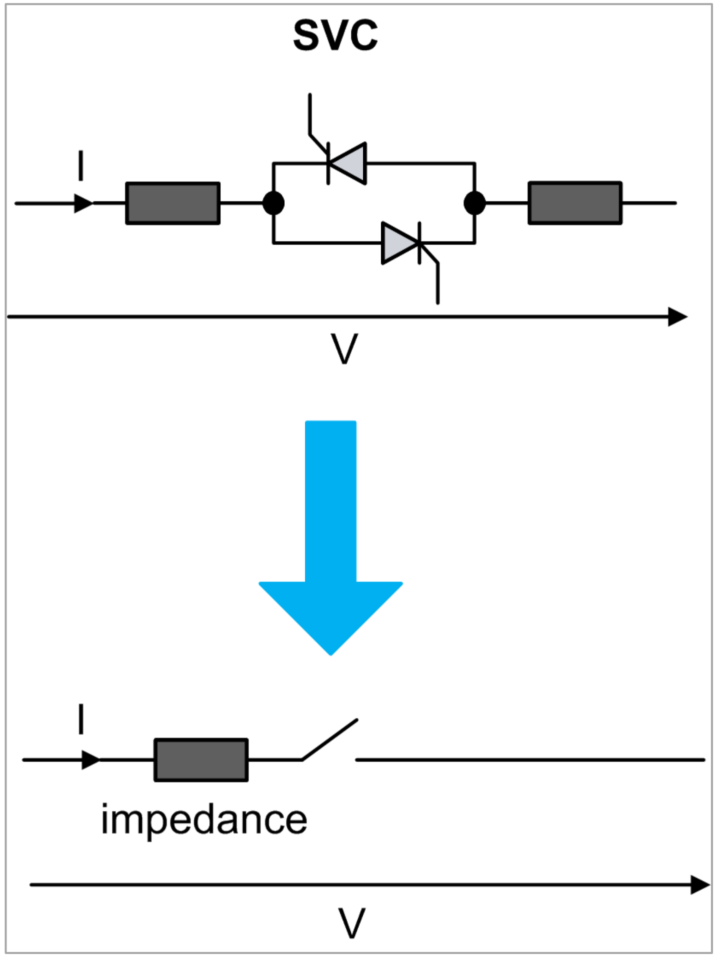


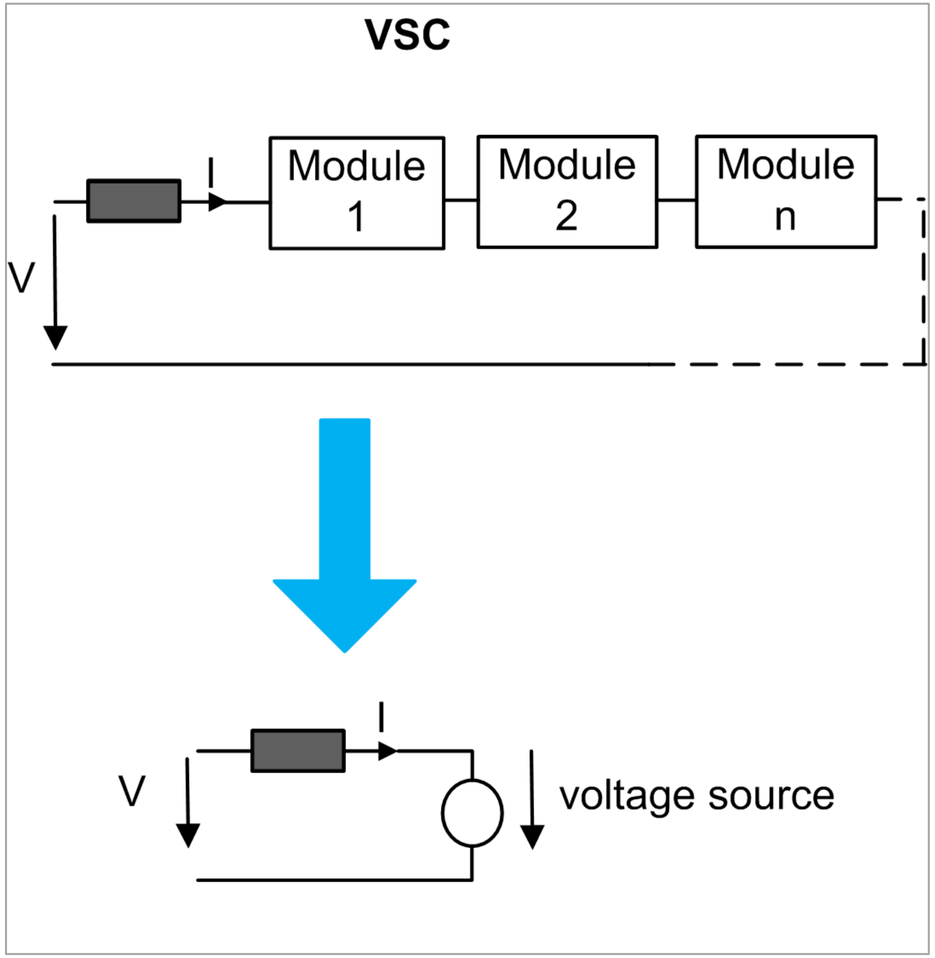
Voltage [pu]	STATCOM [Mvar]	SVC [Mvar]
1.0	100	100
0.5	50	25
0.3	30	9
1.3	130	169

- At 0.3 pu voltage the STATCOM delivers up to 3.3 times more reactive power!
- At 1.3 pu voltage the SVC delivers up to 1.3 times more reactive power!

Principles of Operation

Line vs. self commutated





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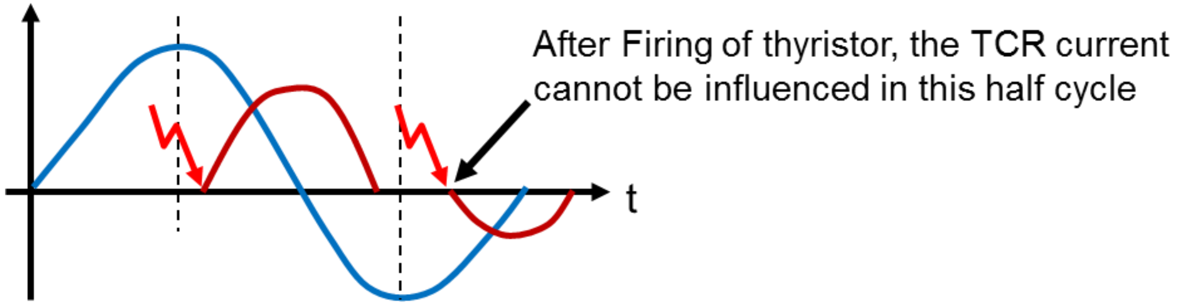
Principles of Operation
Line vs. self commutated

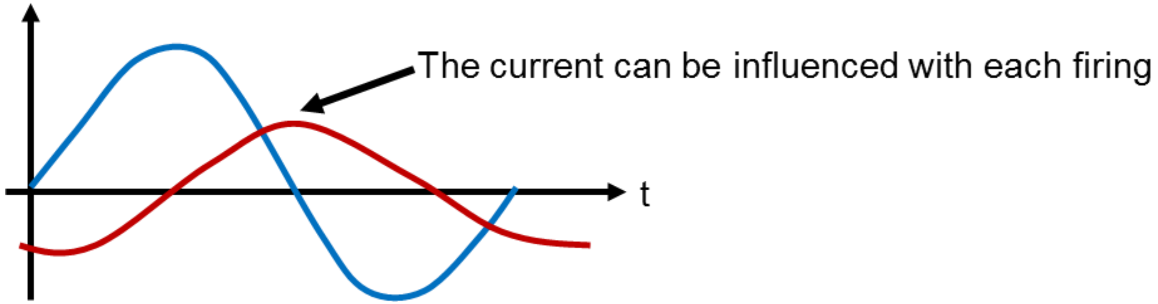
Line commutated - SVC:

SVC has a certain switching delay because there is “only“ one control event in a half cycle:



Self commutated - STATCOM:

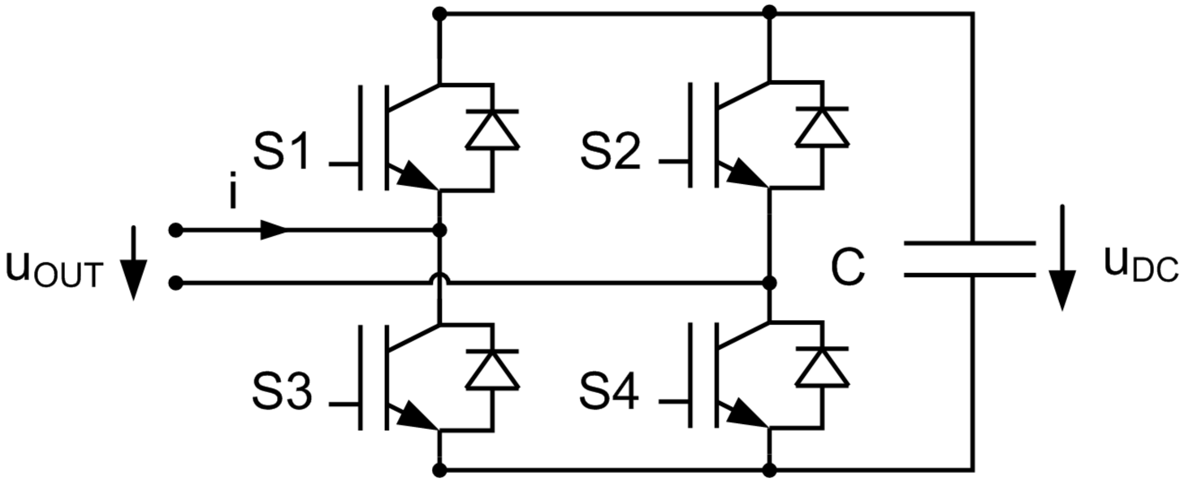
STATCOM has almost NO switching delay because IGBT modules can be switched at any time:



Main component

Module structure (full bridge)

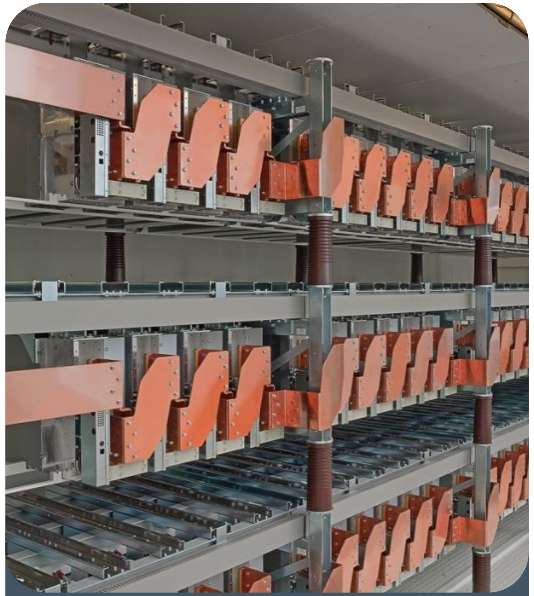
- H-bridge configuration consist of 4 IGBTS with free-wheeling diodes
- Each bridge has a capacitor for energy storage
- Each sub-module can output either u_{DC}, 0 V or $-u_{DC}$



Main component
Module structure (full bridge)

IGBT Module

Power/Sub-Module

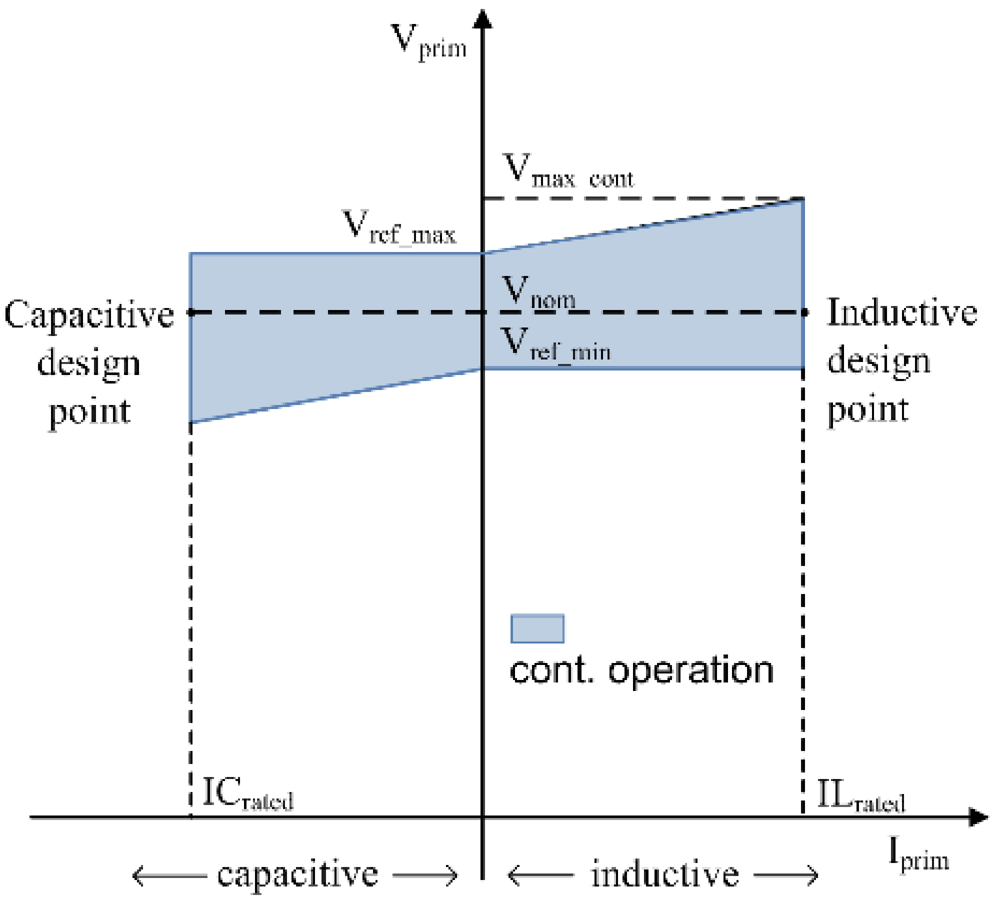


Converter – 3ph

Power/Sub-Module

Control Modules for IGBTs & Cooling Pipes

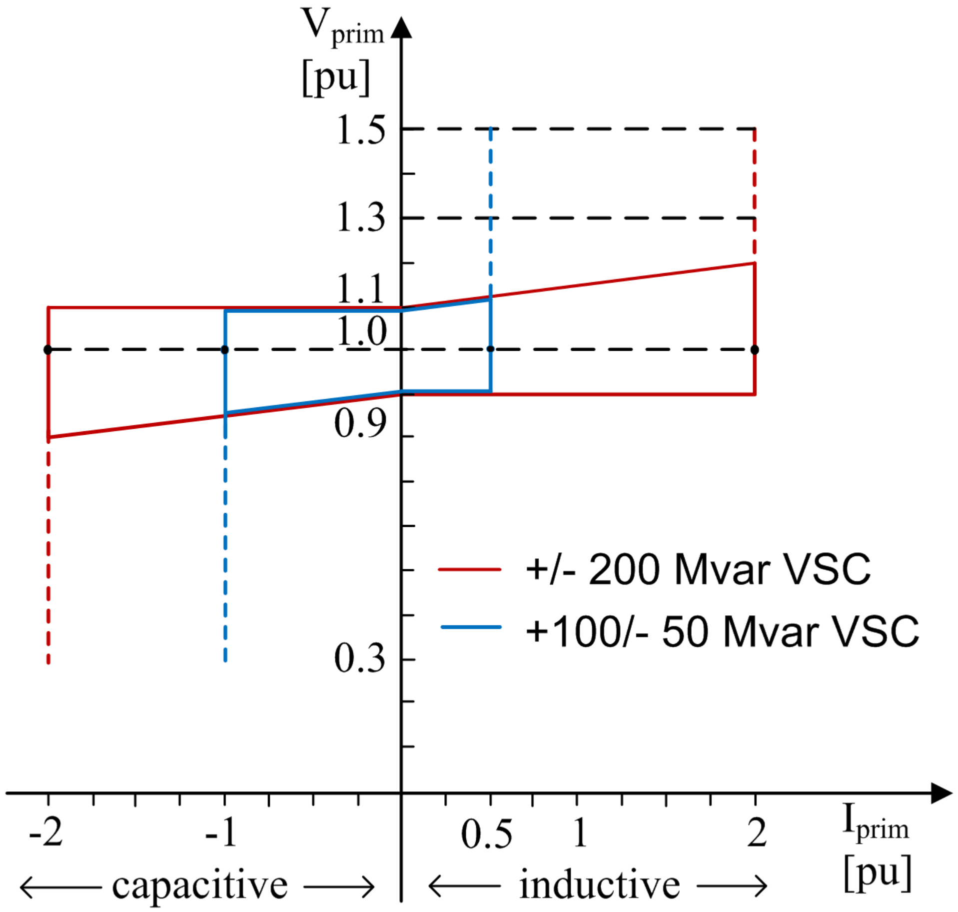
Performance
Steady State



- STATCOM is a dynamic device mainly used for dynamic system support
- Most of its operation time @ zero output or other offset point

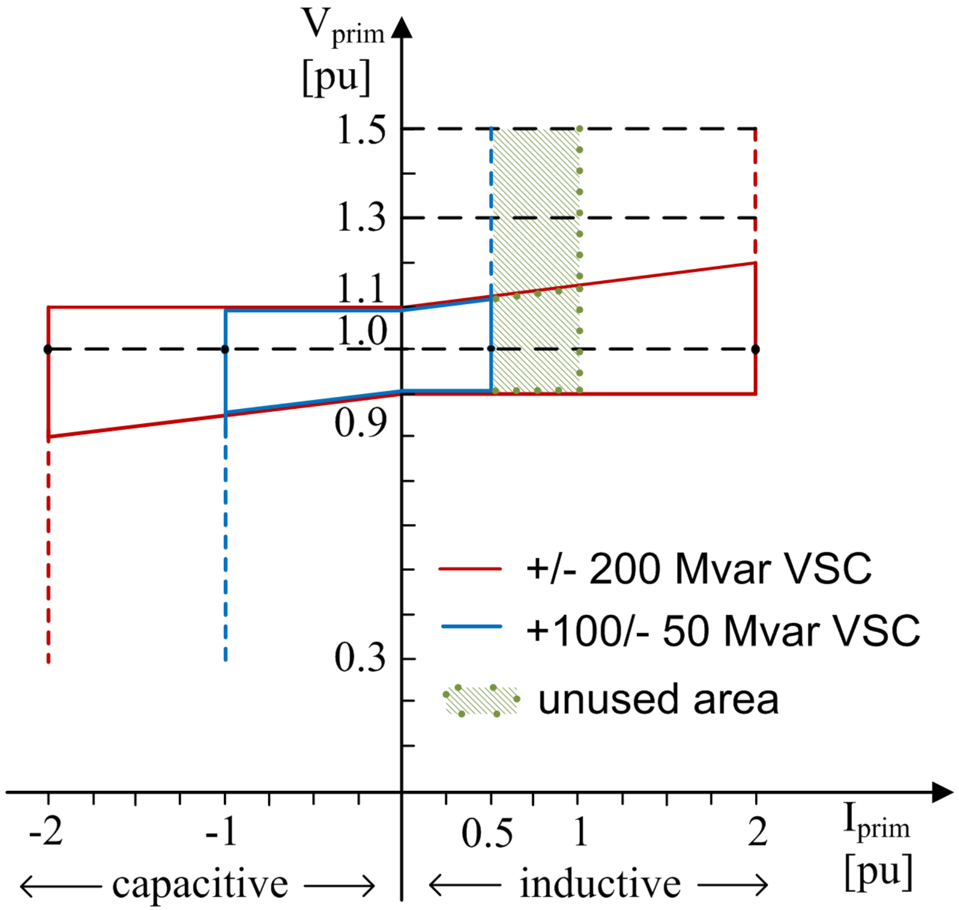
Performance

Symmetrical vs. Unsymmetrical output



Performance

Symmetrical vs. Unsymmetrical output



- The maximum current rating on the inductive side is not used for the unsymmetrical solution

Performance
Step Response

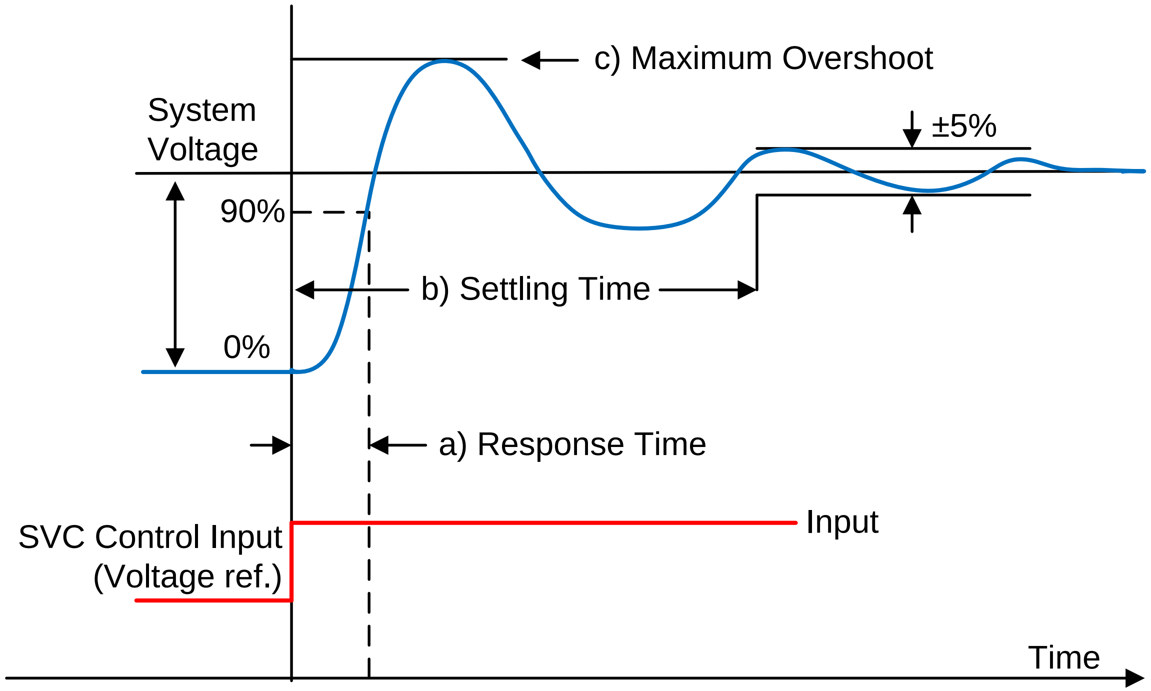


Figure above:
Definition of response and settling time acc. IEEE 1031-2011

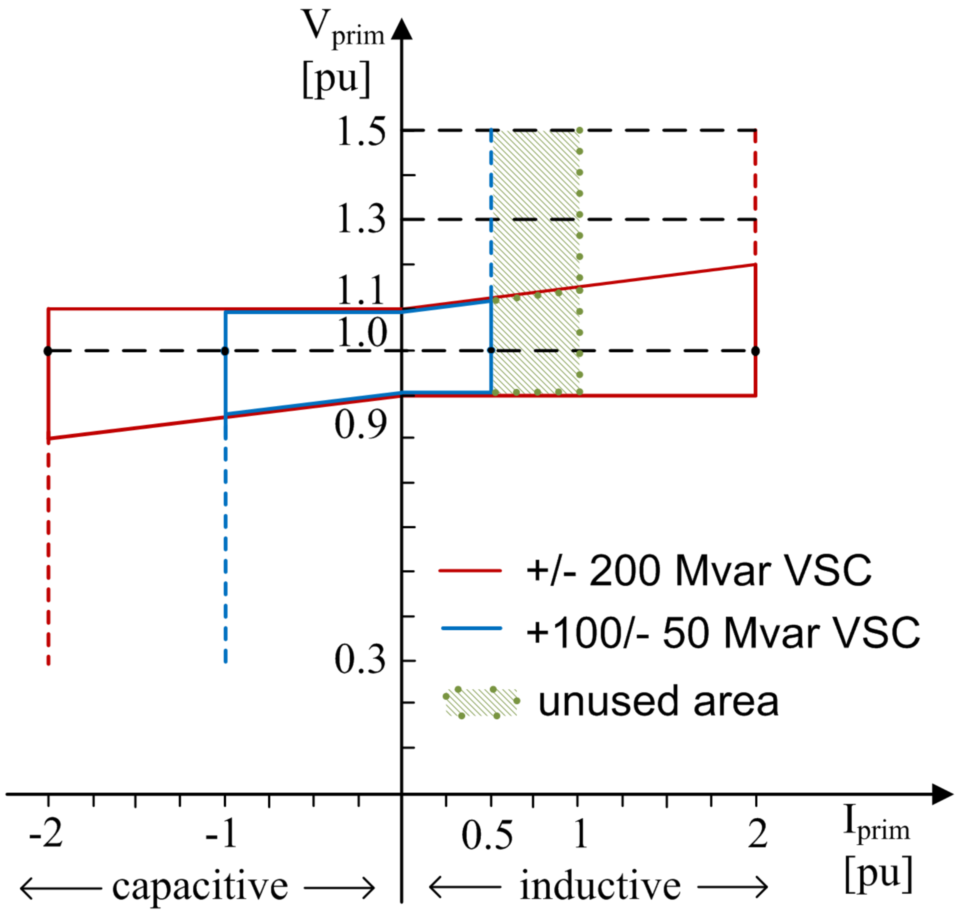
Typical values for STATCOM:

a) 1.5 cycles

b) 5 cycles

c) < 10%

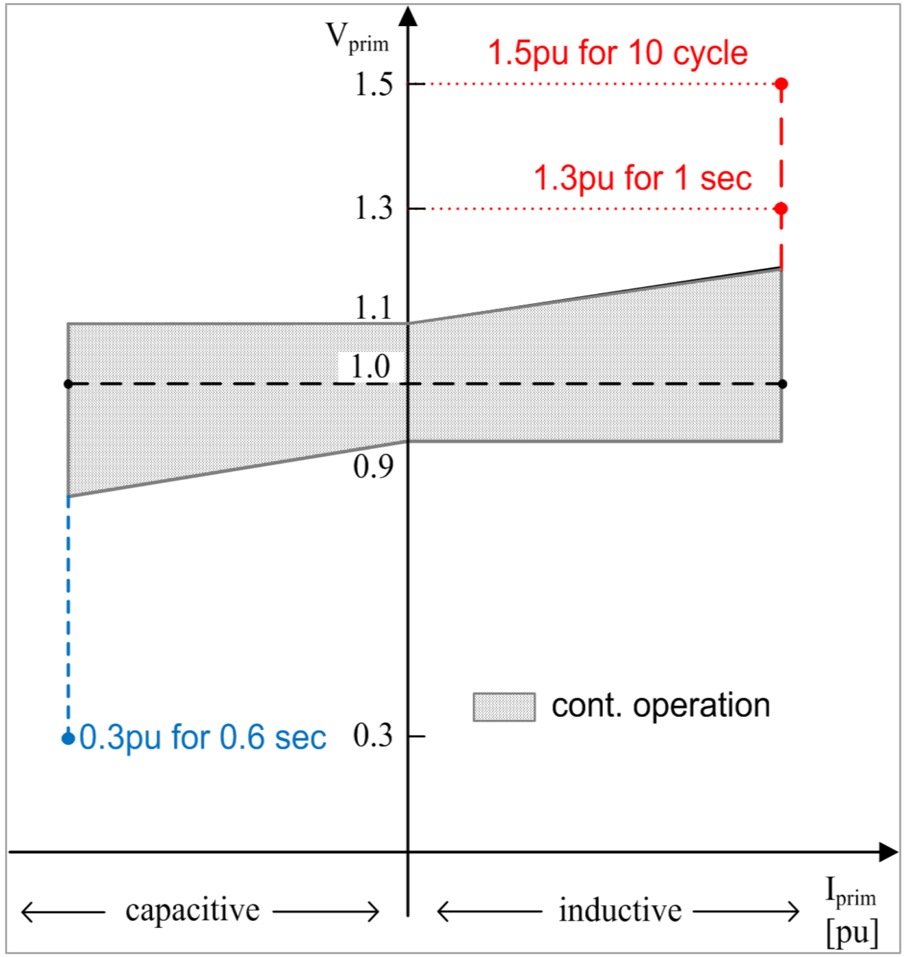
Performance
Overload Capability

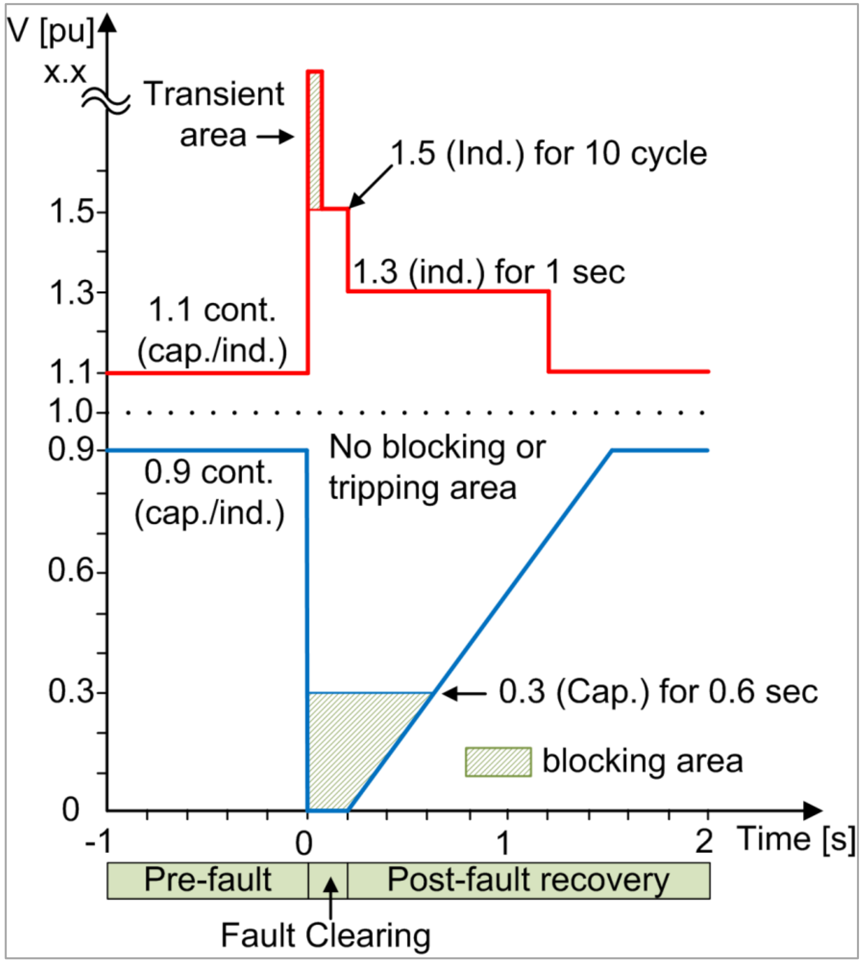


- Except for design margins and dynamic current capabilities in the order of a few milli seconds, there is no inherent overload in the VSC itself – it's a design parameter
- Large overload capability generally means thermally de-rated power electronics
- Power electronics has to stay within design limits

Performance

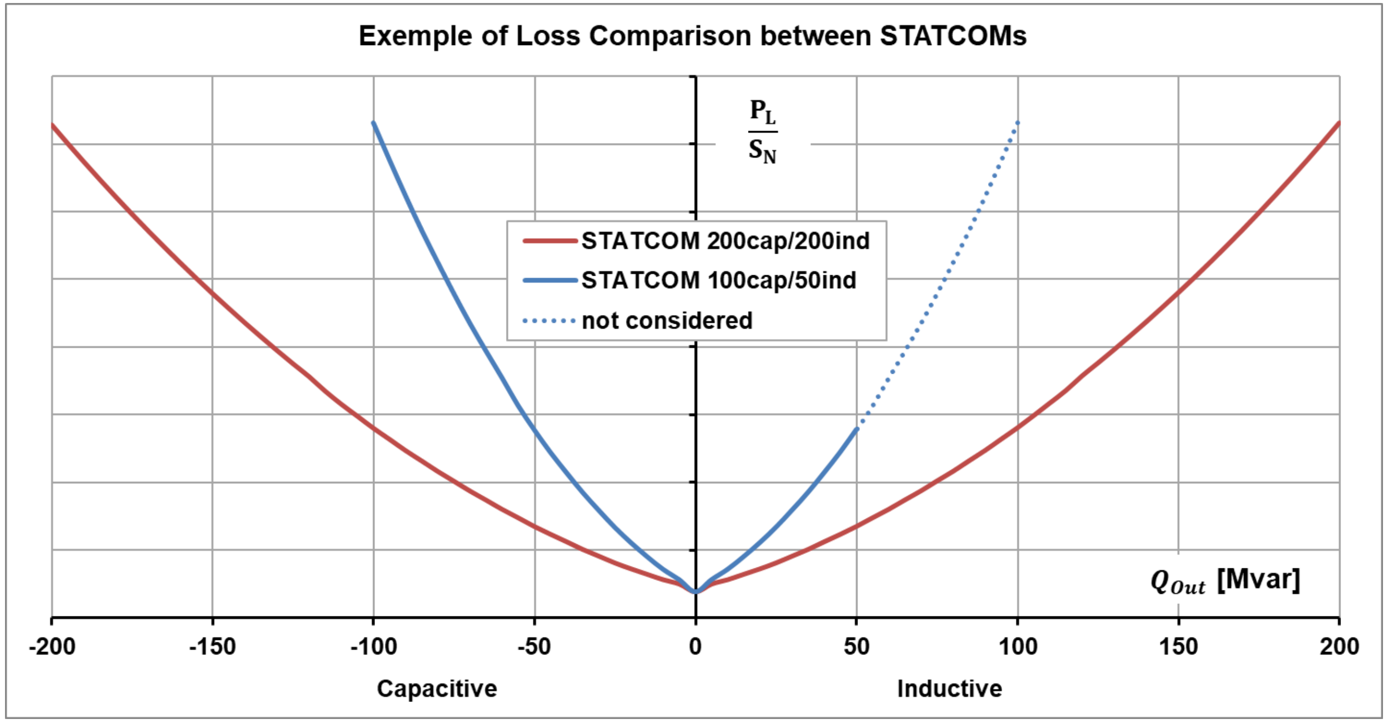
Ride Through Capability





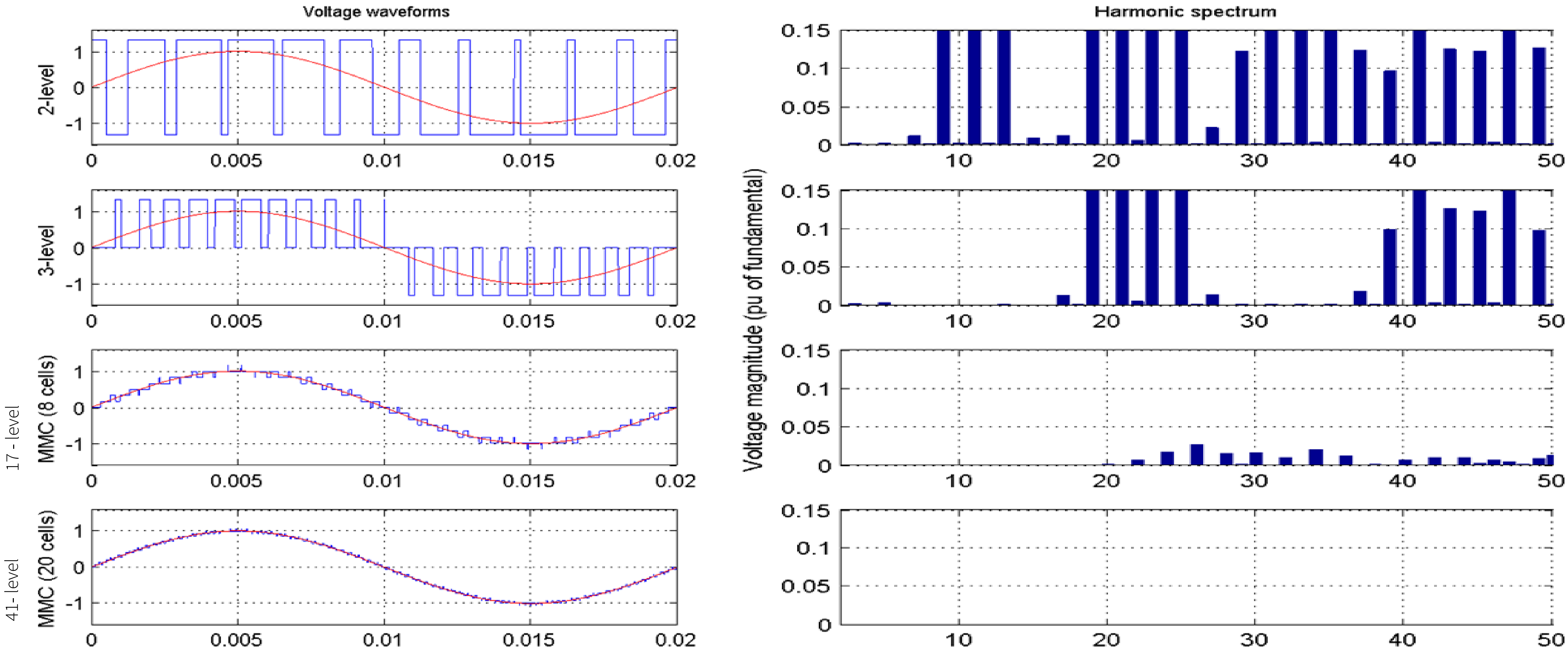
Performance

Losses



The losses of the 100 Mvar STATCOM at 0 Mvar output is slightly smaller compared to the 200 Mvar STATCOM,
because of the smaller cooling pump and transformer auxiliary losses.

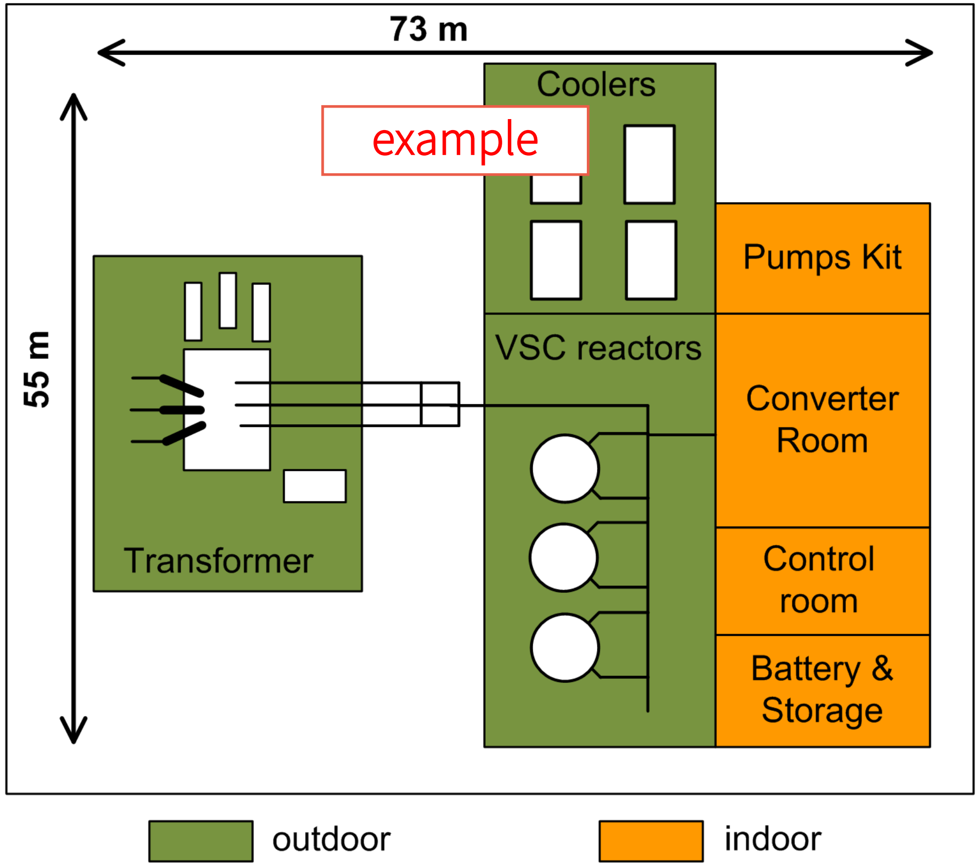
Performance
Harmonic Generation



Harmonics
Mitigation

- Harmonic generation is dependent on switching frequency of the converter (higher than SVC)
- Equivalent switching frequency is a function of
  - Topology, 2-level (highest), 3-level and MMC (lowest)
  - The number of modules used in the topology
  - The switching frequency of individual switches
- Filtering requirements depend upon the allowable voltage distortion and the equivalent switching frequency
- Filters typically used
  - Tuned LC or low pass LC, 2 and 3-level converters
  - Possibly none for MMC based converters

Footprint
STATCOM: 200 cap. / 200 ind. at 230 kV



~ 10 m^2 (108 ft^2)/ Mvar:

150 Mvar, 1500m^2, 39 x 39m
128 x 128 ft

400 Mvar, 4000m^2, 64 x 64m
210 x 210 ft

550 Mvar, 5500m^2, 75 x 75m
246 x 246 ft

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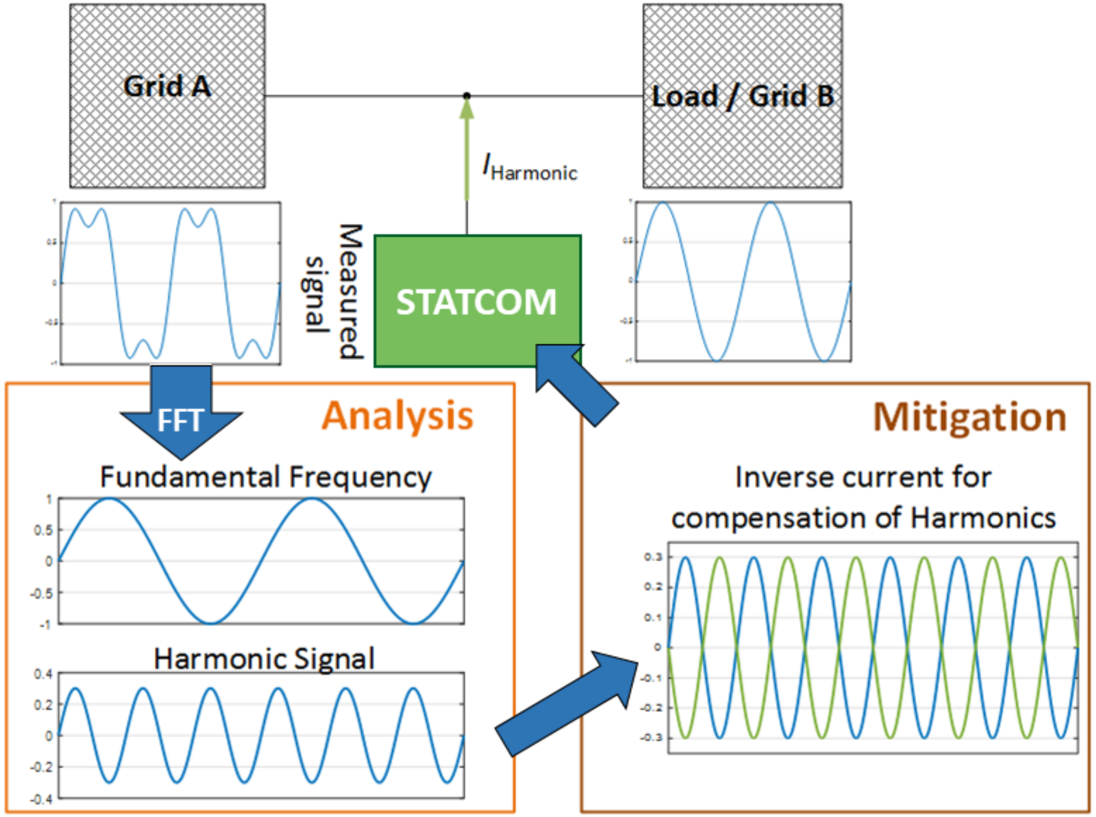
Supplementary Functions (optional)

- POD – Power Oscillation Damping
  - Damping of low frequency power system oscillations (typically from 0.2 to 2 Hz)
- NPS – Negative Phase Sequence Control
  - Mitigation of negative sequence system voltage
  - Single- or two-phase load balancing (traction load)
  - No impact to STACOM harmonic generation
- AF – Active Filtering
  - Supressing selected low order harmonics
  - Possible to compensate multiple harmonic content
  - Special harmonic voltage measurement

Supplementary Functions (optional)

- External Devices Control – HV MSC and/or MSR
    - Preserves the full dynamic range of the STATCOM for system faults
- Slow Var Control – Offsetting Var output
    - Preserves the dynamic range of the STATCOM, when MSC /MSR / Tap Chager are not directly controlled by the STATCOM

Supplementary function
Active filtering



- Operates as a harmonic voltage source, injecting inverse harmonic currents
- System harmonic current/voltage can be selectively eliminated up to 9th harmonic
- Two Options:
  - 1). AF output in dependency of fundamental frequency operation
  - 2). Additional power for AF function

Active Filtering

RCVT with High Accuracy Harmonic Measuring Capacity - ARM Reactor in Background

Evaluation of Shunt Compensation Solutions

Comparison Summary

		SynCon	SVC	STATCOM (GFL)	STATCOM (GFM)	STATCOM with Energy Storage
1	Experience	++++	++++	+++	+	
2	Step Response	+	+++	++++	++++	++++
3	Overvoltage Output Capability	+	+++	++	++	++
4	Undervoltage Output Capability	+++++	+	+++	++++	++++
5	Losses at 0Mvar	+	++	+++	+++	+++[ ]
6	Losses at full output	+	++++	++	++	++[ ]

Note: [ ] Depending on the rating & operation for energy storage

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Comparison Summary

		SynCon	SVC	STATCOM (GFL)	STATCOM (GFM)	STATCOM with Energy Storage
7	Harmonics generation	+++++	+	+++	+++	+++
8	Harmonics amplification	+++++	+	+++	++++	++++
9	Footprint	+++	+	+++	+++	+++[ ]
10	Maintenance	+	++	++++	++++	+++

Note: [ ] Depending on the rating for energy storage

Comparison Summary

		SynCon	SVC	STATCOM (GFL)	STATCOM (GFM)	STATCOM with Energy Storage
11	Short Circuit Contribution	10 +		+	++[++]	++++
12	Inertia	+++++				> 10 +
13	Reactive Power Rating	+++	+++	+++	+++	+++
14	System Strength	+++			+++	++++

Note: [ ] Short circuit contribution dependent on fault type & configuration e.g., delta, wye, wye-wye

System Strength: The power system capability to maintain the voltage waveform

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Thank you.

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