Power Electronics for Grid Applications

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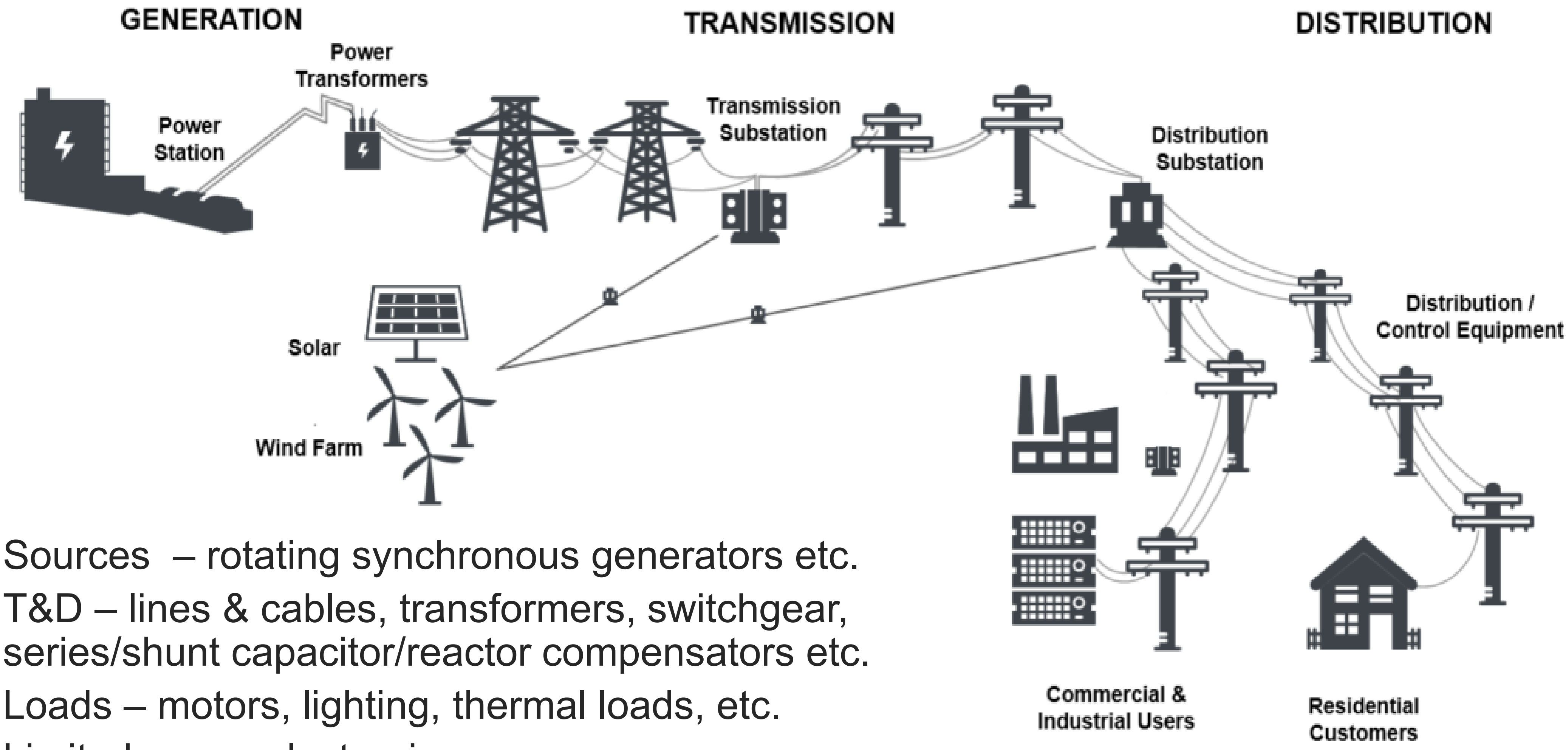
March 8, 2024

Traditional Power Grid Equipment



- Sources – rotating synchronous generators etc.
- T&D – lines & cables, transformers, switchgear, series/shunt capacitor/reactor compensators etc.
- Loads – motors, lighting, thermal loads, etc.
- Limited power electronics

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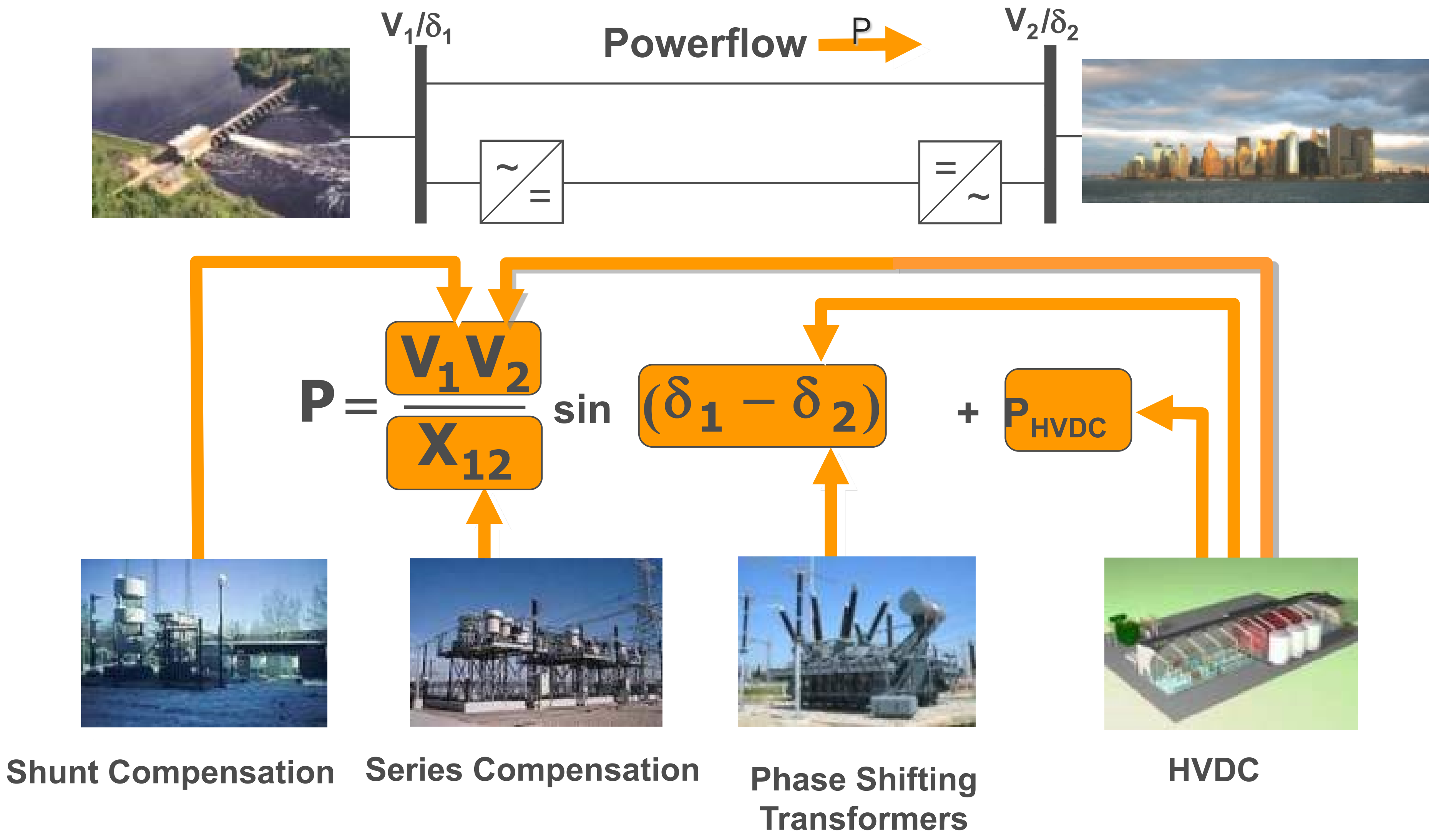
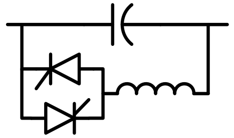
Power Transfer in Grid - From "AC *vs* DC" to "AC *and* DC"

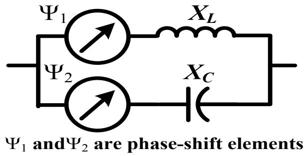


Power Electronics for AC Transmission – Flexible AC Transmission Systems (FACTS)

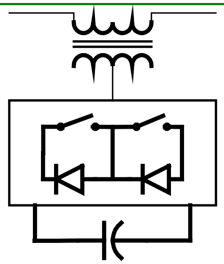
- **Series connected compensators**



Thyristor-controlled series compensator (TCSC)

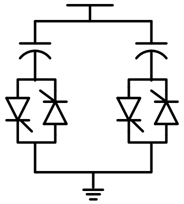


Interphase power controller (IPC)

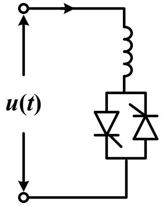


Static synchronous compensator (STATCOM)

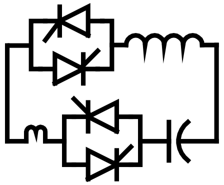
- **Shunt connected compensators**



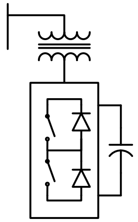
Thyristor-switched capacitor (TSC)



Thyristor-switched reactor (TSC)

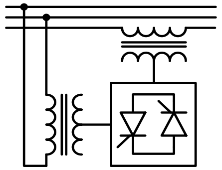


Static var compensator (SVC)

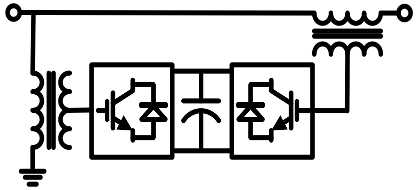


Static synchronous compensator (STATCOM)

- **Series and shunt connected compensators**



Thyristor-controlled phase shifting transformer (TCPST)

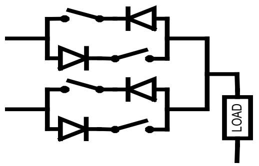


Unified power flow controller (UPFC)

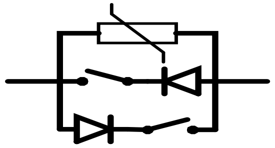
Conventional FACTS mostly based on Si thyristor technology, with limited performance and capabilities

Power Electronics for AC Distribution – Custom Power

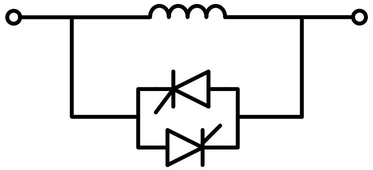
- **Power flow control and interruption**



Solid-state transfer switch (SSTS)

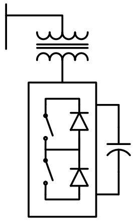


Solid-state circuit breaker (SSCB)

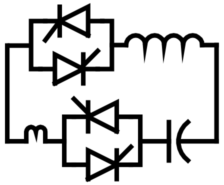


Solid-state fault current limiter (SSFCL)

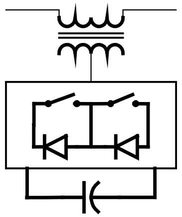
- **Power system conditioning and compensation**



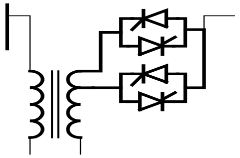
Distribution static synchronous compensator (DSTATCOM)



Static var compensator (SVC)

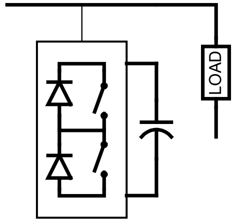


Dynamic voltage restorer (DVR)

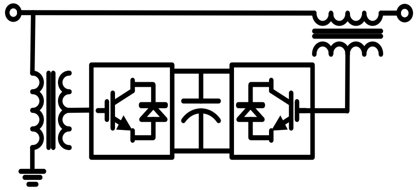


Thyristor-controlled voltage regulator (TCVR)

- **Power quality enhancement**

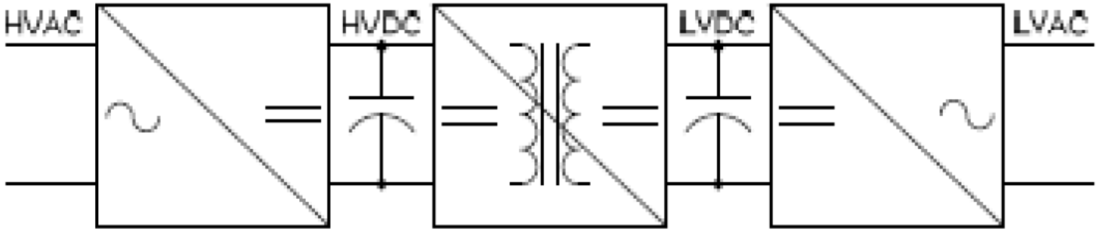


Active power filter (APF)

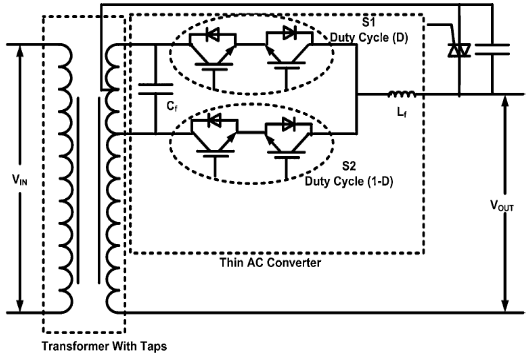


Unified power quality conditioner (UPQC)

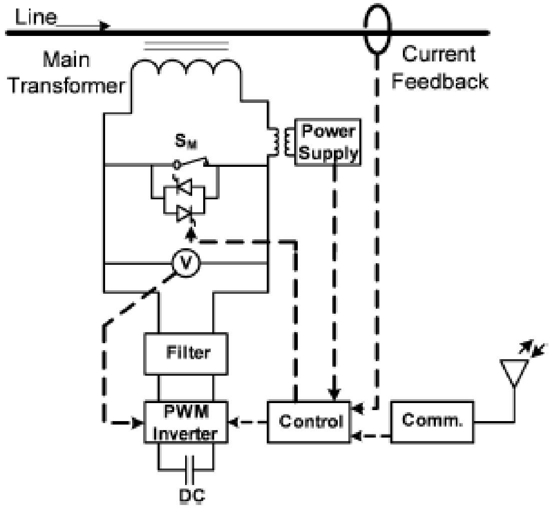
Power Electronics for T&D – More Recent Development



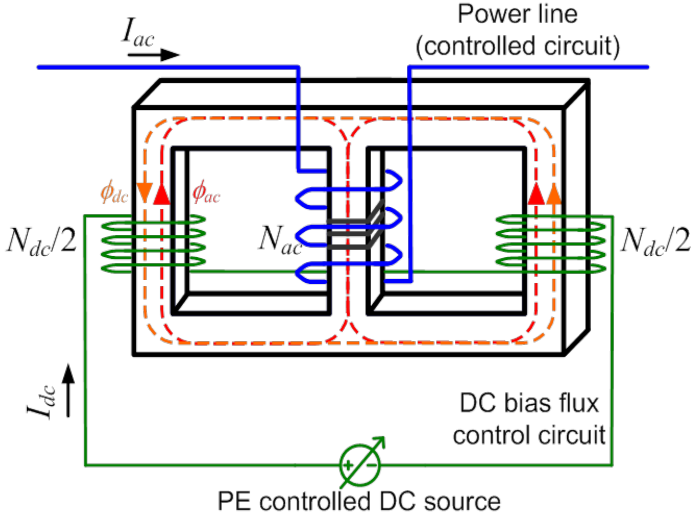
Solid-state transformer



Controllable network transformer



Distributed static series compensator



Continuously variable series reactor (CVSR)

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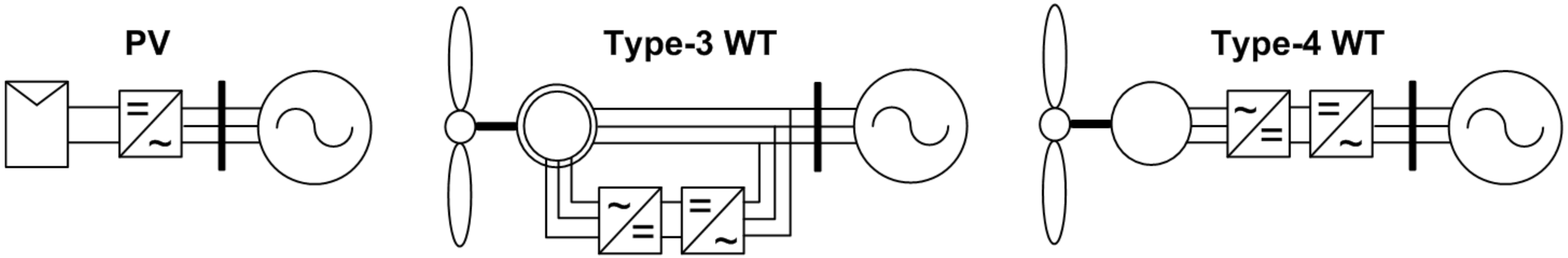
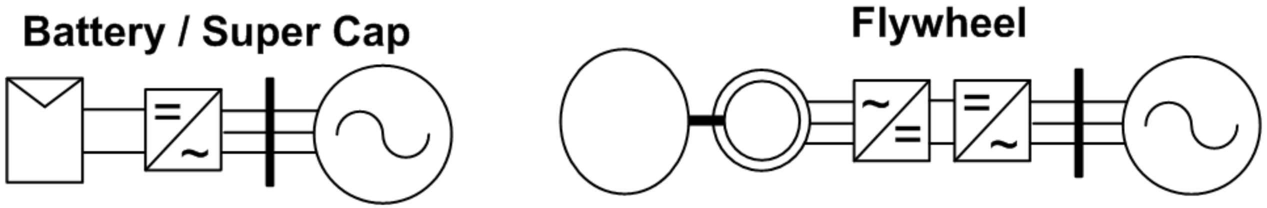
Grid Power Electronics – Sources and Loads

- **Renewable energy source interface**



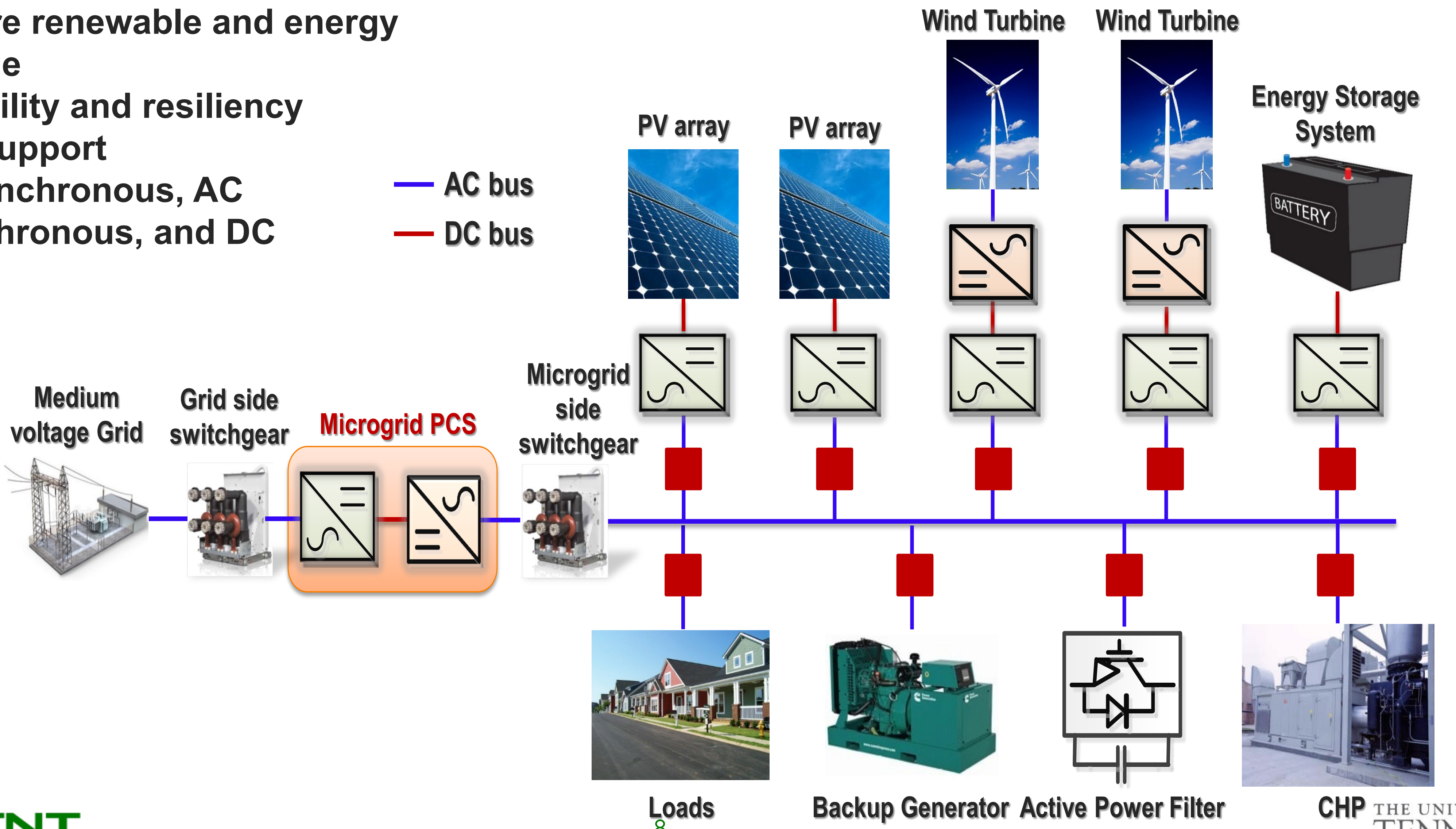
- **Energy storage systems**



- **Power electronic loads: data center, EV charging station, large motor drive**

Microgrids

- Feature renewable and energy storage
- Reliability and resiliency
- Grid support
- AC synchronous, AC asynchronous, and DC



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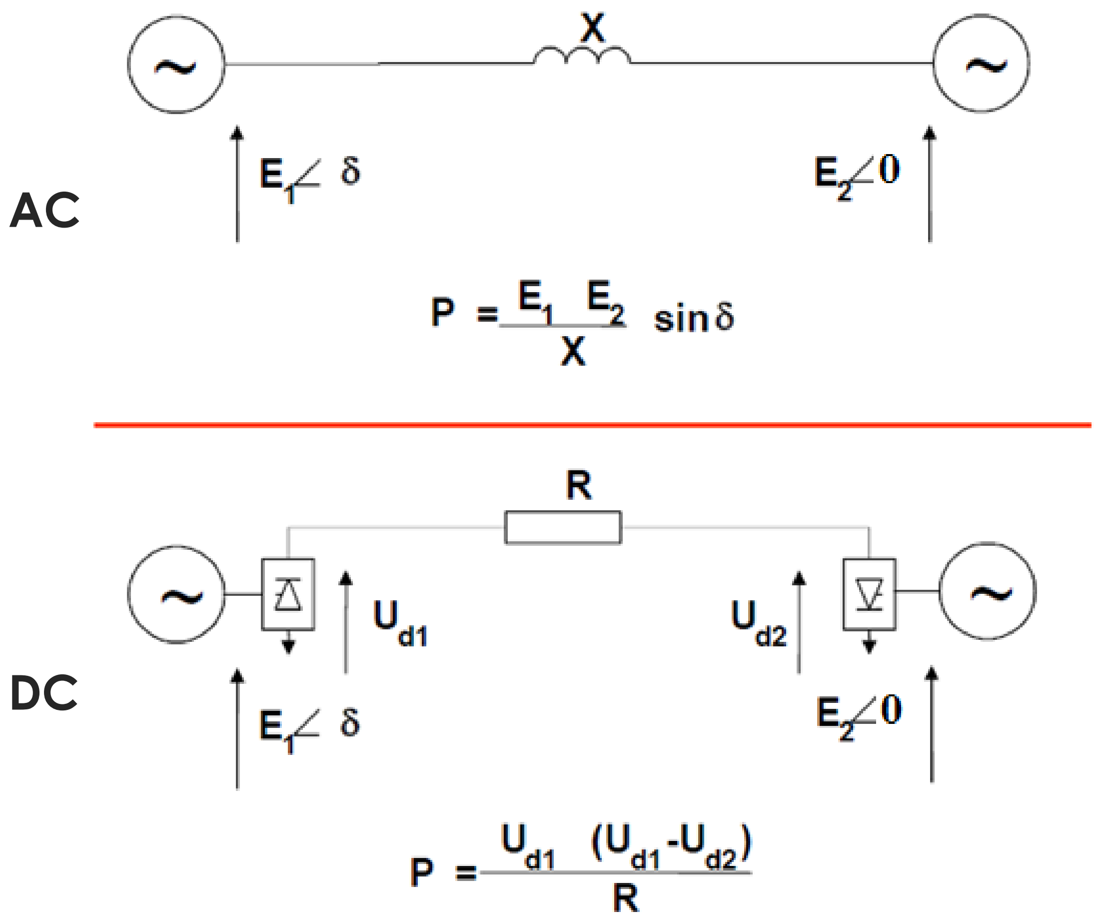
AC and DC Transmission Principles



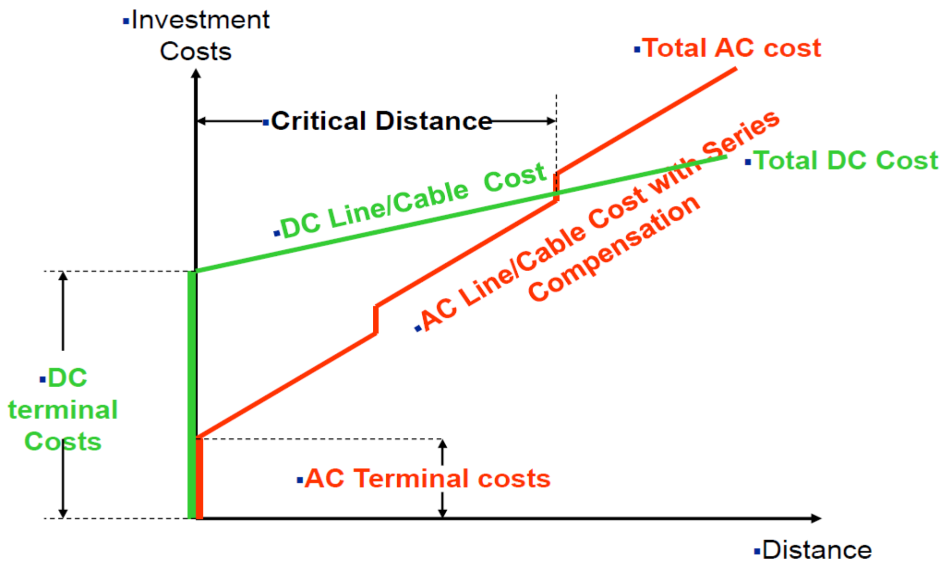
Compared with AC, the main features of DC transmissions:

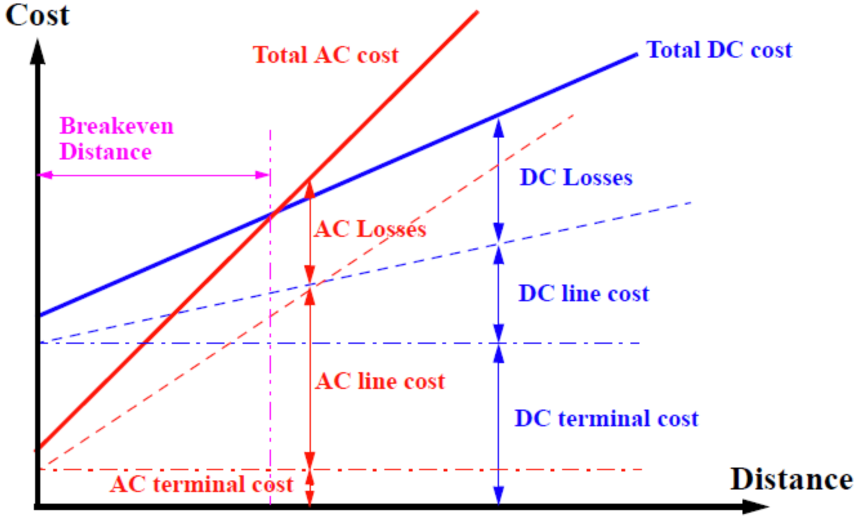
- Long distance
- Asynchronous interconnection
- Controllability

DC does require AC/DC converters and other associated equipment

- Filters and var compensators
- Communications
- Special transformers

HVDC vs. HVAC Cost

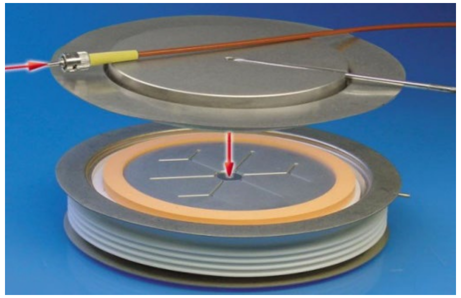


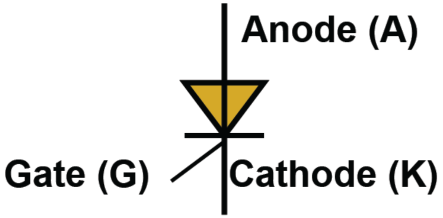


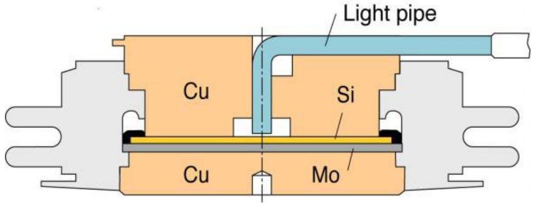
- There is a breakeven or critical distance beyond which the DC scheme will be more economical
- The breakeven distance depends on many factors. For overhead lines in the range of several hundred of miles (300 to 500); for cables, in the range of tens of miles (30 to 60 miles)

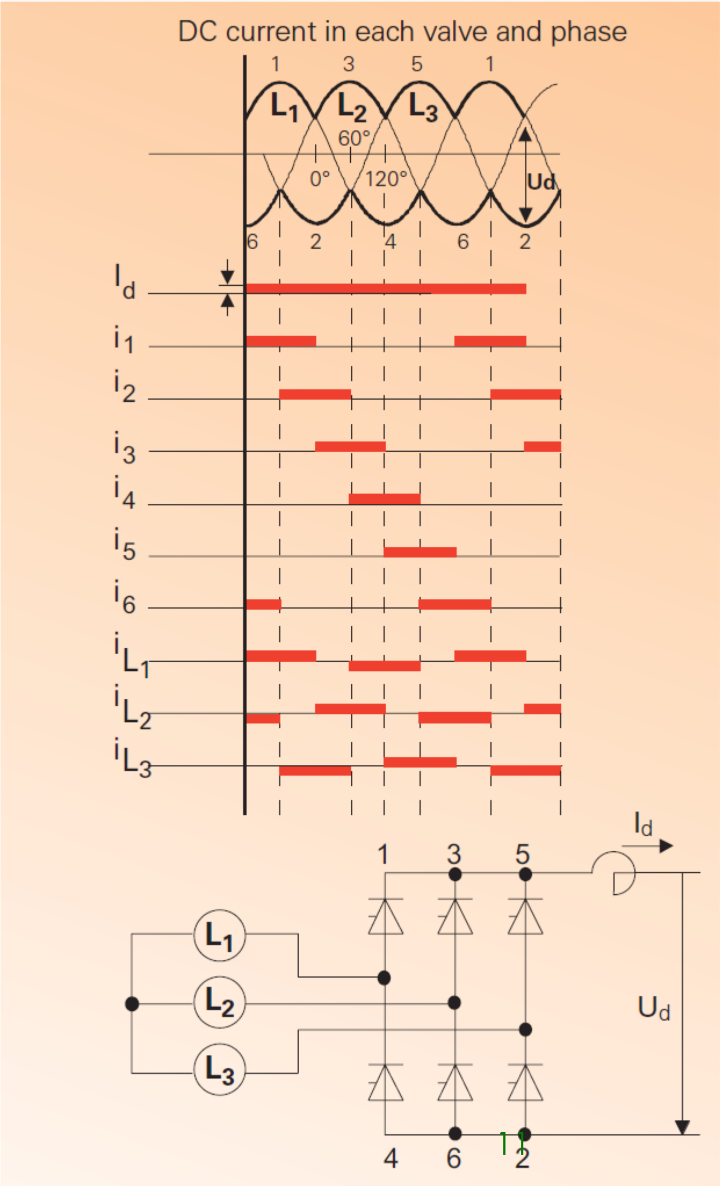
HVDC Converter – Principle of Load Commutated Converter (LCC)

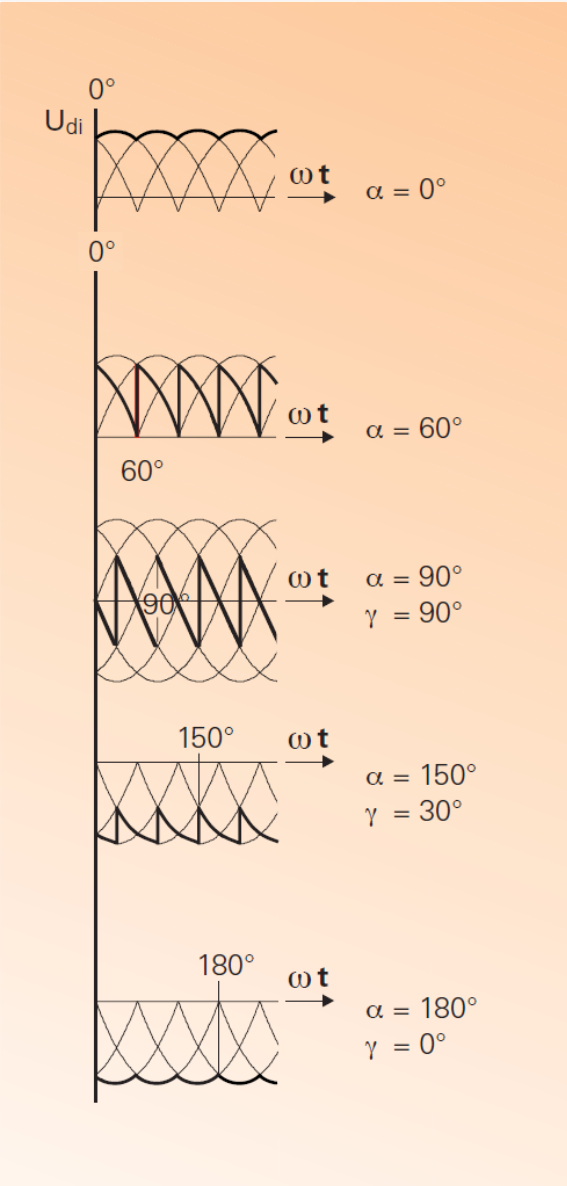
Thyristor or SCR







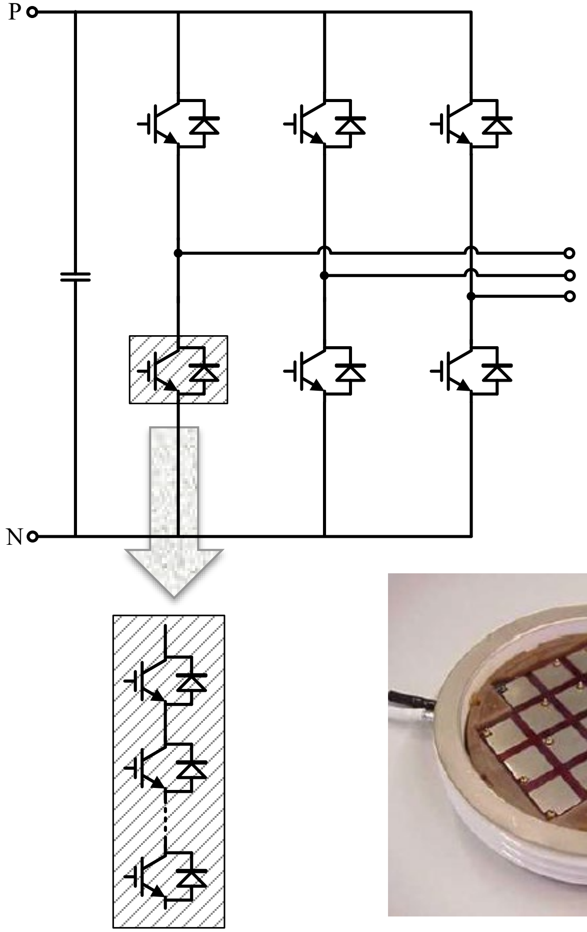




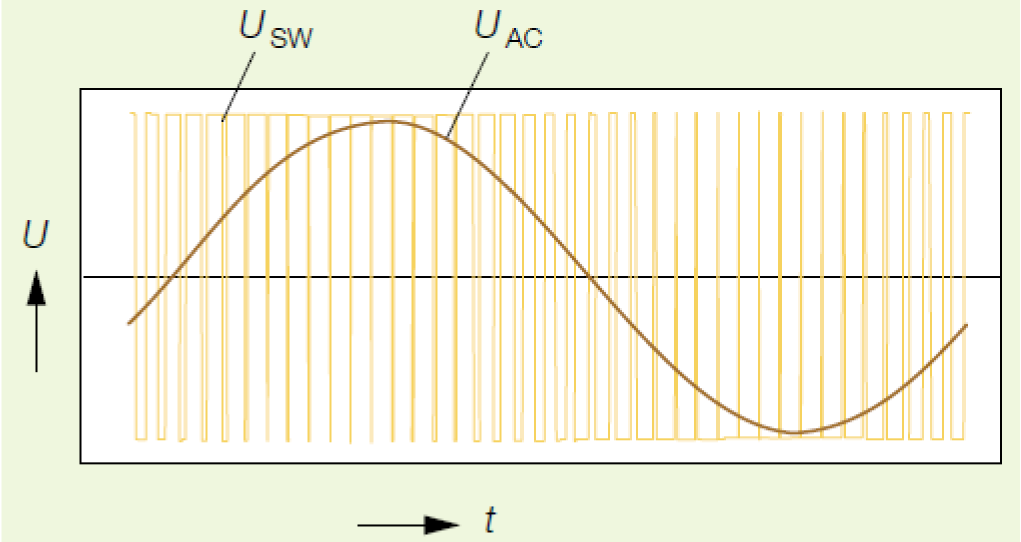
Six Pulse LCC Converter Bridge and Its Operation

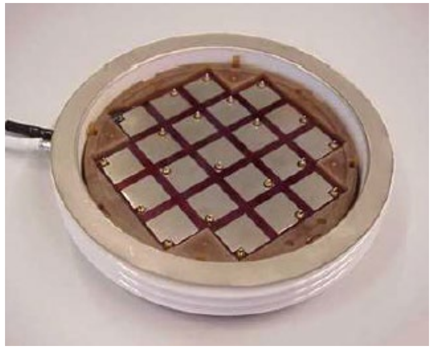
HVDC Converter – Principles of Voltage Source Converter (VSC)

VSC – Voltage Source Converter

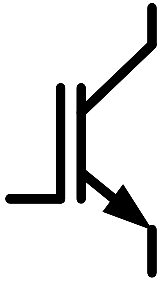


Pulse Width Modulation (PWM) Control

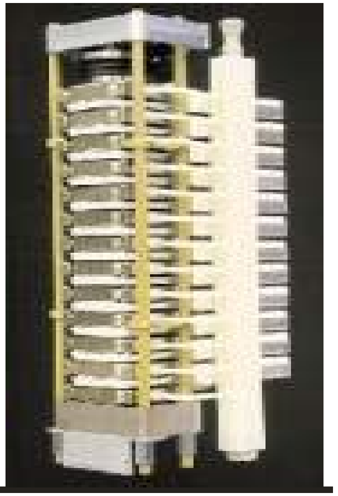




IGBT



HVDC Technology Development

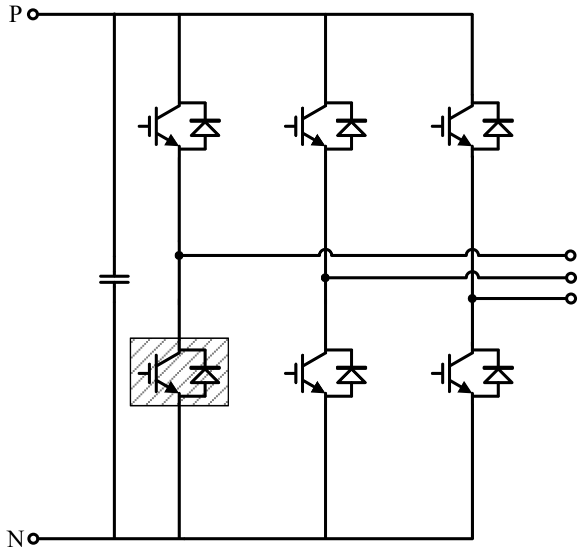
Mercury Arc Valve HVDC (Phased out)	Thyristor Valve HVDC Classic	IGBT (Transistor) HVDC Light (VSC HVDC)
		

Year

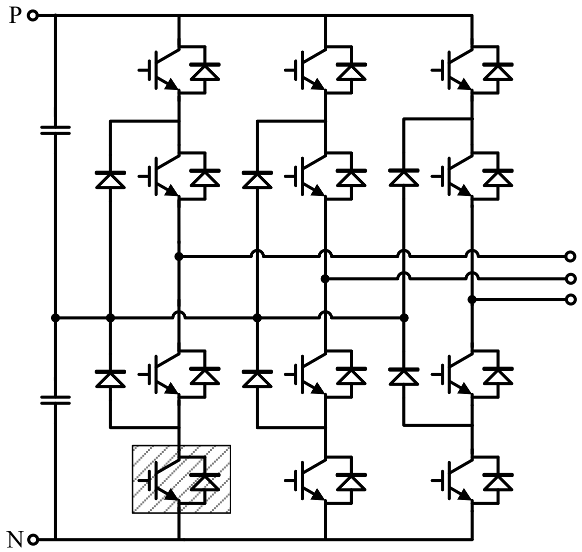
1954 1970 1980 2000

Pros: Low losses Cons: Reliability Maintenance Environment	Pros: Reliable Scalable Cons: Footprint	Pros: Controllability Footprint DC Grids Cons: Losses

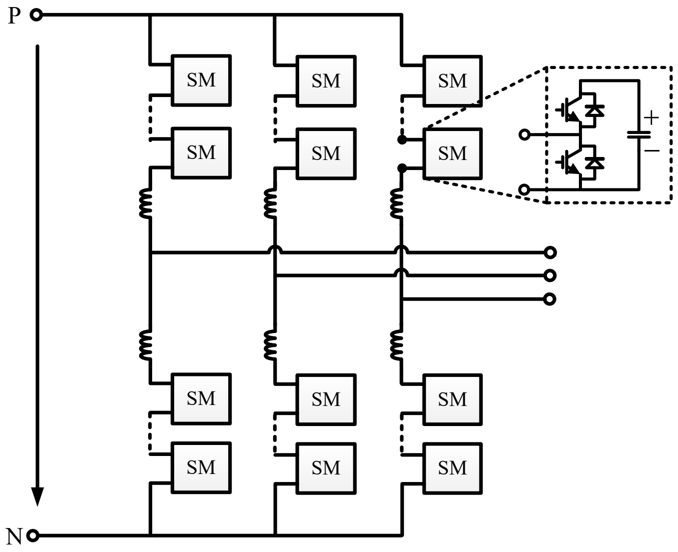
HVDC Technology Evolution: Voltage Source Converter (VSC) Topologies



Two-level



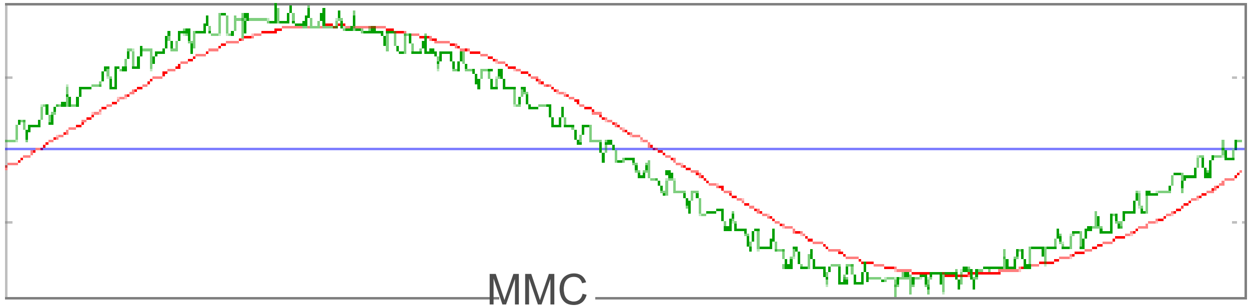
Three-level (NPC)



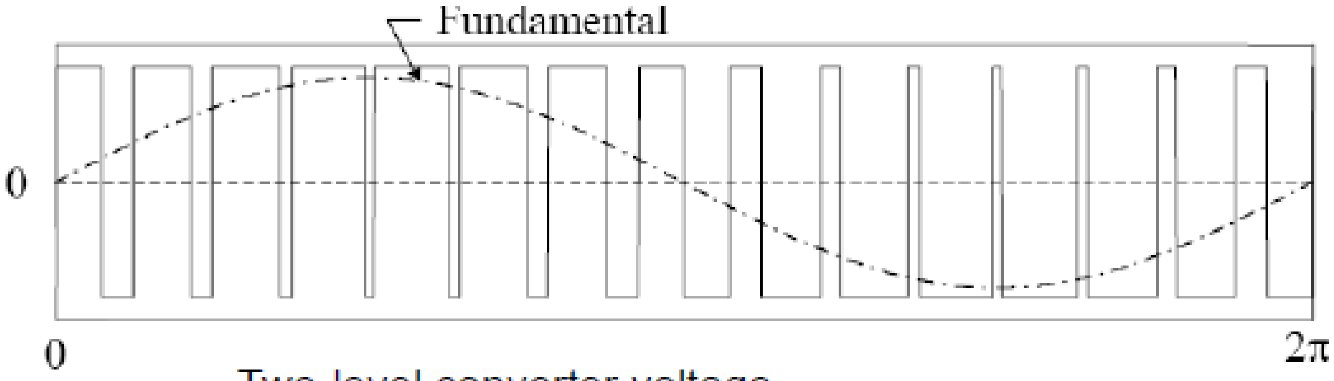
Modular multi-level converter (MMC)

- VSC based on switching devices (IGBT/IGCT), with better performance than thyristor based LCC, and significantly reduced converter station footprint and less right-of-way
- MMC latest generation of VSC topology: low loss, and no series devices

MMC VSC vs. Conventional VSC



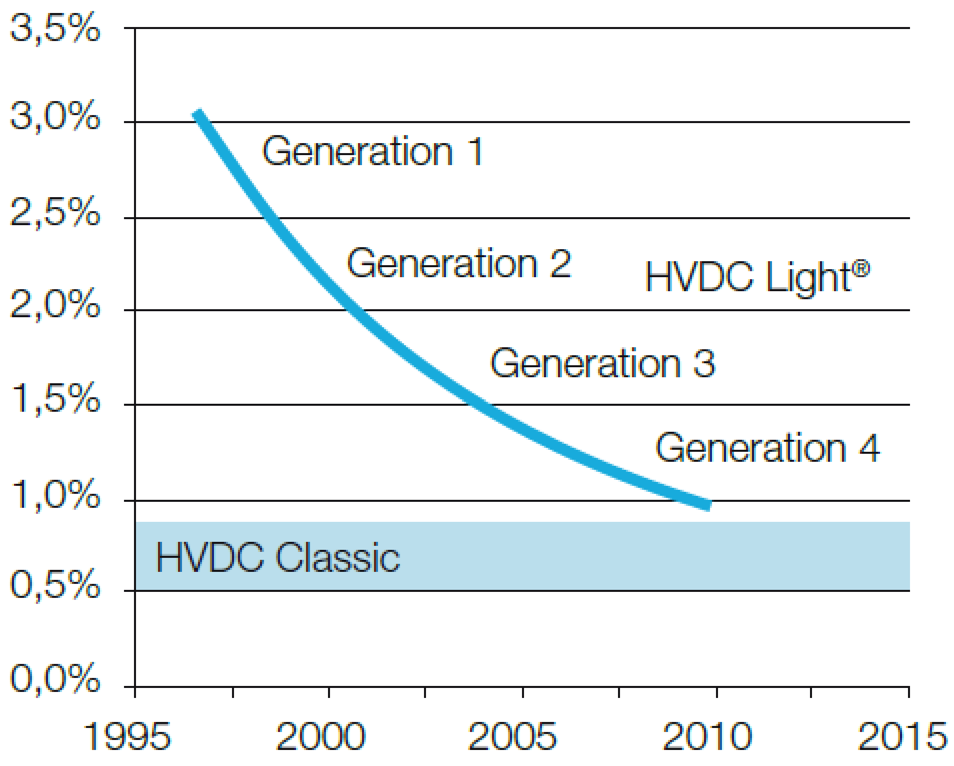
CTL converter voltage



Two-level converter voltage

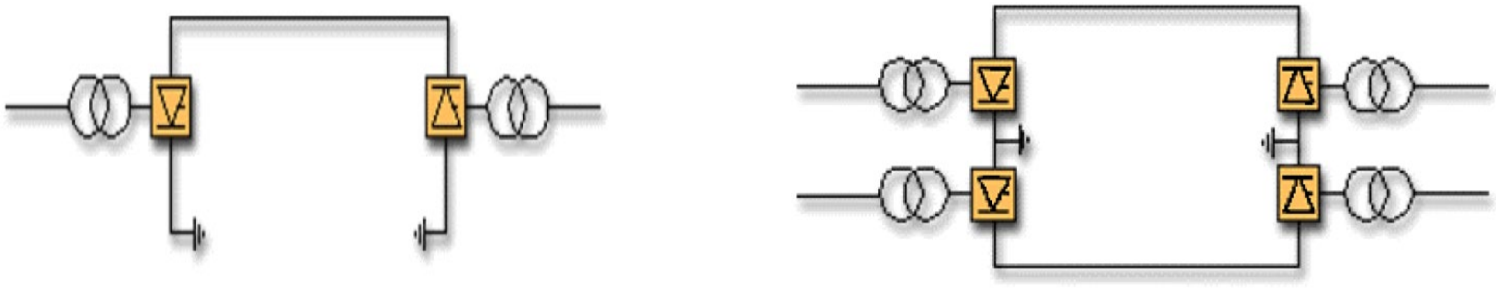
Technology Evolution – VSC Efficiency

- Generations 1-3 adopt the two-level converter and 3-level converter
- Generation 4 adopts MMC, and the converter efficiency is comparable to LCC HVDC

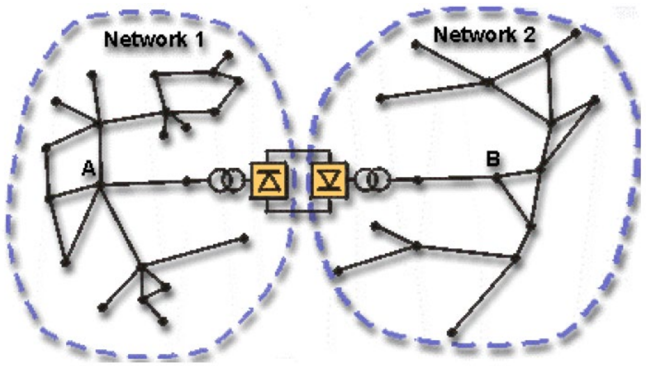


HVDC System Types

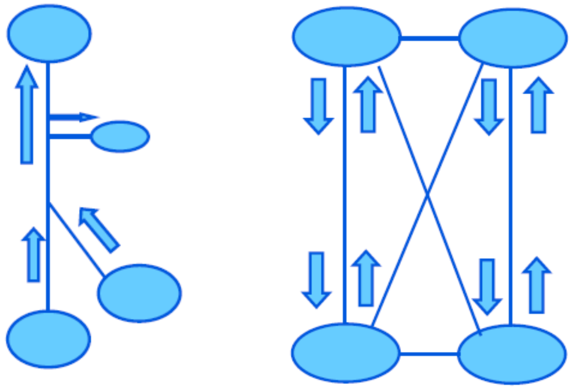
- Point-to-point transmission



- Back-to-back system



- Multi-terminal system



HVDC more economical for long-distance transmission; HVDC can decouple dynamics of AC systems, benefiting system stability and protection

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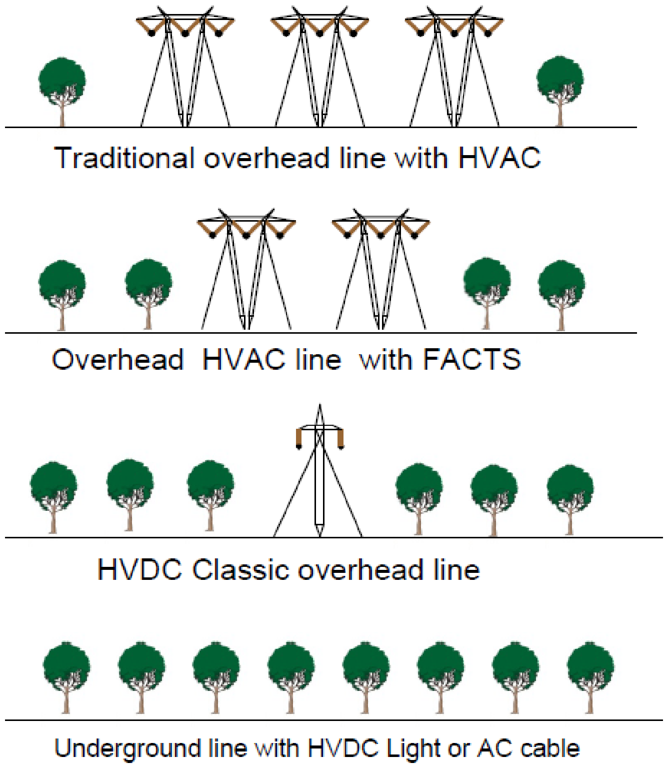
Summary of HVDC Benefits

- Long distance bulk power transmission
- Asynchronous interconnections
- Lower cost for cable transmission (subsea, offshore)
- AC system support
  - Controllability (including damping, f support, power flow and voltage control)
  - Limitation of faults
  - Low short-circuit current contribution
- Better use of right-of-way
- Environmental benefits (corona, noise, etc.)

Better Use of Right-of-Way

Different technologies: Same power transmitted



Based on information from ABB

Several aspects on this point:

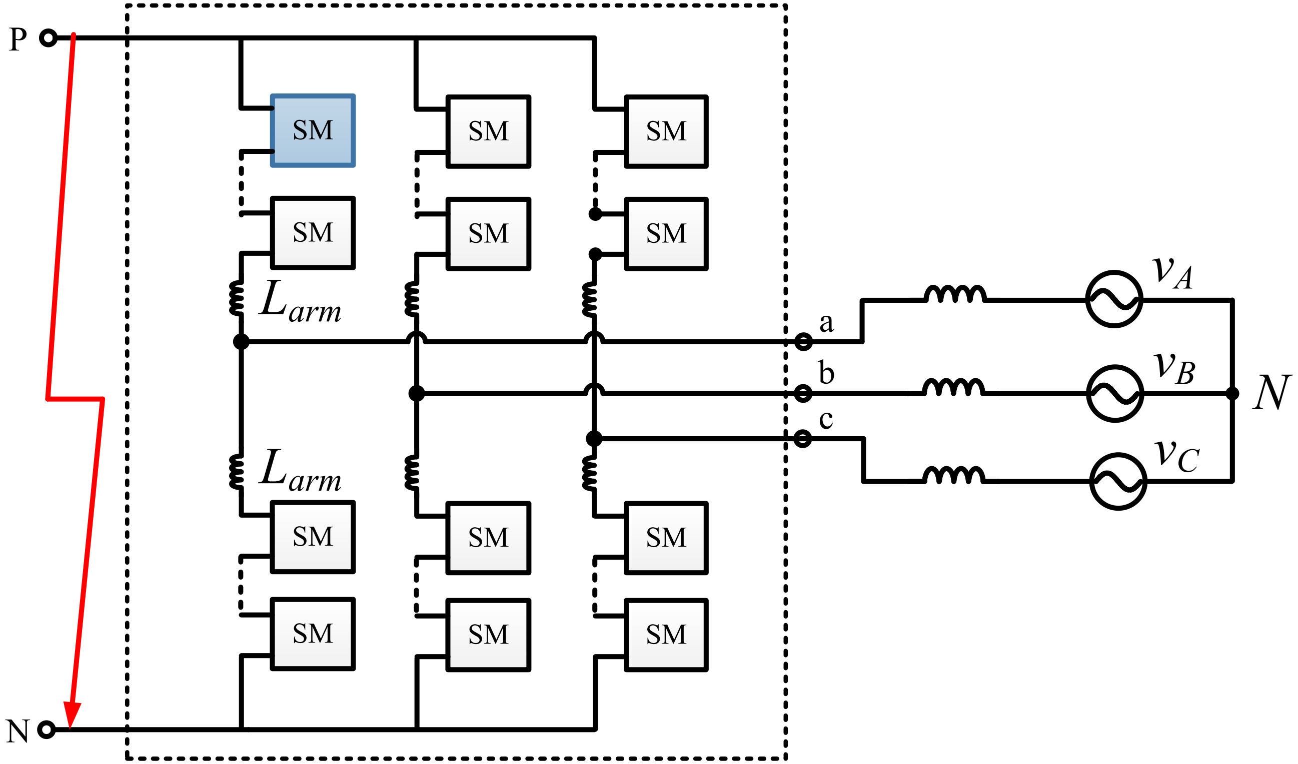
- For the same power transmitted, HVDC requires less right-of-way
- For the same right-of-the-way, HVDC can transfer more power
- With the same lines, HVDC can have lower loss

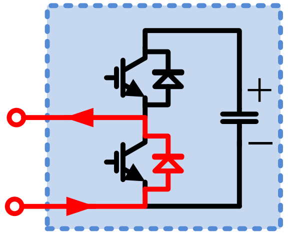
Disadvantages and Issues with HVDC

- High cost and complex converters
- Converters generate harmonics
- LCC HVDC require large var compensation and filters
- Challenges on grounding electrodes and converter transformers
- Difficulty of breaking DC current (DC breaker)

VSC HVDC Protection – Challenge

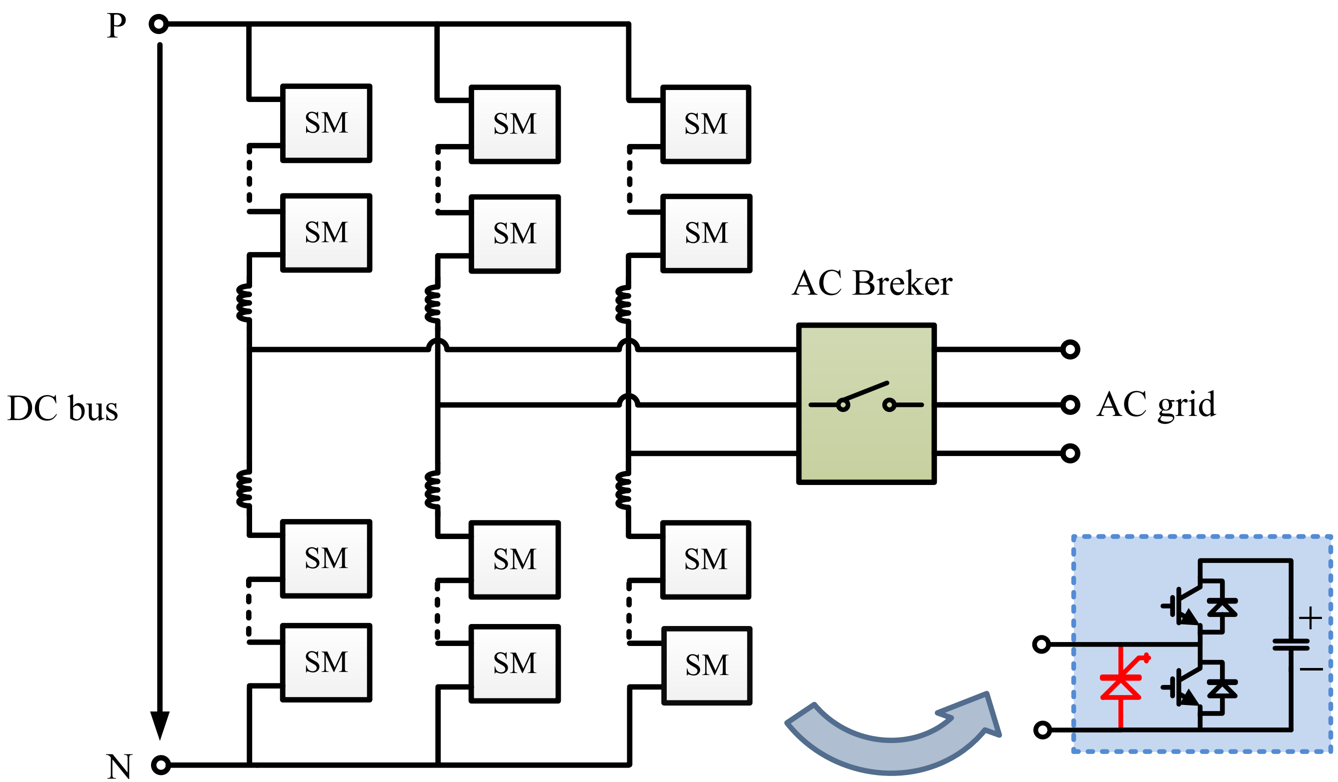
- VSC is vulnerable to DC side short circuit fault, as the fault current can still flow through the diode after IGBT switches turned off
- DC current is difficult to clear without zero-crossing





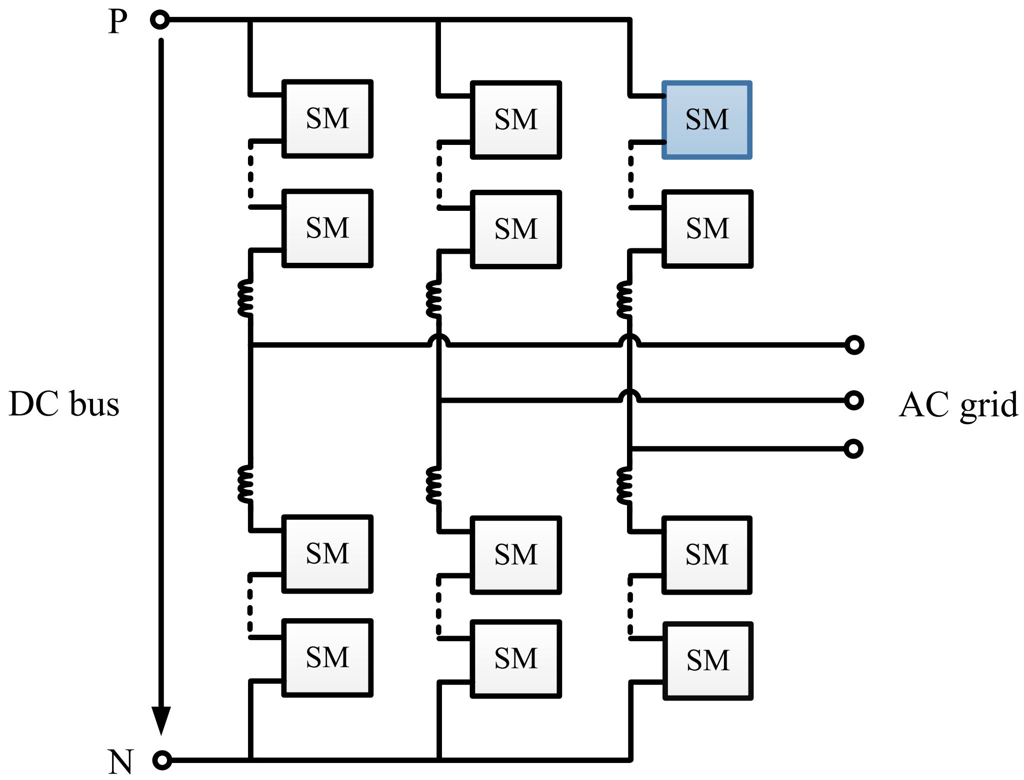
VSC HVDC DC Fault Protection – Solution

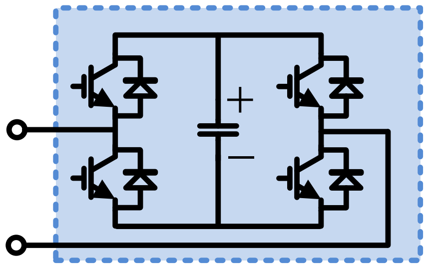
- State of art solution: AC breaker + bypass thyristor (if necessary)
- 100 ms to clear the fault, and 2 s to restart the system



VSC HVDC DC Fault Protection – Solution

- Fast fault clearance solution (<5 ms)
  - ❖ Siemens method: MMC with fault blocking sub-module





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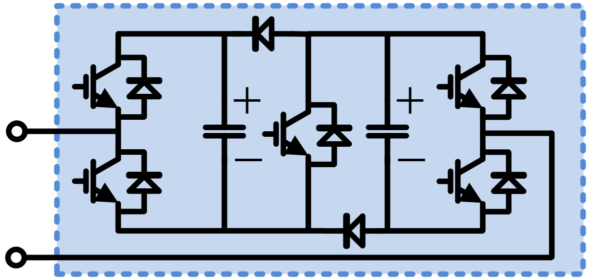

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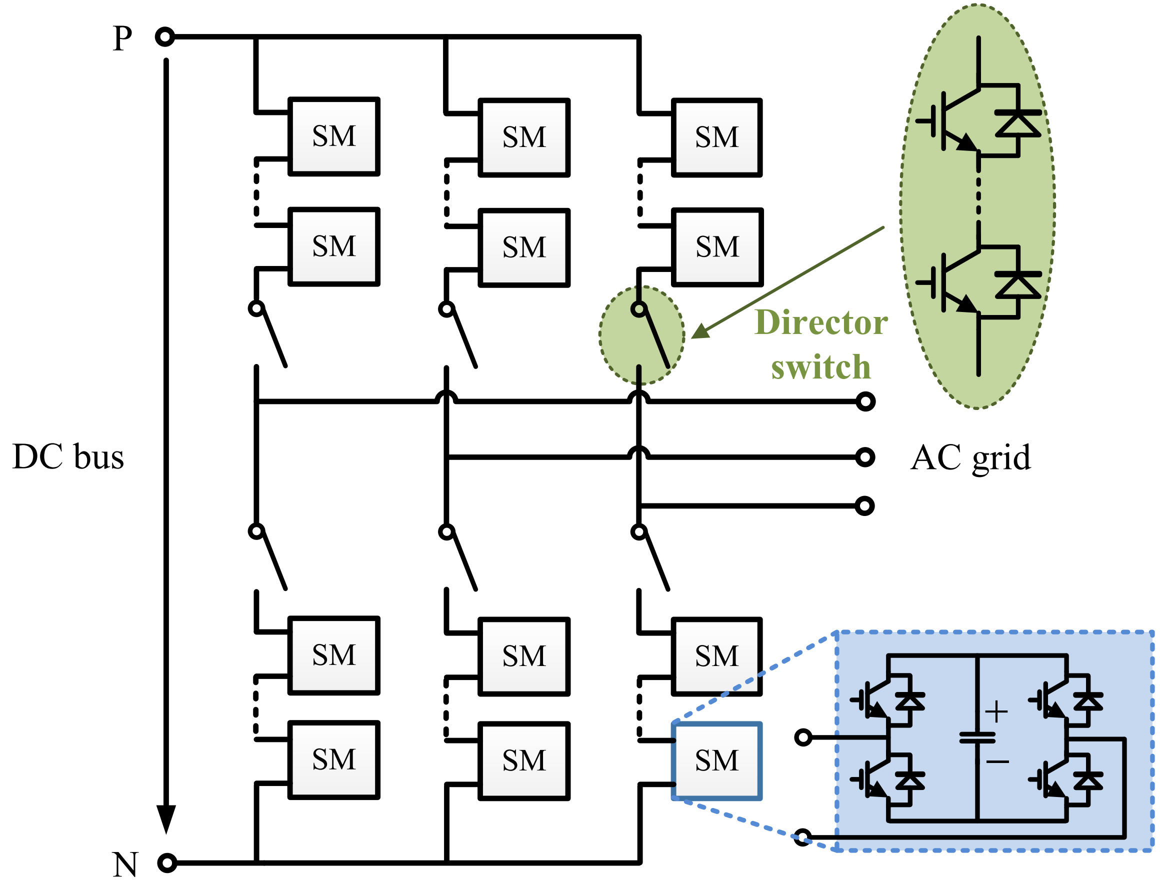
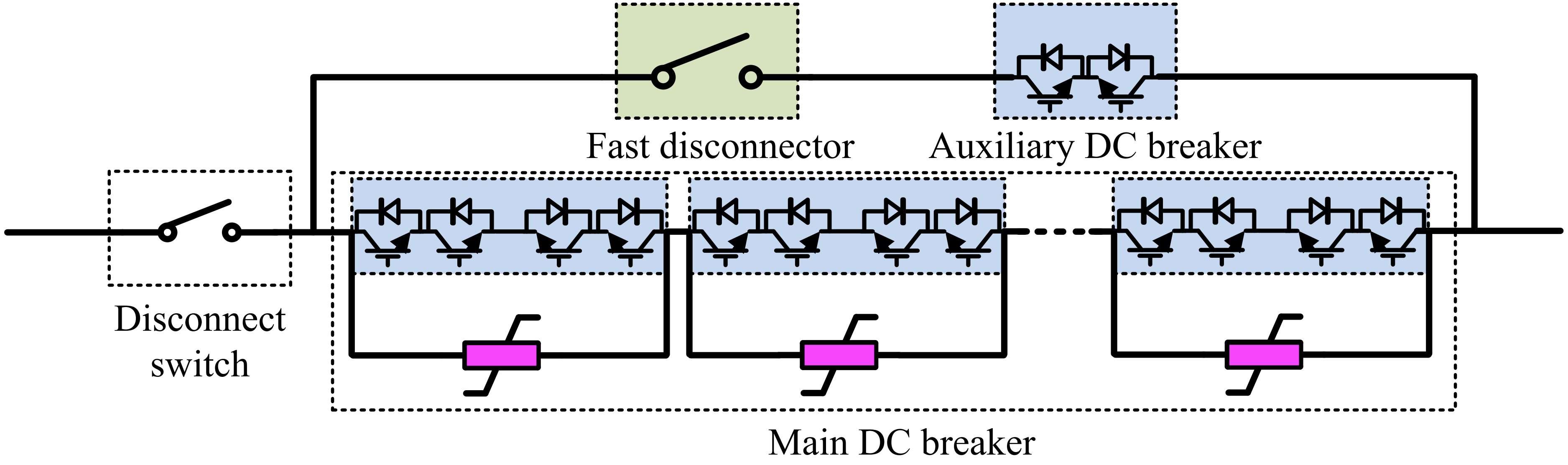
VSC HVDC DC Fault Protection – Solution

- Fast fault clearance solution (<5 ms)
  - ❖ GE/Alstom method: hybrid MMC



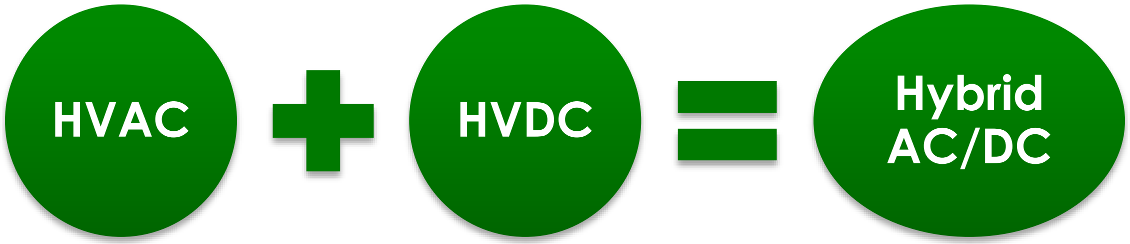
VSC HVDC DC Fault Protection – Solution

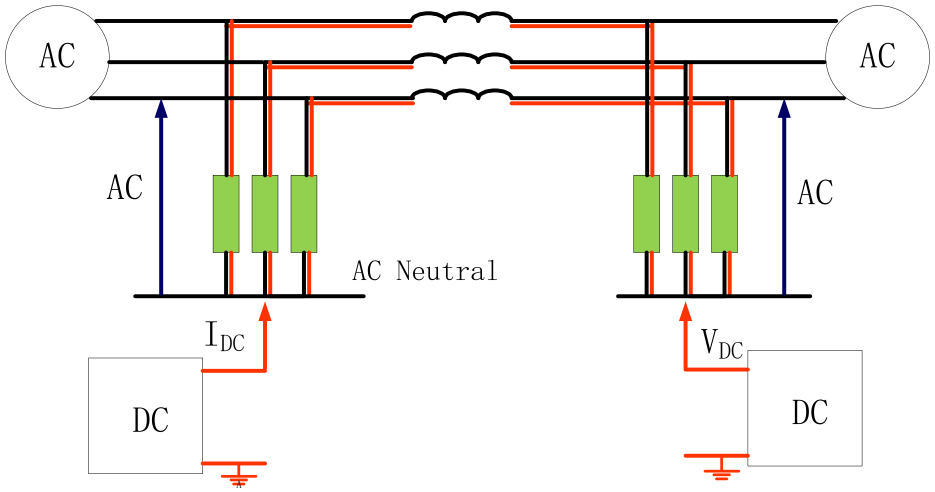
- Fast fault clearance solution (<5 ms)
  - ❖ Hitachi/ABB method: Hybrid DC breaker

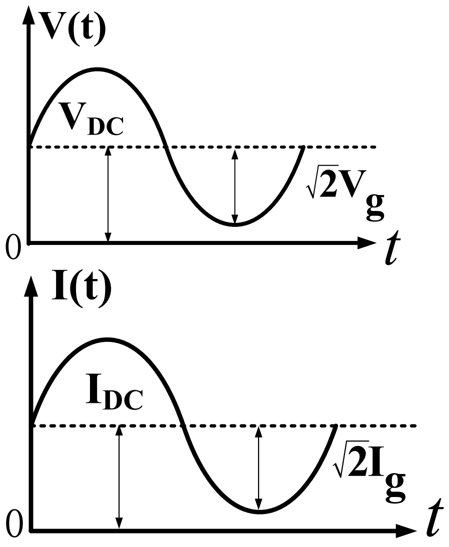


Hybrid AC/DC System

Objective: Upgrade existing AC lines to hybrid AC and DC lines, to expand the power transmission capability

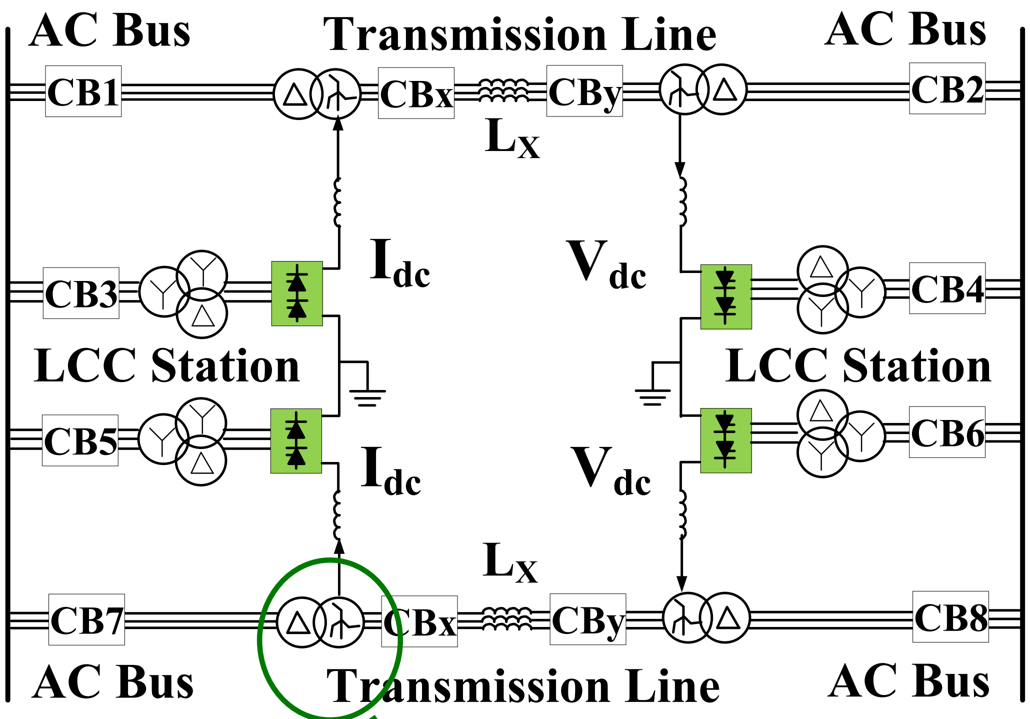




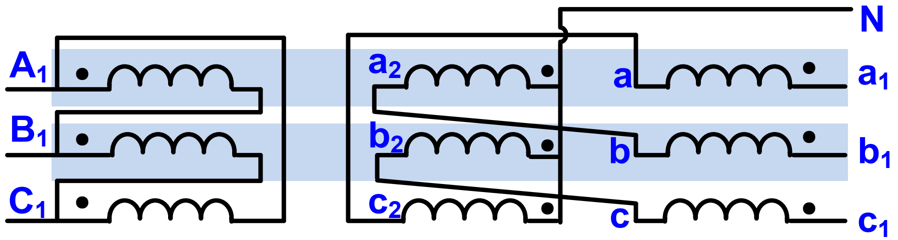


Basic Concept of Hybrid AC/DC System

System topology:



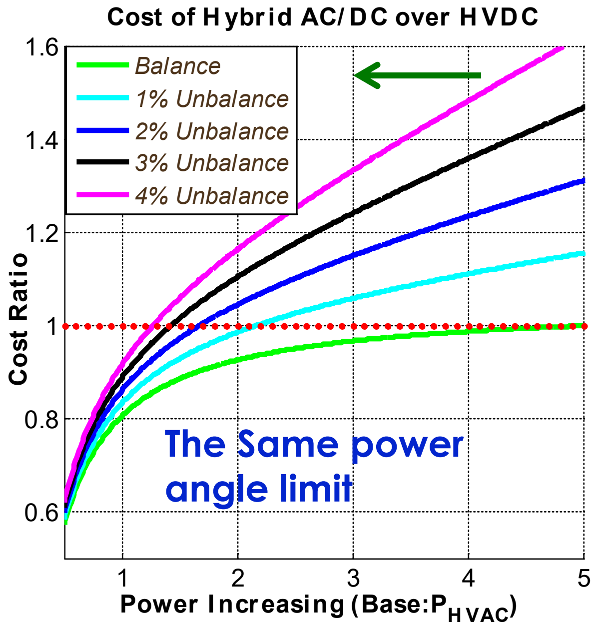
DC injection link: zigzag transformer

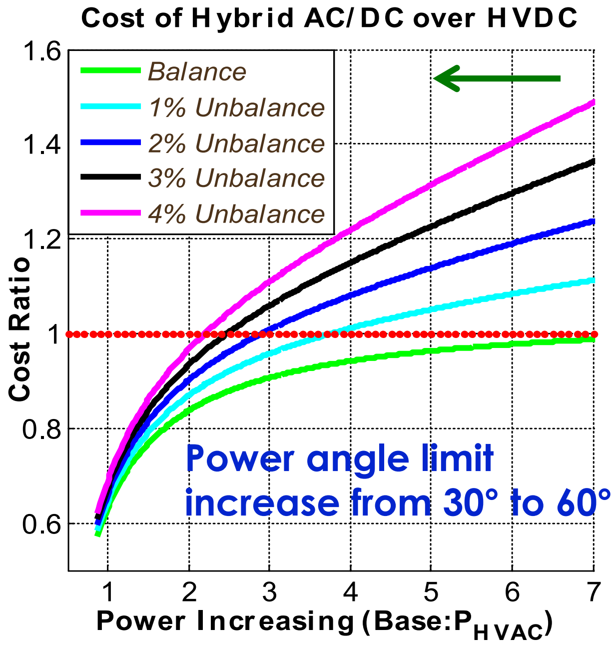


Benefits and Issues

Benefits:

- A lower cost solution for increased power transfer and improved stability





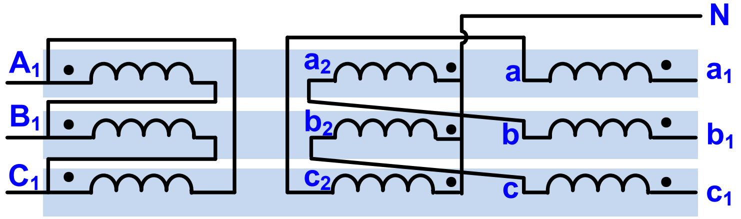
Issues:

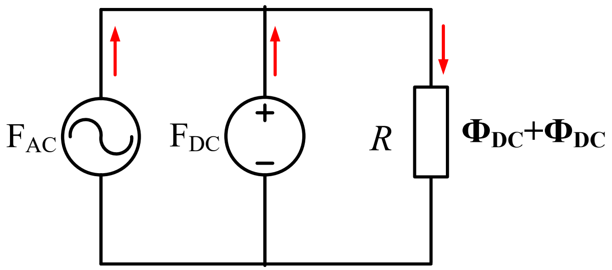
- **Zigzag transformer may be saturated with unbalanced AC line resistance, due to the uncanceled DC flux within zigzag windings.**
- **Neutral point of zigzag transformer needs extra insulation to withstand dc bias voltage**

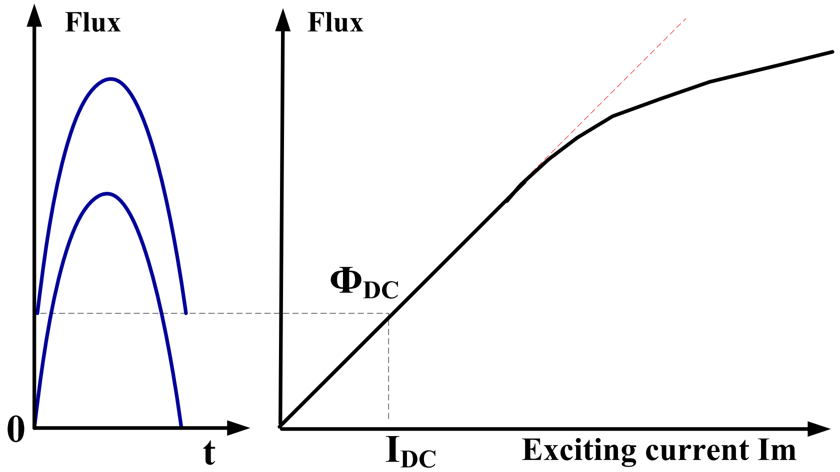
Method 1: Design Tolerance Margin

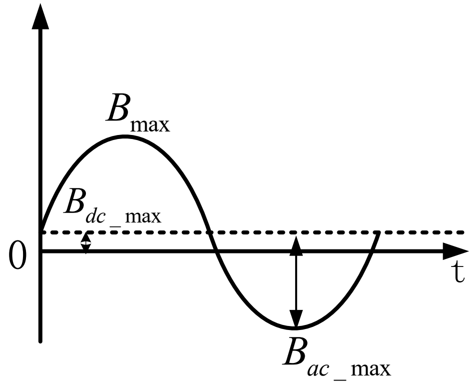
Method 1: DC tolerance design

- **Can tolerate a certain unbalance range (±β)**
- **To tolerate more unbalance will cause more power loss and/or VAR loss**
- **Effective AC flux density is reduced, lead to higher cost**





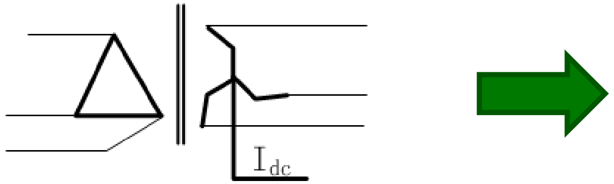




Method 2: Adjust Transformer Turns

Method 2: DC flux cancelation design by adjusting turns

- Less power or VAR loss compared to method1 for the same rating
- Cost closest to normal AC transformer.
- Introduces a certain extra voltage unbalance
- Sensitive to real-time unbalance

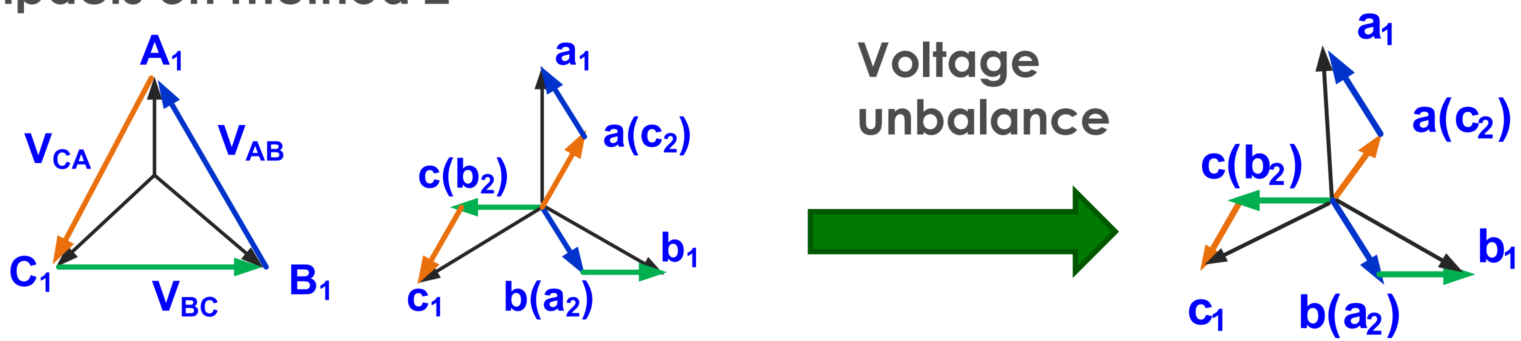


$$N_{z1} I_{a\_DC} - N_{z2} I_{b\_DC} = 0$$

$$\frac{N_{z1}}{N_{z2}} = \frac{I_{b\_DC}}{I_{a\_DC}}$$

For a general design: use tap changers for each winding

Impacts on method 2

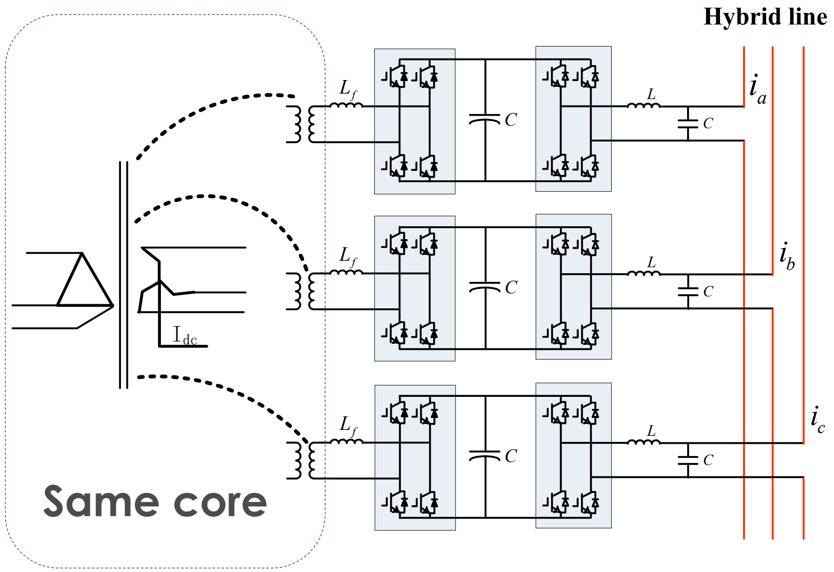


Method3: Active Unbalance Mitigation

Method 3: Hybrid line balance control

- Immunity to unbalance
- Low voltage rating, no insulation issue
- Active impedance with low loss
- With extra converter cost, but low compared to main HVDC converters

Hybrid line impedance conditioner:



Bidirectional Active Hybrid Line Impedance Conditioners
(Two conditioners are active, at the most)

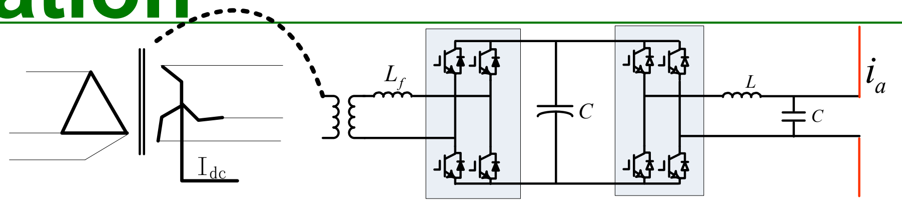
Adjust the line resistance by phase.

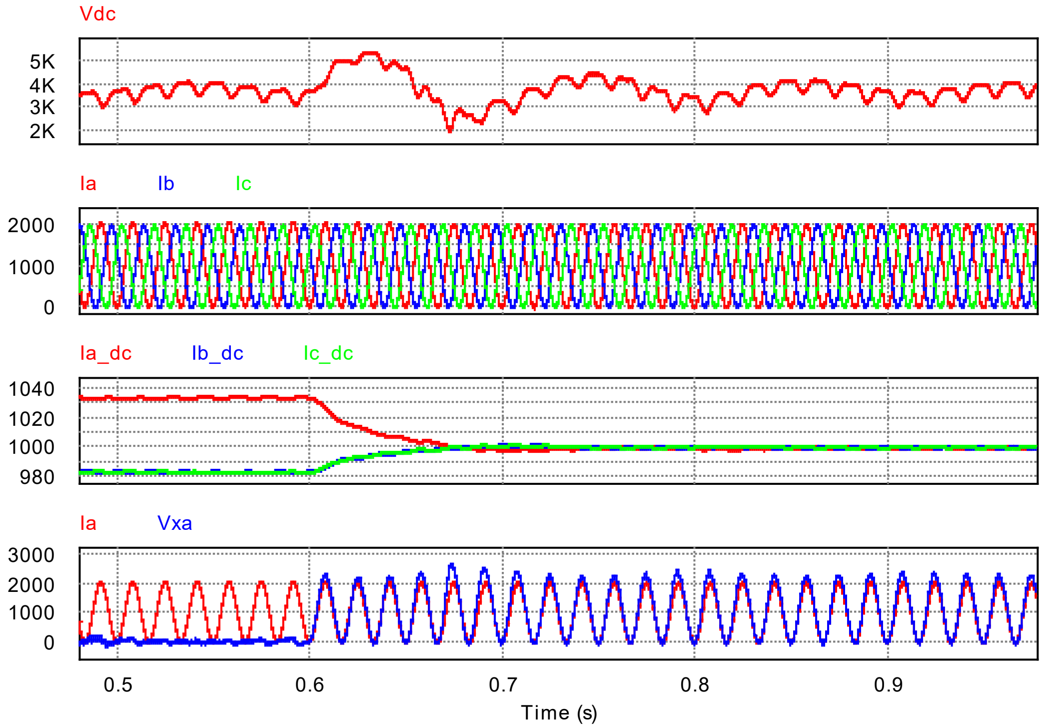
Can be enabled or bypassed

$$\Delta R = \frac{V_{AC/DC}}{I_{AC/DC}} \approx \frac{\Delta V_{DC}}{I_{DC}/3}$$

Method3: Impedance Conditioner Design and Simulation

System Parameters	
Line Length	650km
Impedance	0.035Ohm/km+ 0.9337mH/km
Unbalance	**5%**
Line voltage (phase)	AC: 115 kV; DC 180 kV
Line current	AC: 612A, DC: 1000A
Transmission Power	729 MW (189 AC and 540 DC)
Inverter AC voltage	3.183kV(peak)
DC link voltage	3.617kV
DC link Capacitance	**3300uF**
Rectifier AC voltage	3.183 kV(peak)
Zigzag transformer windings	balance design + conditioner winding (170/138/138/3)

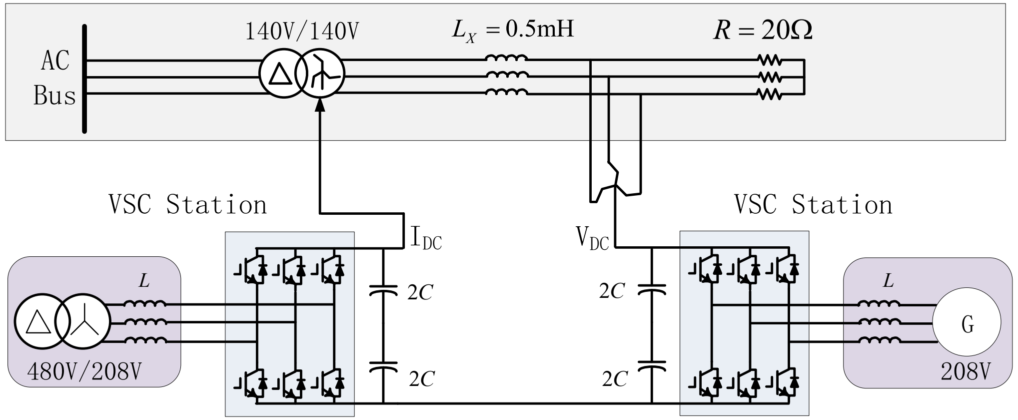




Conditioner enabled at 0.6s. Control reference goes from zero to the desired impedance.

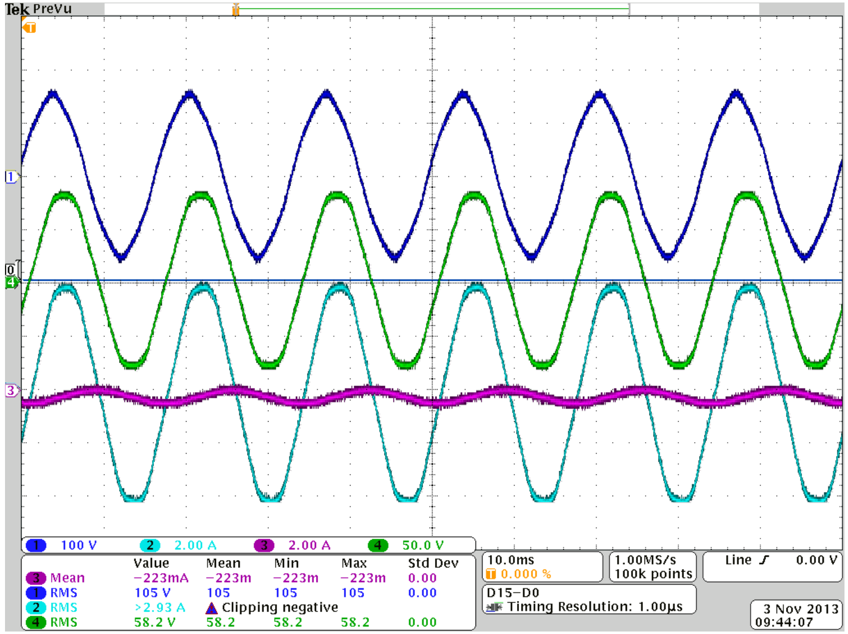
Scaled Hybrid AC/DC System Prototype

Prototype:



Scaled Hybrid AC/DC System Experiments

Before DC injection:



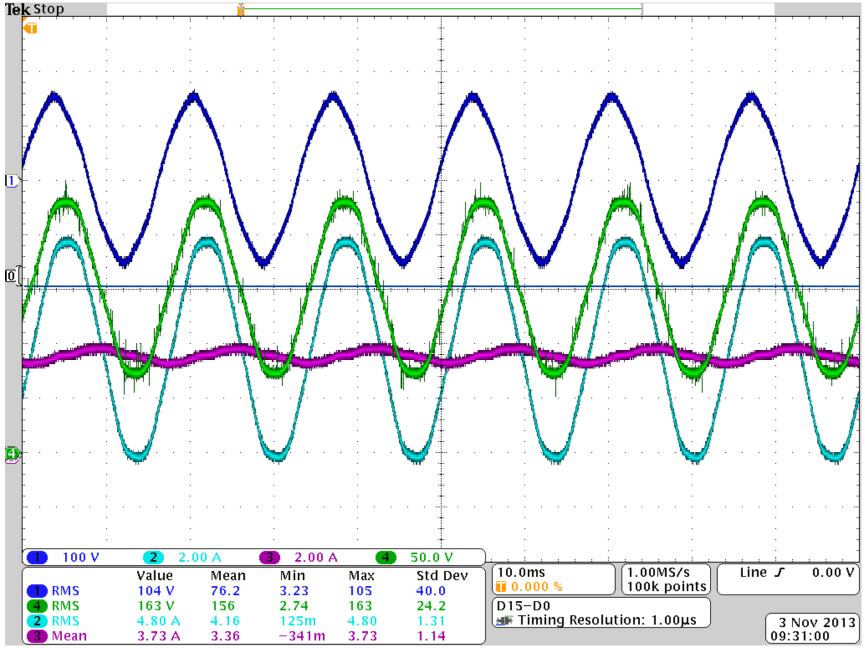
v_{AB} (100V/div)

i_a (2A/div)

i_{a_zig2} (2A/div)

v_{an} (250V/div)

After DC injection:



v_{AB} (100V/div)

i_a (2A/div)

i_{a_zig2} (500mA/div)

v_{an} (250V/div)

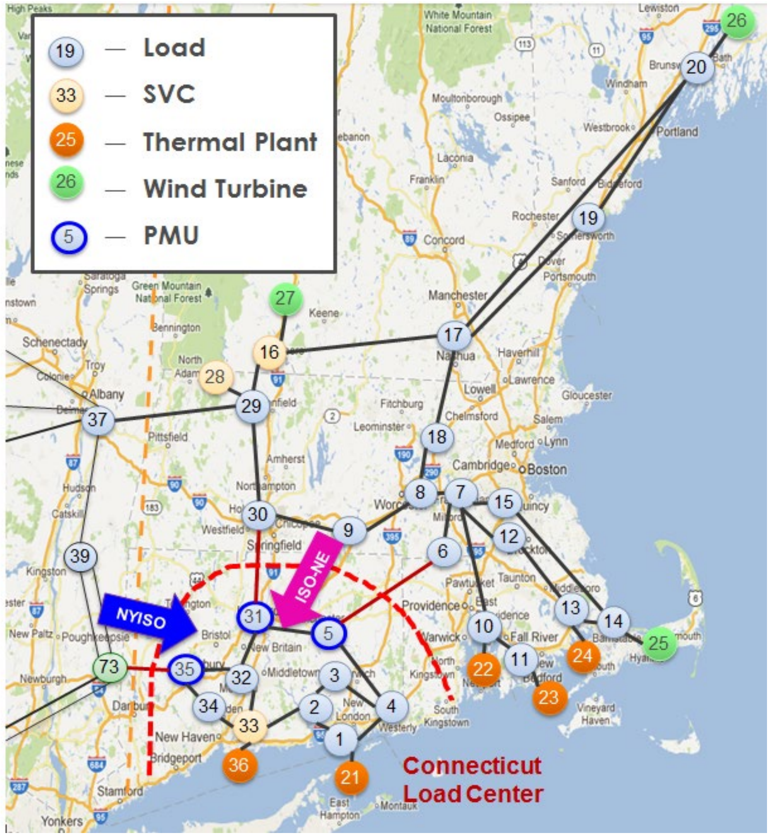
BTB AC grid voltage: 80V

Rectifier: V_{DC_ref} = 150V, Q_{ref} = 0var

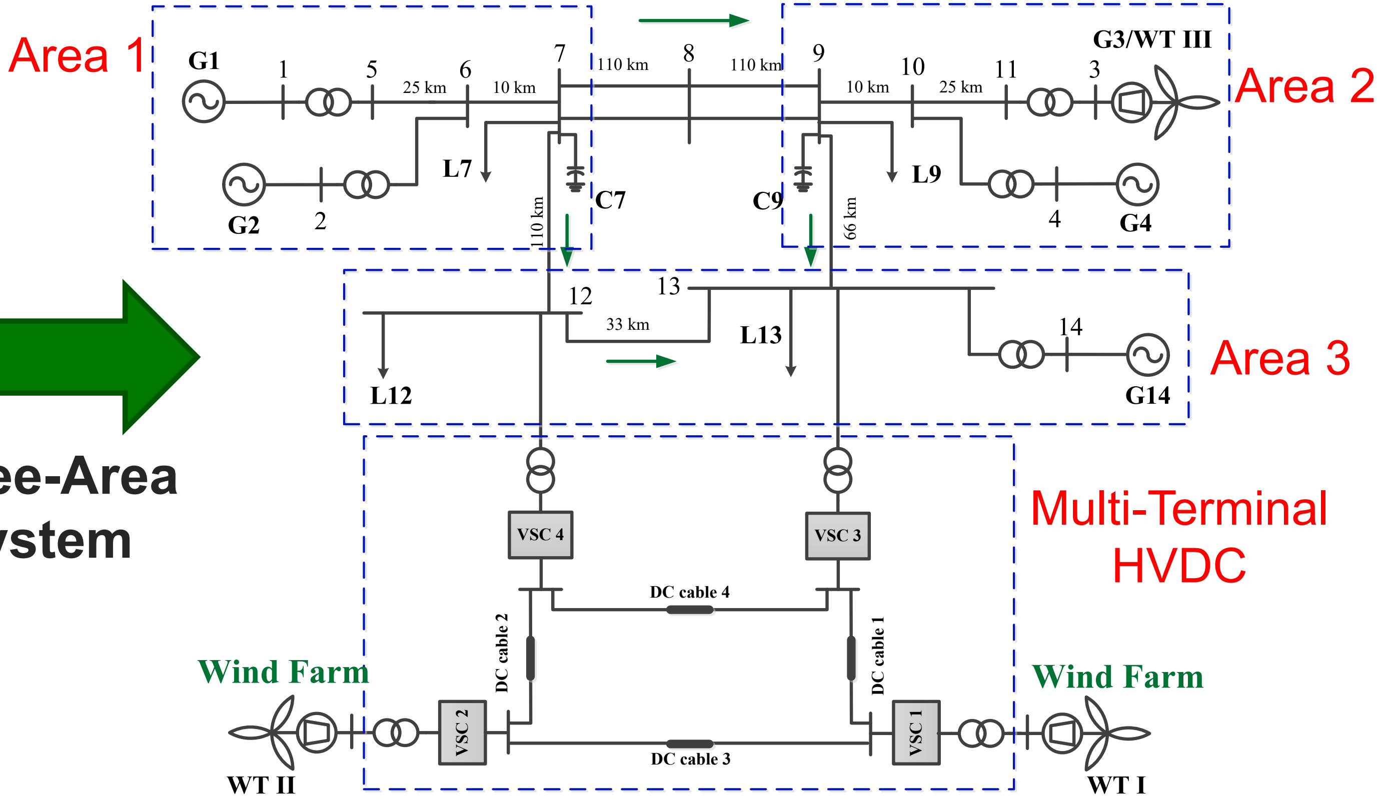
AC line voltage: 104V

Inverter: I_{DC} = 12A, Q_{ref} = 0var

HTB 3-Area Structure – NPCC Representation

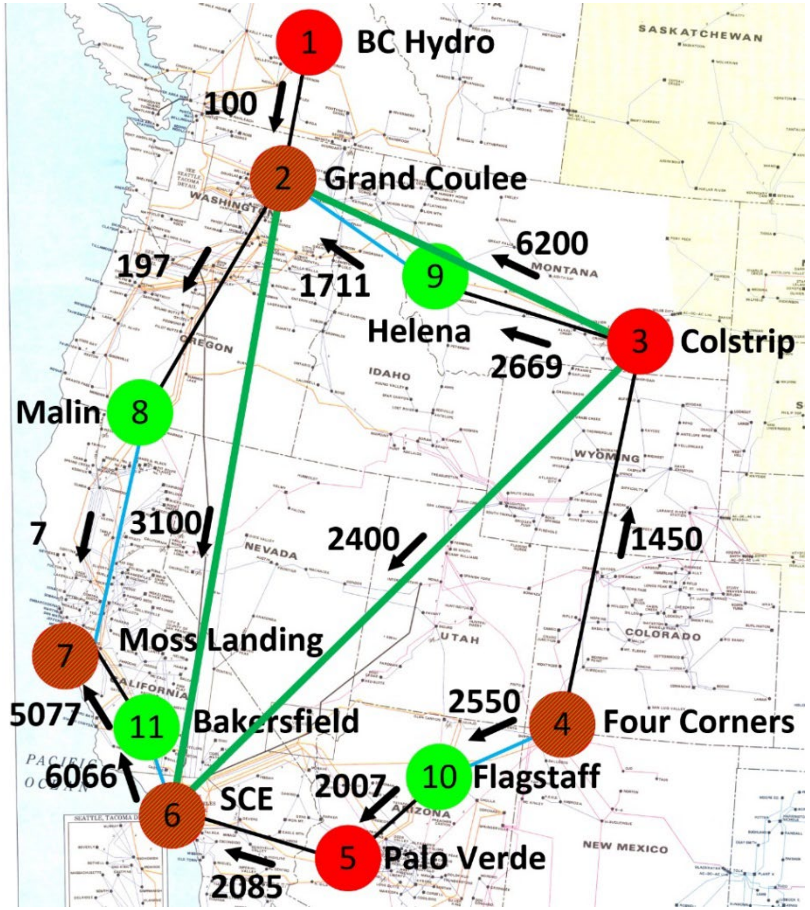


Three-Area System

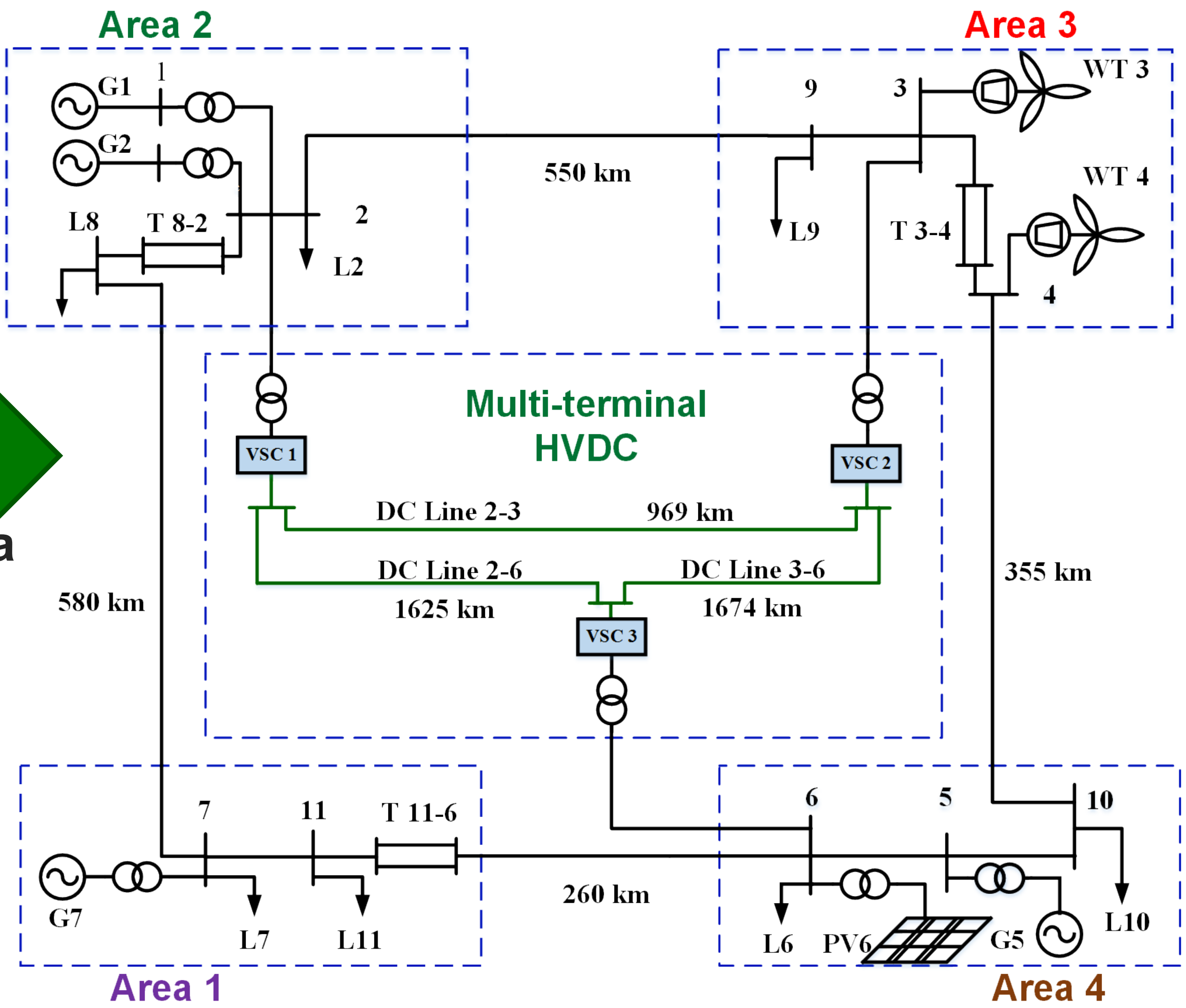


- Emulate various grid scenarios with interconnected clusters of scaled-down generators, loads, and energy storage.

HTB 4-Area Structure – WECC Representation



Four-Area System



Four-area WECC system including multi-terminal HVDC, high penetration of renewables

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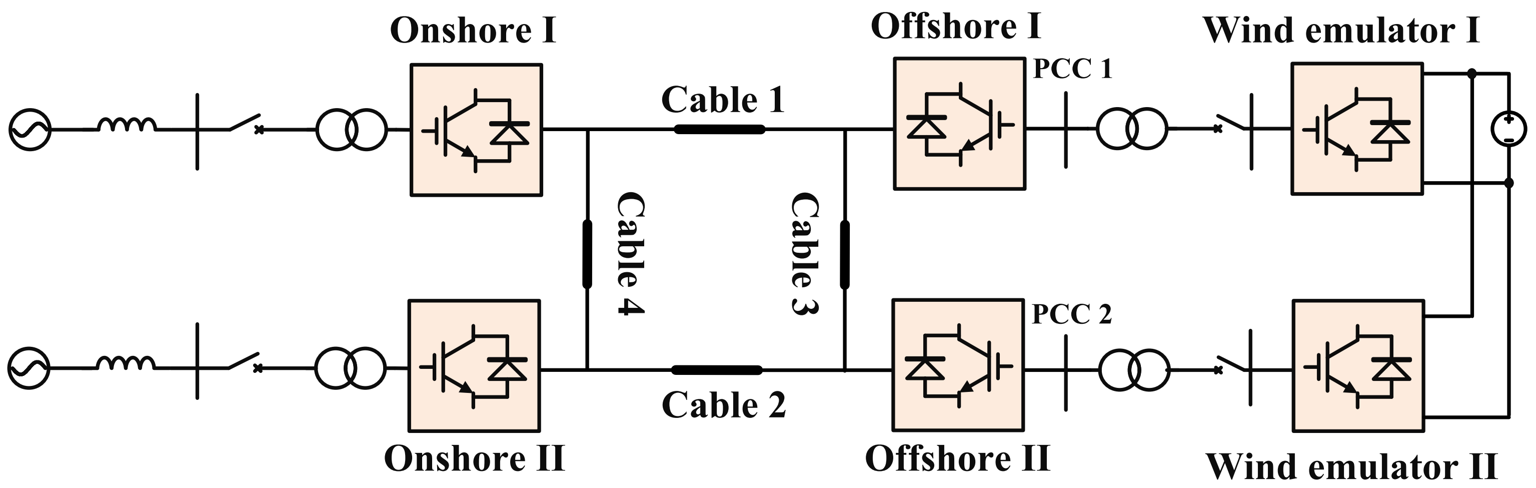
Multi-Terminal HVDC Testbed

Objective: Build a hardware platform for MT-HVDC system operation/control/protection development and demonstration

System Structure



MTDC Testbed Hardware

Testbed Capability on Scenario Emulation:

- System start-up
- Station online re-commission
- Wind farm power variation
- Station outage
- Transmission line trip
- Station online mode transition

Acknowledgements

Other government and industry sponsors are also acknowledged.

Thank You!

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