CURENT
CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

Overview of Actuation Thrust

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ECE 620 CURENT Course
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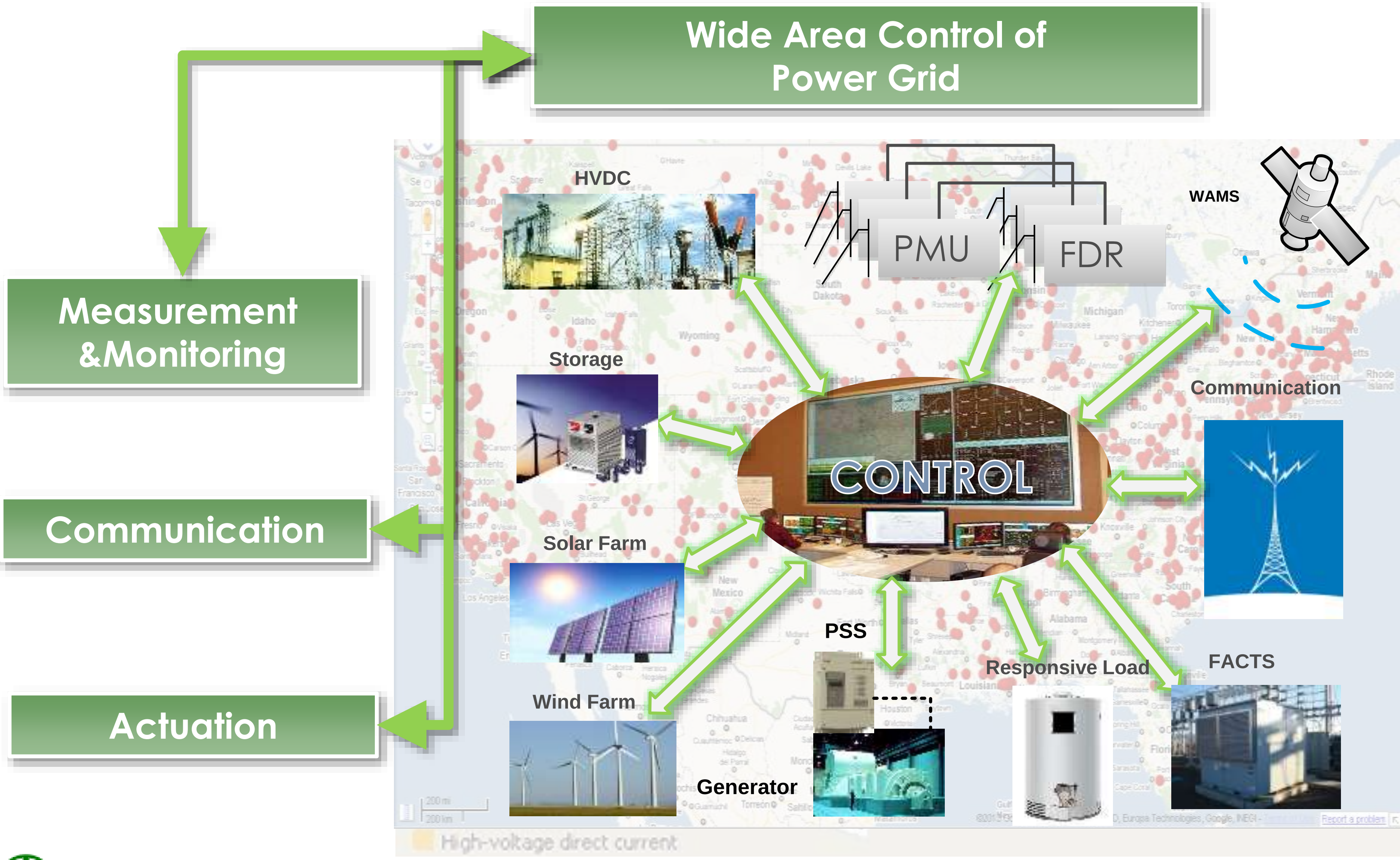
THE UNIVERSITY OF TENNESSEE KNOXVILLE · Northeastern · Rensselaer · TUSKEGEE UNIVERSITY

Actuation in CURENT



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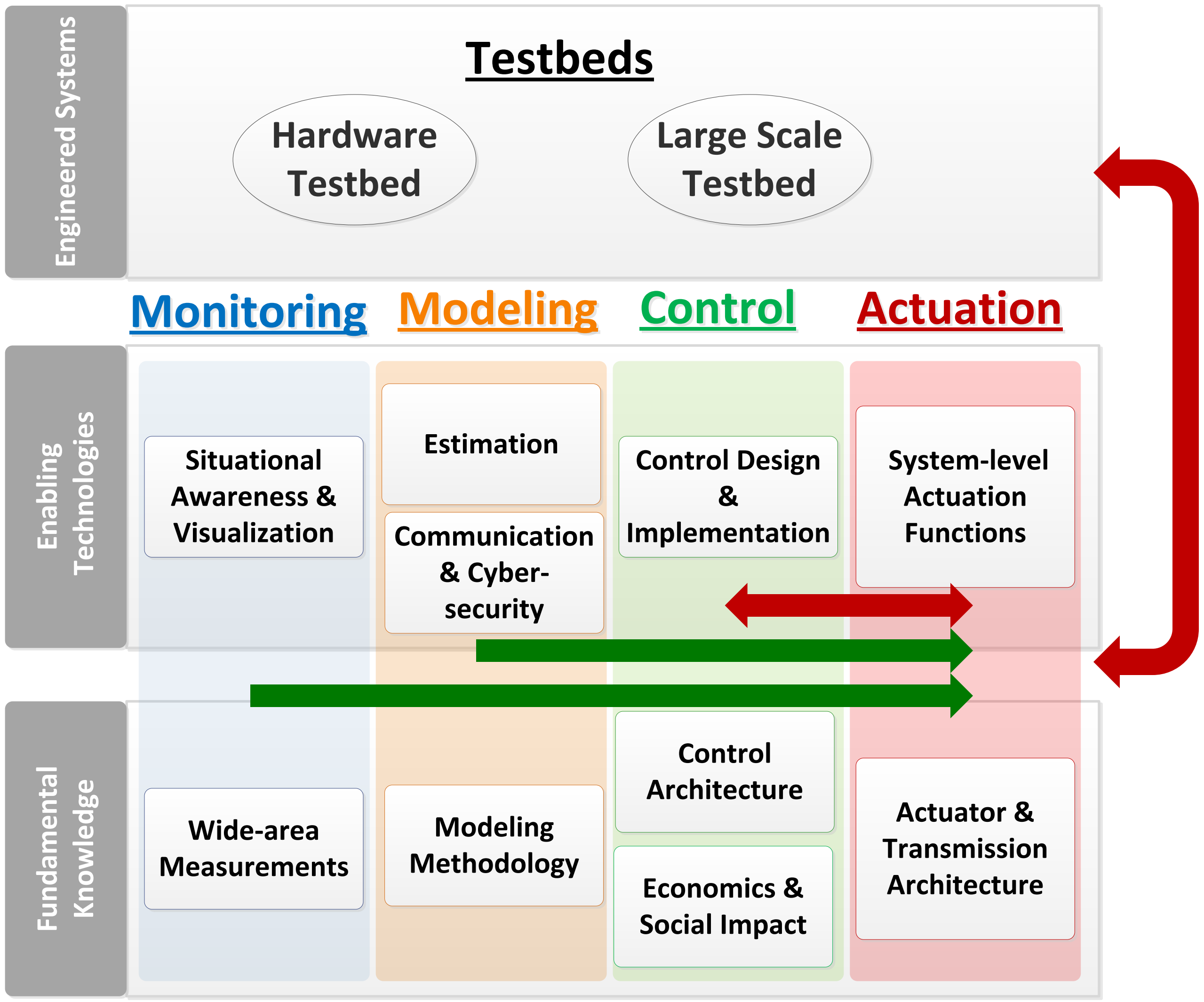
Actuation Technology Linkages



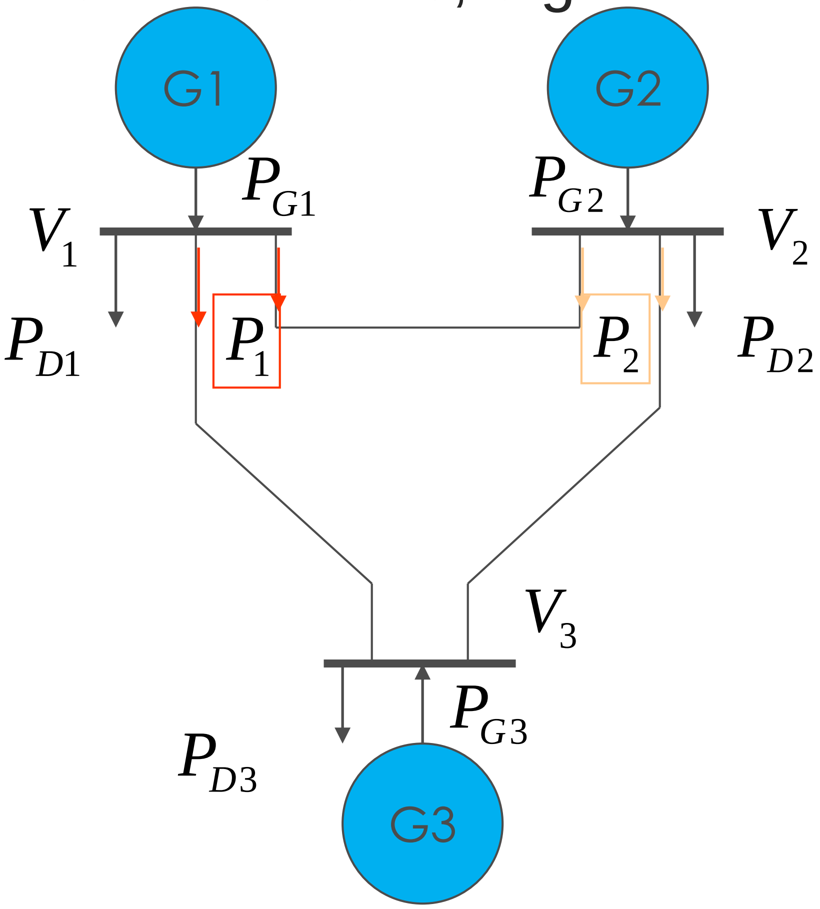
Basic Actuation Functions in Power Systems

- Power flow control
- Voltage and var support
- Stability
- Protection
  - Separation
  - Fault current limiting
  - Overvoltage suppression
- Energy source and load grid interface

Power Flow Control

- Power flow is determined by Kirchhoff's Laws, e.g.

$$P_{12} = \frac{V_1 \cdot V_2}{X_{12}} \sin(\delta_1 - \delta_2)$$



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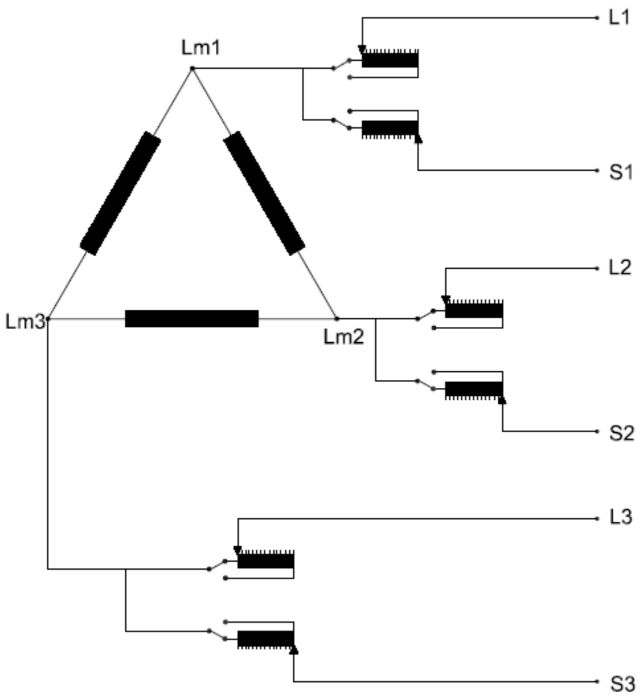
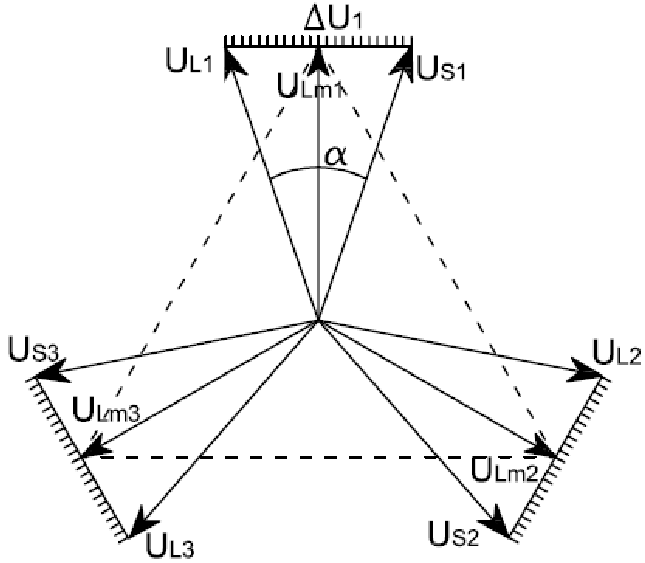
Non Power Electronics Power Flow Actuators

- Voltage
  - Generators (exciter control - PE)
  - Switched shunt capacitor banks
  - Transformer tap changer
- Impedance
  - Switched lines
  - Series compensation (switched series capacitors)
- Angle
  - Phase-shifting transformers

Example of Phase-shifting Transformers





- A direct, symmetrical PST with limited range and voltage magnitude change.
- There are also other types (e.g. indirect PST)

Non Power Electronics Voltage & Var Actuators

- Generator (exciter)
- Condenser
- Switched capacitor banks
- Transformer tap changer
- Load management

Non Power Electronics Actuator for Stability

- Generator
  - Governor
  - Power system stabilizer (excitation)
- Switchgear
  - Line switching
  - Source and load switching
- Switched compensators
  - Reactors
  - Capacitors

Protection - Breakers

Live-tank breakers

Dead-tank breakers

Breaker with Switching Resistors

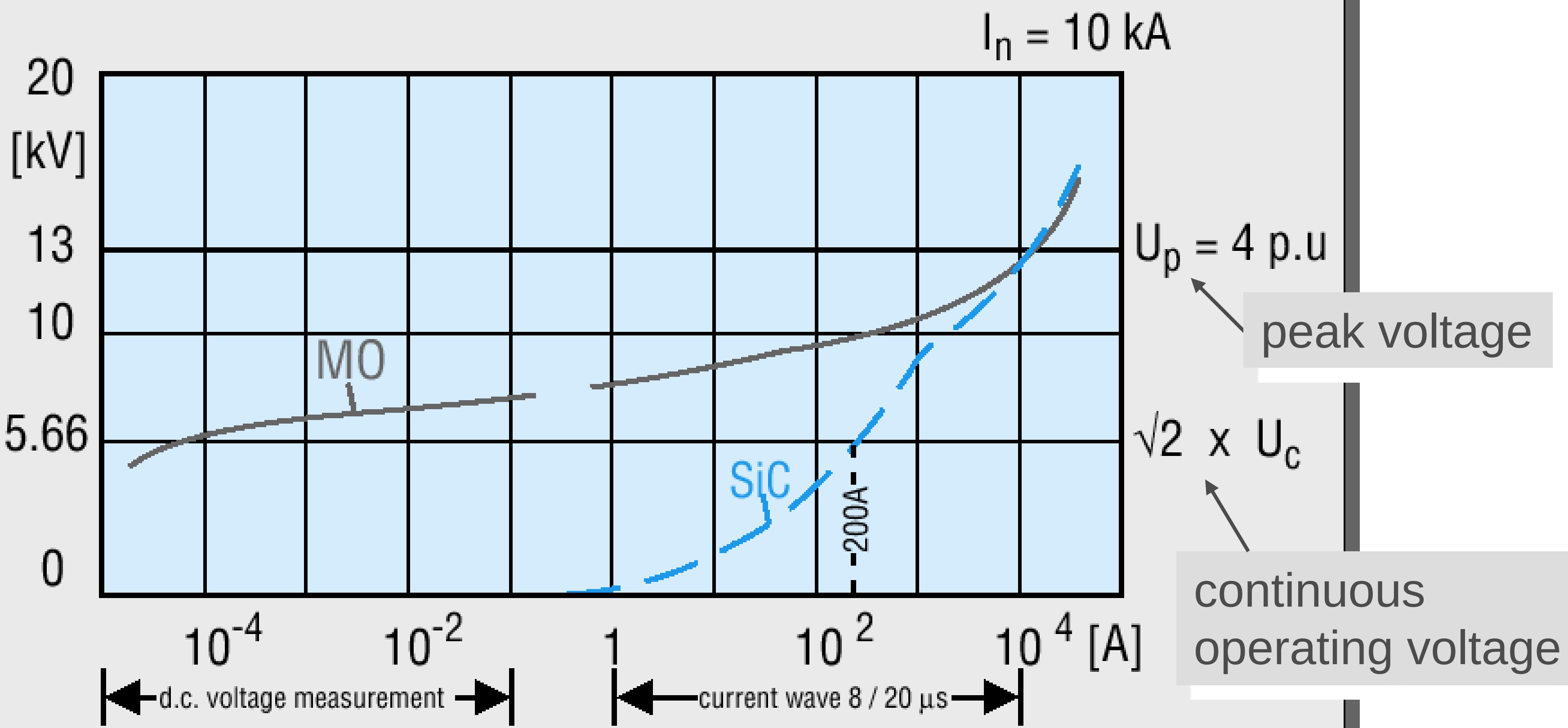
Switching resistors

Must absorb energy during switching
=> shorted after several ms!

Overvoltage Protection

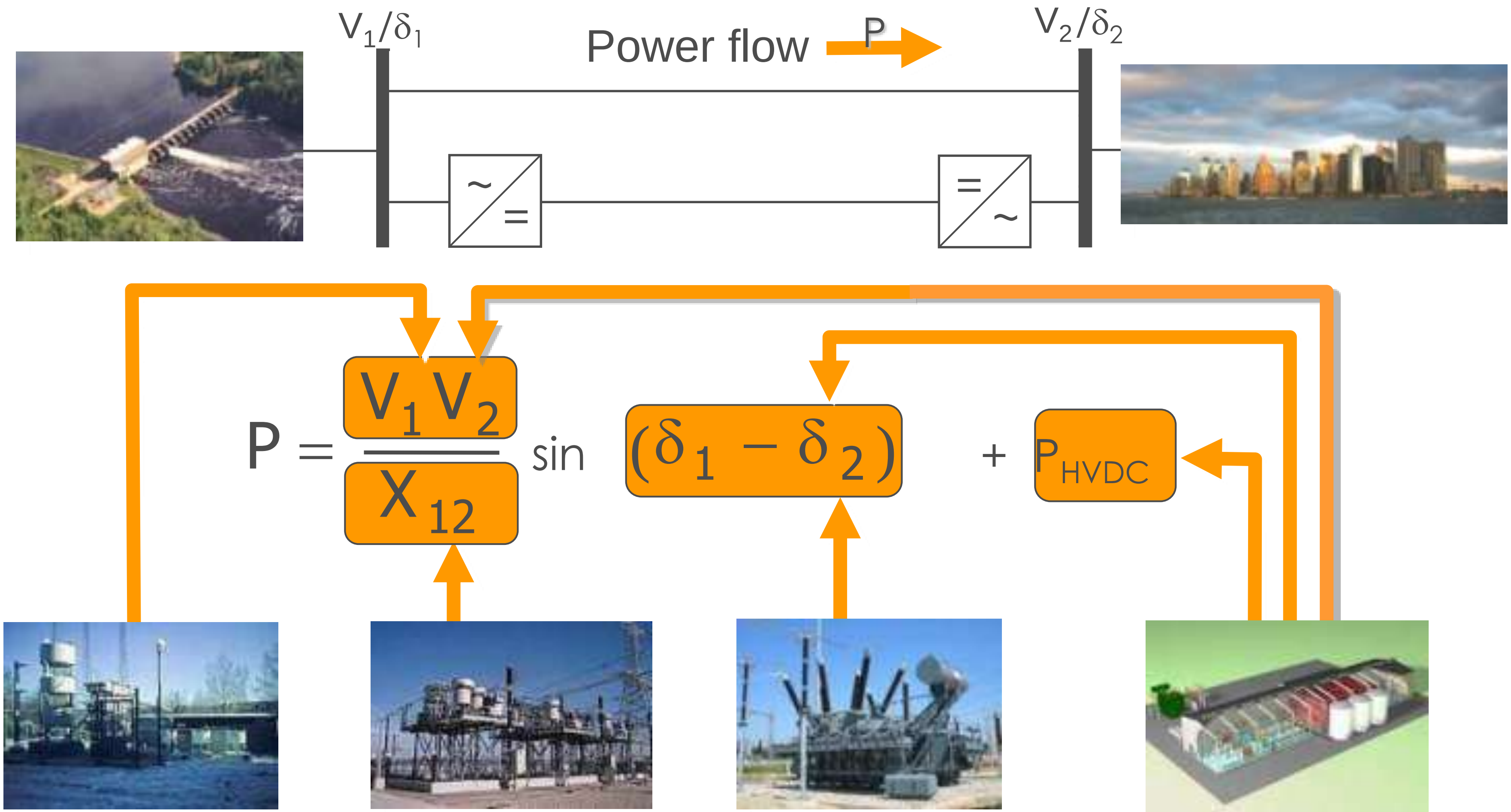
- Spark Gaps
  - Metallic electrodes providing a gas insulated gap to flash over
  - Very robust, but large variance in protection level
- Magnetically blown Surge Arresters
  - Same basic principle as spark gaps, adopt SiC varistors but can handle much higher energy dissipation
- Metal Oxide Varistor (MOV)
  - Ceramic composites based on zinc, bismuth, and cobalt
  - Highly non-linear current-voltage characteristic $I = V^{\alpha} \quad \alpha > 20$
  - Very precise and stable protection level
  - Limited overload capability

Metal Oxide Varistor (MOV)



Semi-logarithmic plot of the current-voltage characteristics of MO and SiC resistors for U_c = 4 kV

Power Electronics Based Power Flow Control



Static Var Compensation (SVC)

Series Compen-sation (SC)

Phase Shifting Transformers

HVDC and HVDC Light

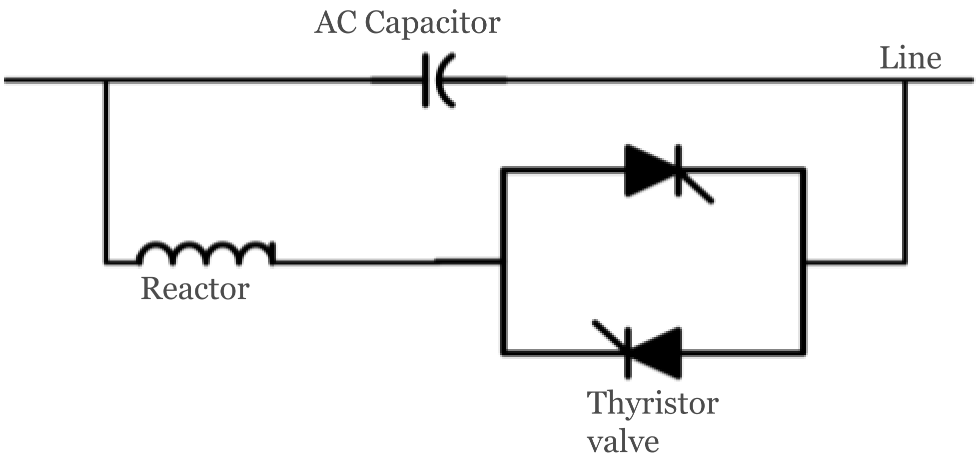
FACTS = Flexible AC Transmission System

Power Electronics Power Flow Actuator

- **Voltage**
  - SVC (Static Var Compensator)
  - STATCOM (Static Synchronous Compensator)
- **Impedance**
  - TCSC (Thyristor Controlled Series Compensator)
  - SSSC (Static Series Synchronous Compensator)
- **Angle**
  - TCPFT (Thyristor Controlled Phase-shifting Transformers or Angle Regulator)
- **All**
  - HVDC
  - UPFC (Unified power flow controller)

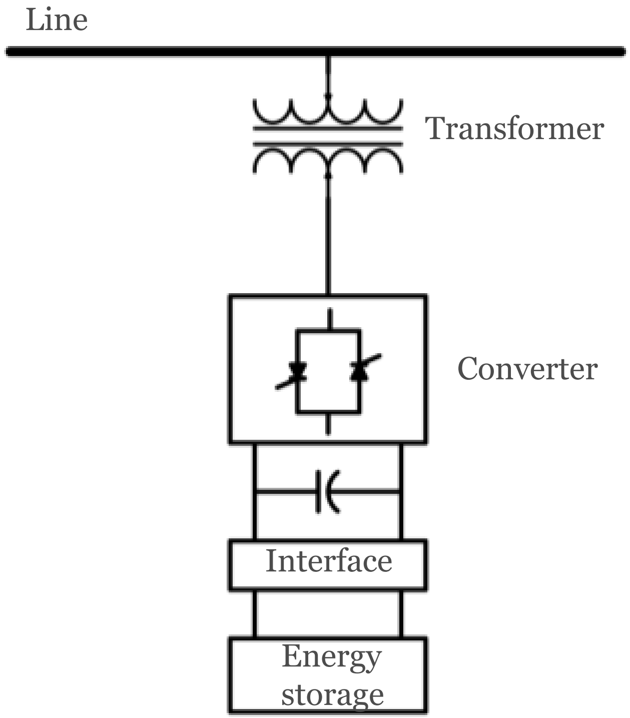
Thyristor Controlled Series Capacitor (TCSC)

- A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.
- Can be one large unit or several small ones. Limits fault current when reactor is fully on.



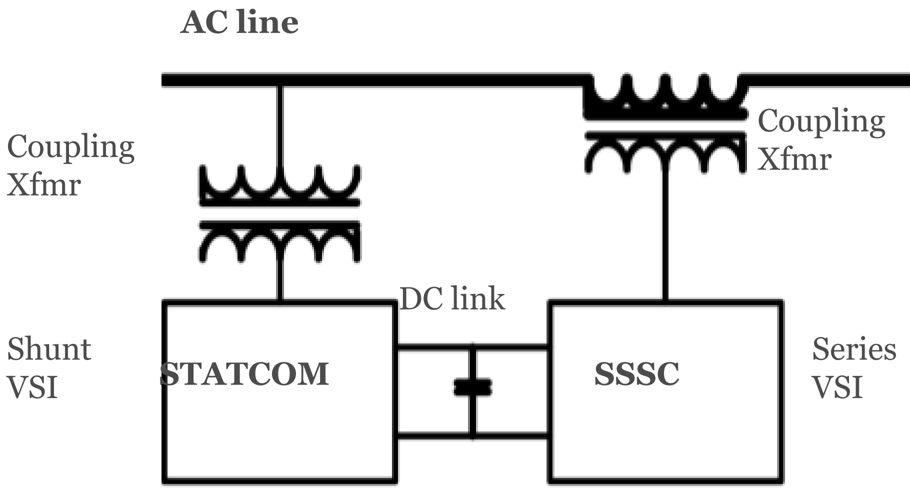
STATCOM and SSSC

- A static synchronous generator operated without an external electric energy source
- Can be shunt or series connected
- As a shunt compensator, can inject reactive power
- As a series compensator , its voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power.



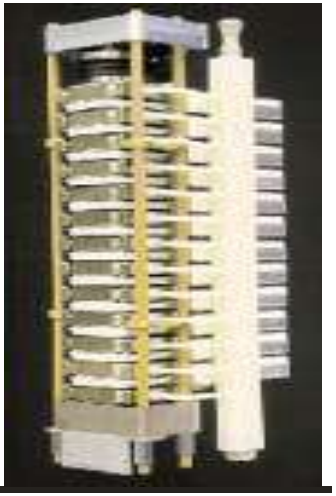
Unified Power Flow Controller

- The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive power flow in the line.
- The UPFC may also provide independently controllable shunt reactive compensation.



HVDC Technology Development

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



Year

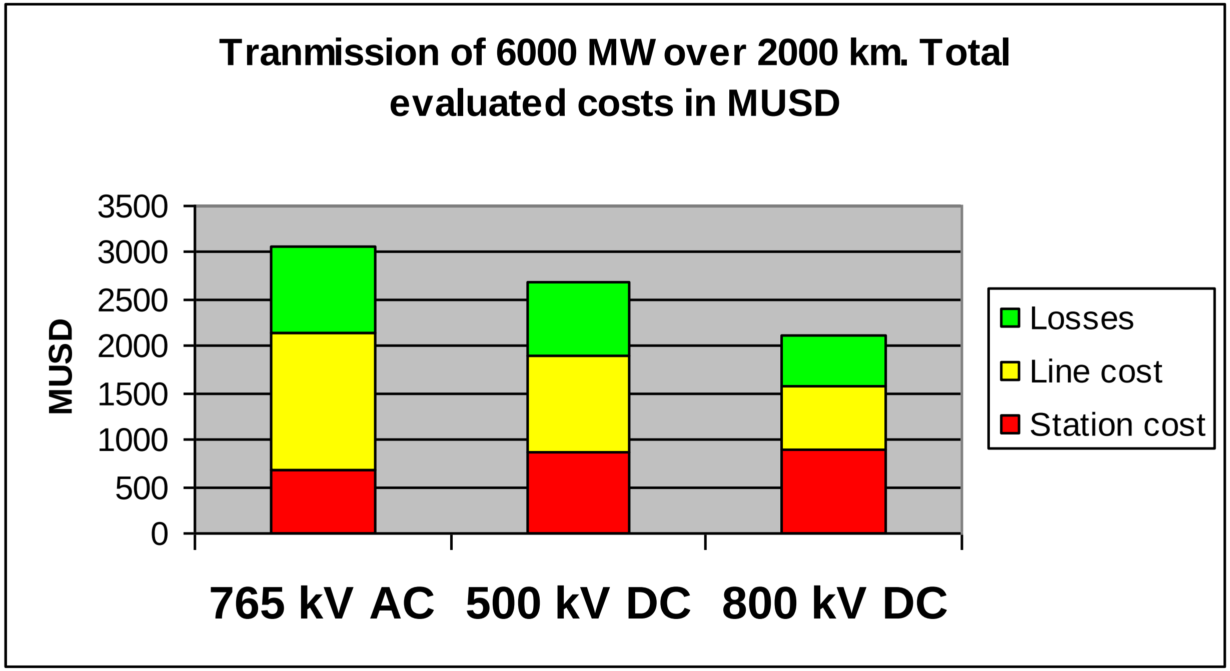
1954 1970 1980 2000

Pros: Low losses
Cons: Reliability
Maintenance
Environment

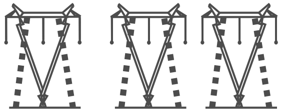
Pros: Reliable
Scalable
Cons: Footprint

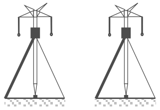
Pros: Controllability
Footprint
DC Grids
Cons: Losses

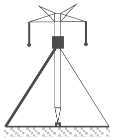
800 kV DC for long distance bulk power transmission



Number of lines:			
Right of way (meter)	~300	~ 120	~ 90







Power Electronics Actuator for Stability

1st Thyristor-Controlled Series Compensation (TCSC) Project

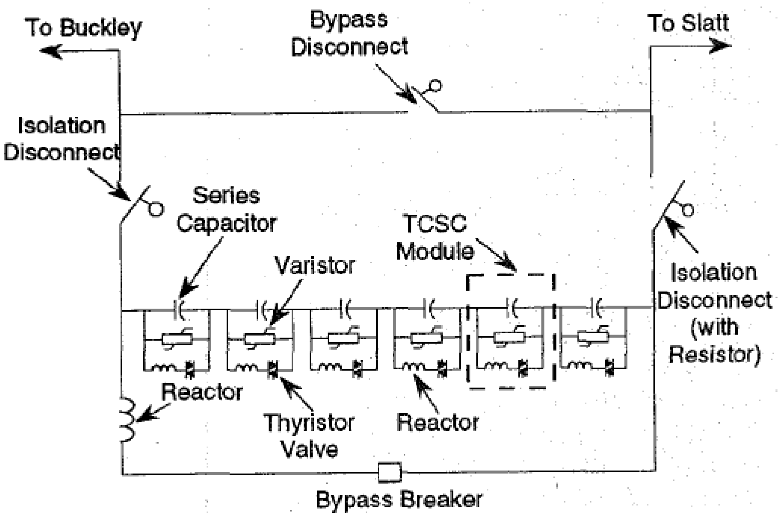


Fig. 1. One-line diagram of Slatt TCSC.

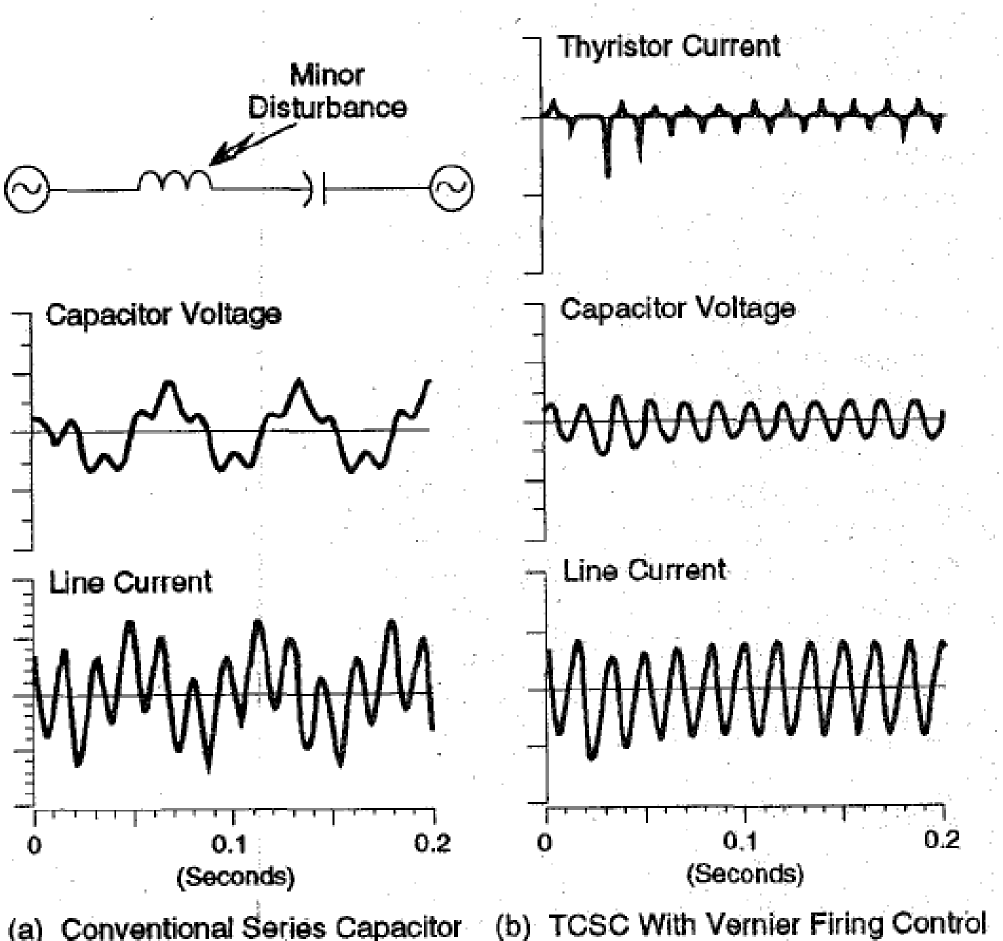


Fig. 2. Example of TCSC damping subsynchronous electrical oscillations.

Power Electronics Actuator for Protection

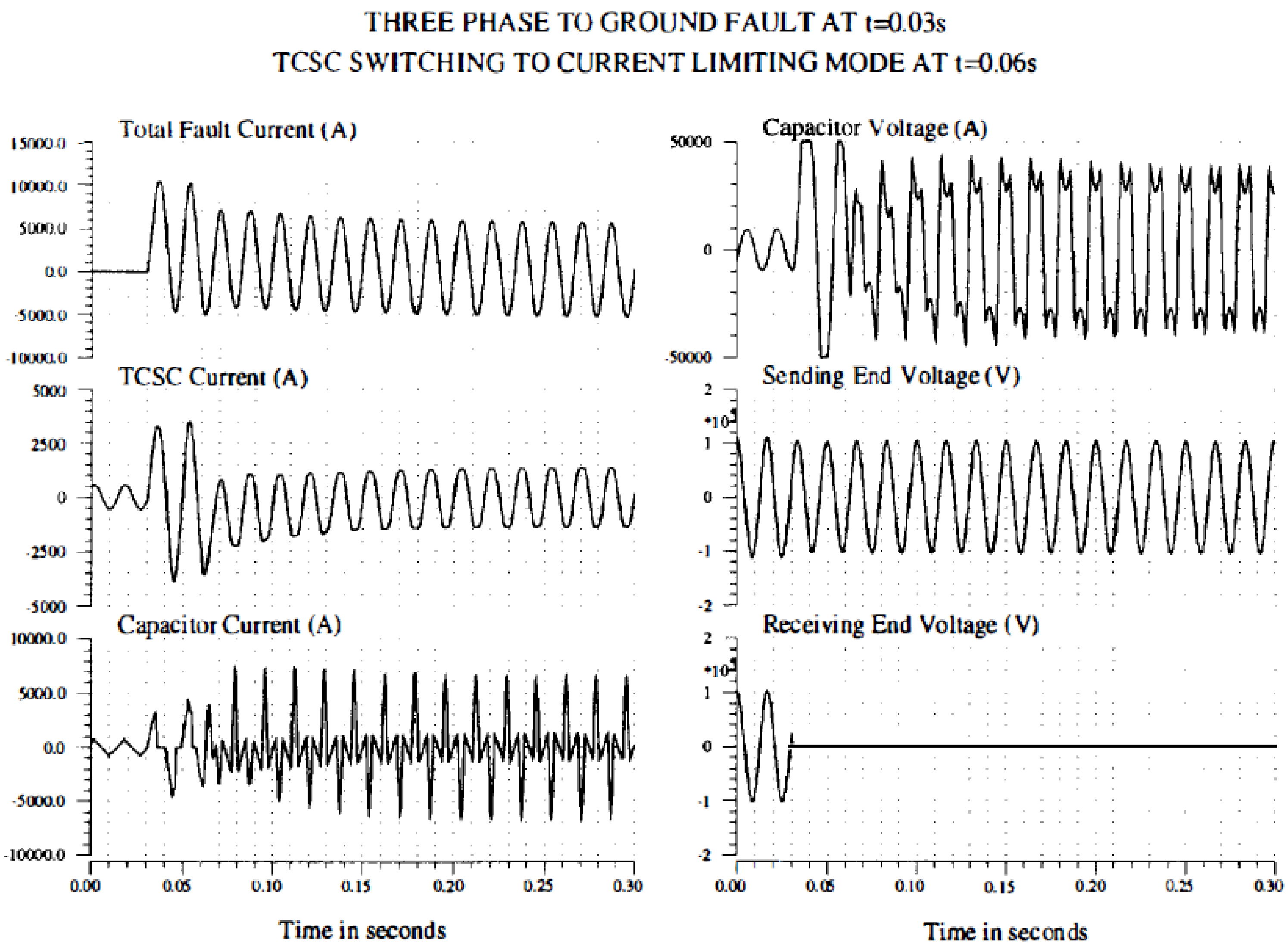
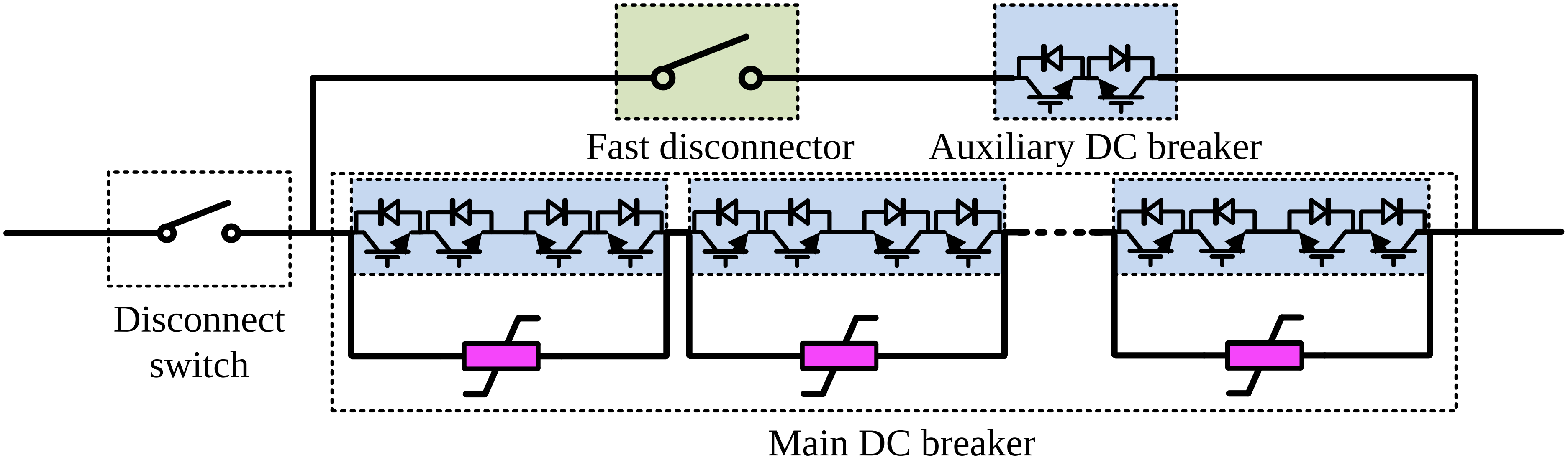


Figure 7. TCSC Fault Current Limiting Capability Demonstration

VSC HVDC DC Fault Protection – Solution

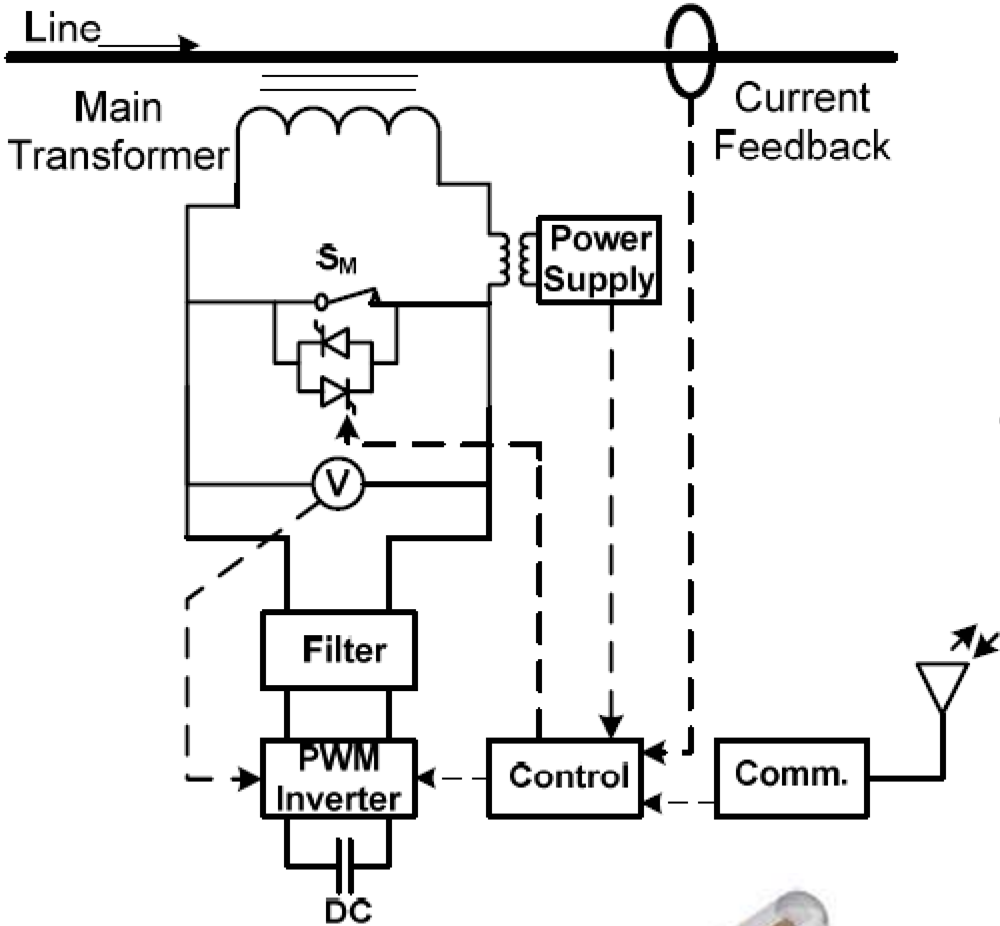
- Fast fault clearance solution (<5 ms)
  - ABB method: Hybrid DC breaker



Summary of Actuation Technologies

- Traditional non power electronics based actuators have limited actuation capability. The system is generally not very flexible
- PE based actuators (FACTS, HVDC) can be very effective for
  - Power flow control
  - Voltage and var control
  - System stability
  - Protection
  - Interface of source and load
- Issues: cost, reliability
- Solutions: new PE technology, modular approach, hybrid approach, different architecture

Modular Approach - Distributed FACTS



Distributed Series Static Compensator

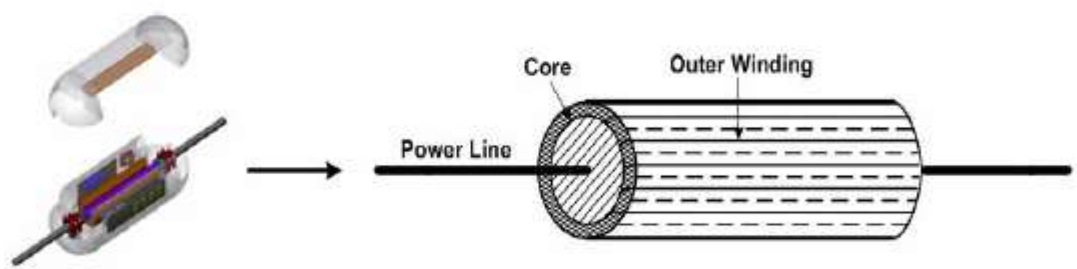
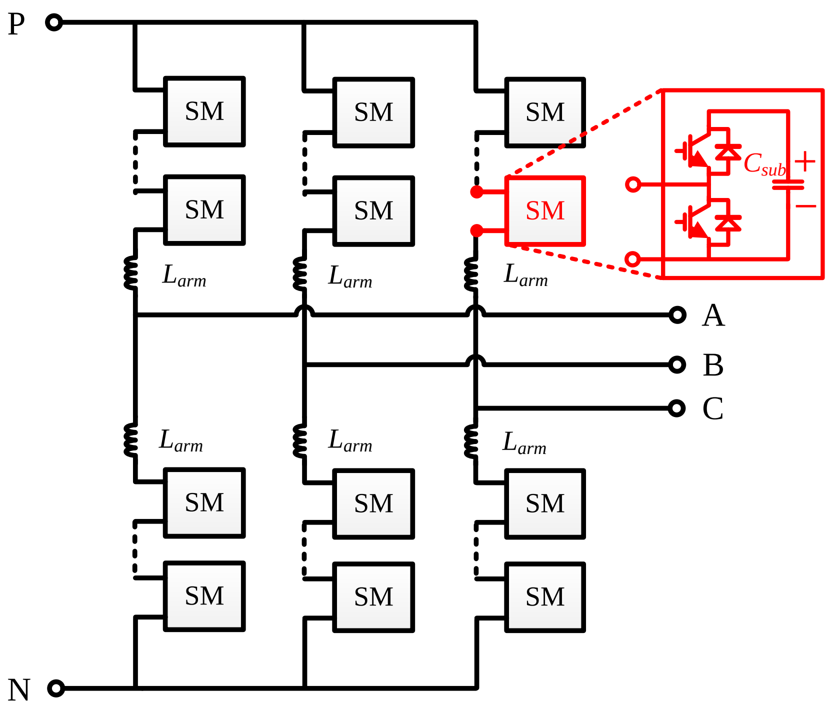


Figure 4. Single Turn Coaxial Transformer

Modular Converters for Multi-Terminal HVDC Systems

Modular multilevel converter (MMC)



Hybrid Approach - Thin AC Converter

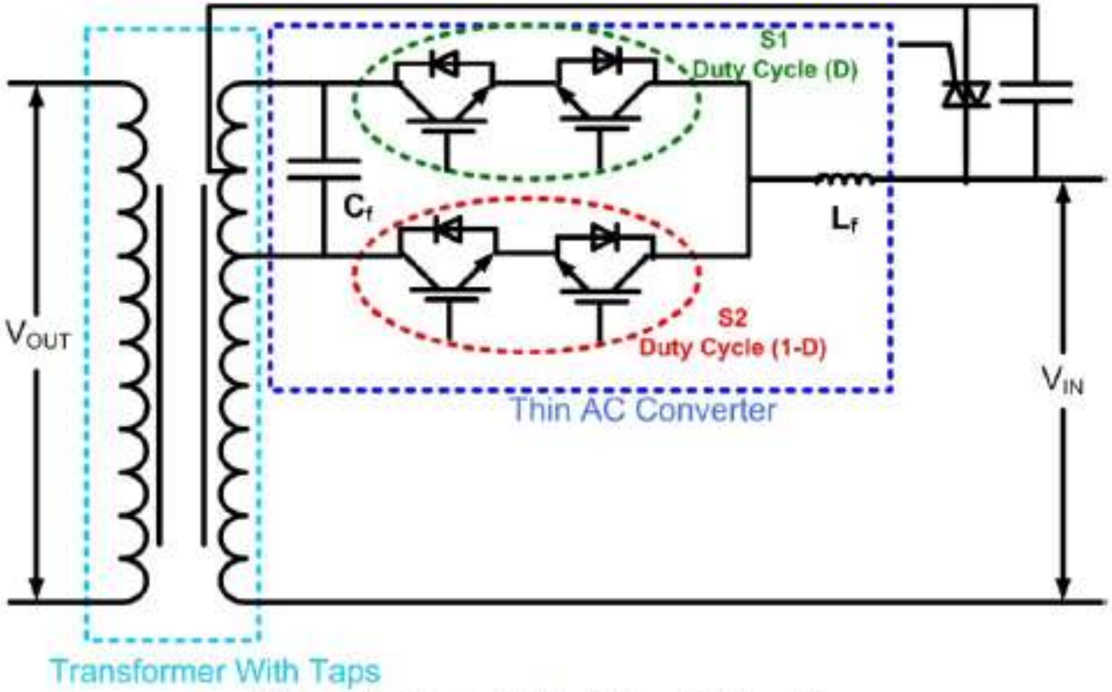


Figure 1: Controllable Network Transformer

Actuation Thrust Objectives and Challenges

- **Objectives**
  - Develop actuation methodology and system architecture that will enable wide-area control in a transmission grid with high penetration of renewable energy sources

- **Challenges**
  1) Lack of cost effective wide-area system-level actuators
  2) Lack of global actuation functions for the existing actuators or lack of knowledge how to use these actuators for global functions
  3) System architecture not best suited for wide-area coordinated actuation and control for network with high penetration of renewable energy sources
  4) Lack of design and control methodologies for systems with power electronics converters interfacing a high percentage of sources and loads

Technical Approaches and Research Focus

- **Multifunctional actuators to exploit full capabilities of existing or future actuators**
  - Renewable energy sources supporting system control
  - FACTS, HVDC
- **Flexible and controllable transmission architecture**
  - Hybrid AC/DC
  - Multi-terminal HVDC

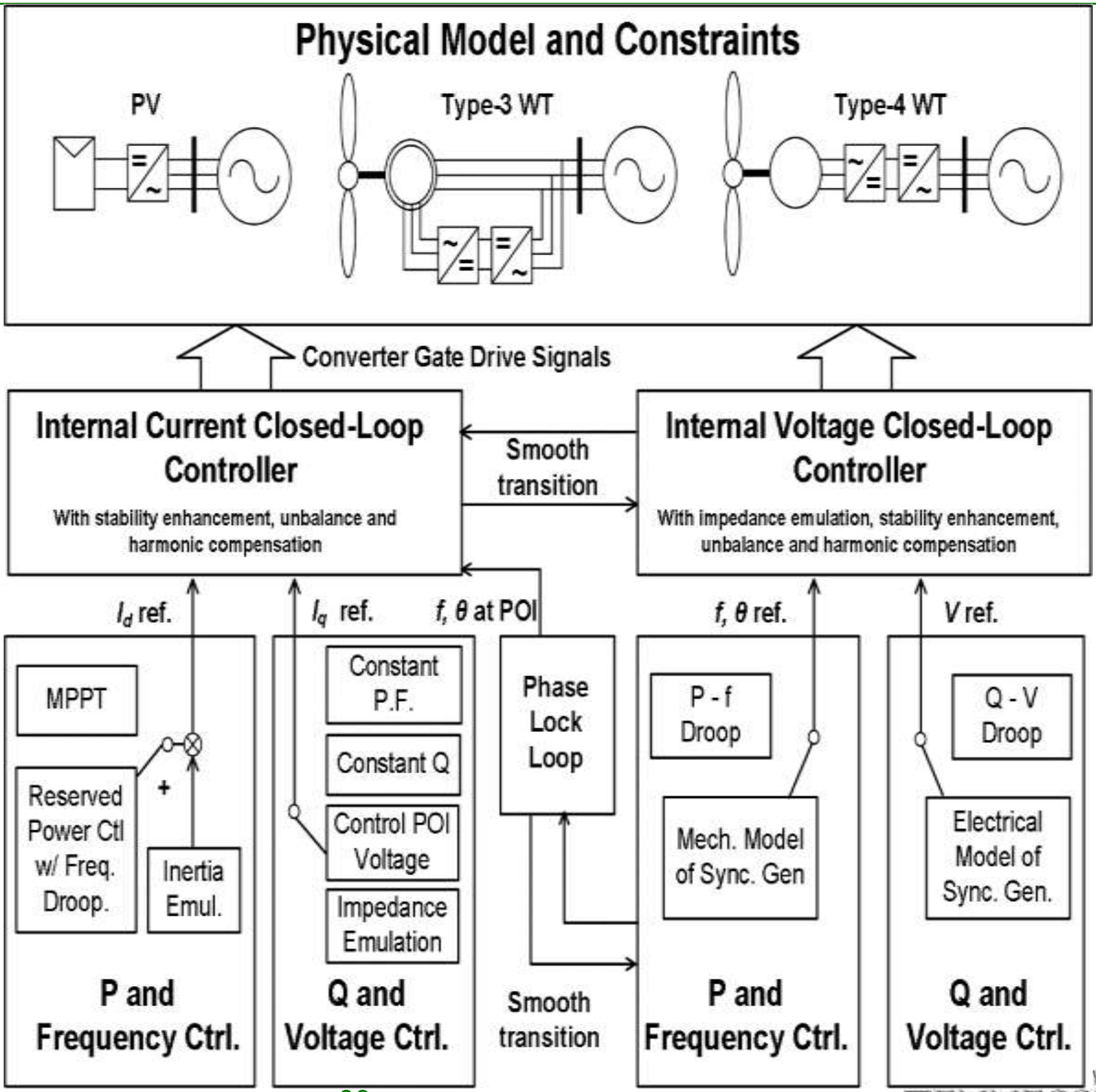
Renewable Energy Sources for Grid Support

Objective:

- Demonstrate grid supporting capability of renewable energy sources and energy storage in systems with >50% of renewables

Accomplishments:

- Renewable energy sources and energy storage working modes implemented in simulation & HTB



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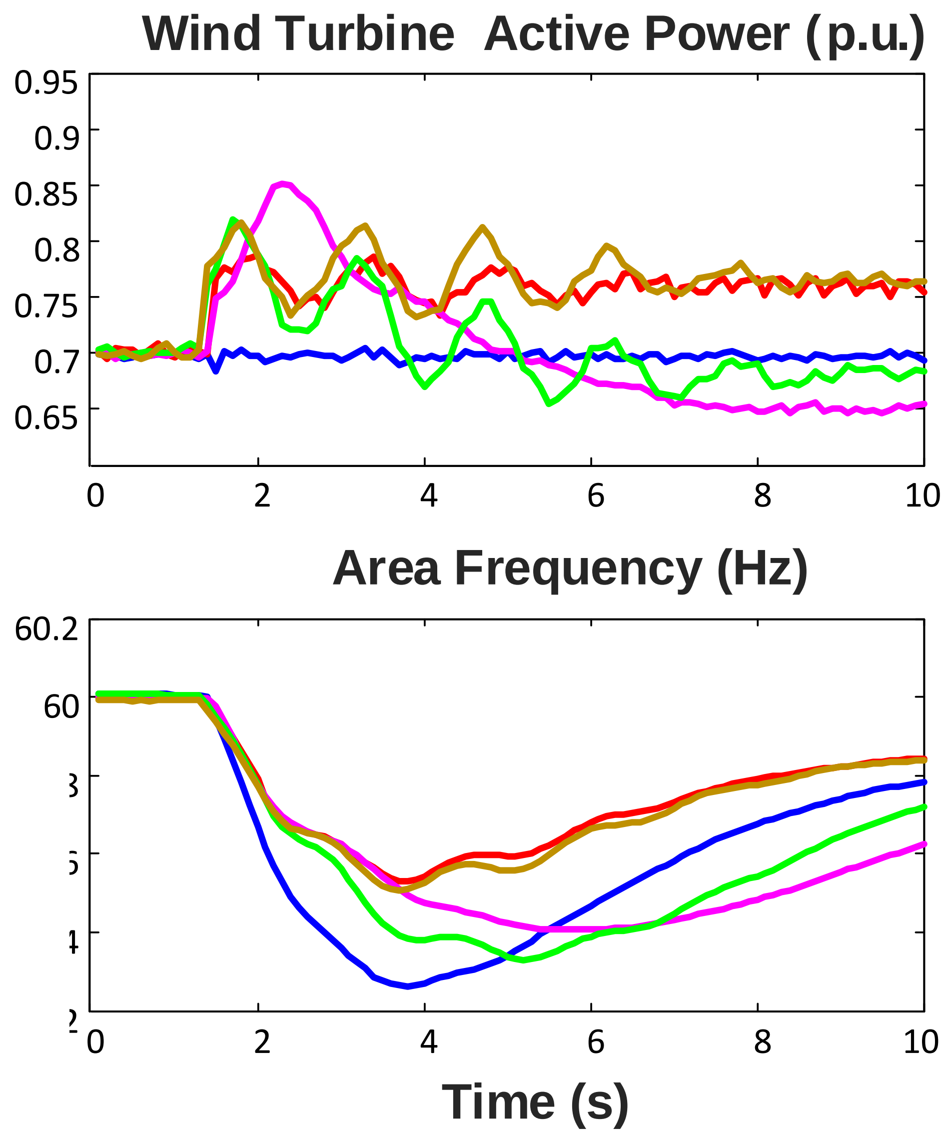
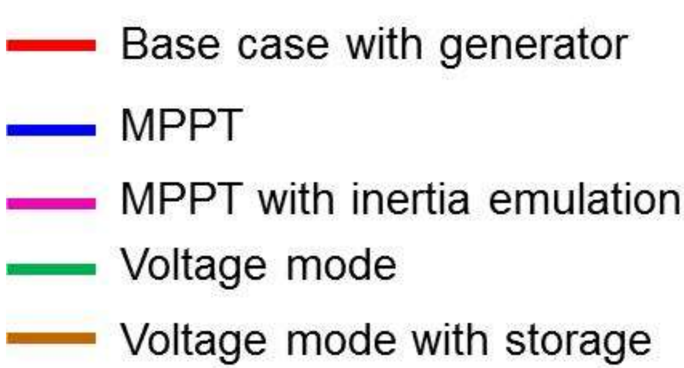
Frequency Support Function Test in HTB

Scenario

- 80% renewable by onshore wind & offshore wind through HVDC
- Event triggered by a HVDC converter failure.
- Frequency and voltage support from onshore wind farm and the HVDC converters
- Curtailment and voltage mode control when necessary
- Integration of energy storage to further enable grid support controls





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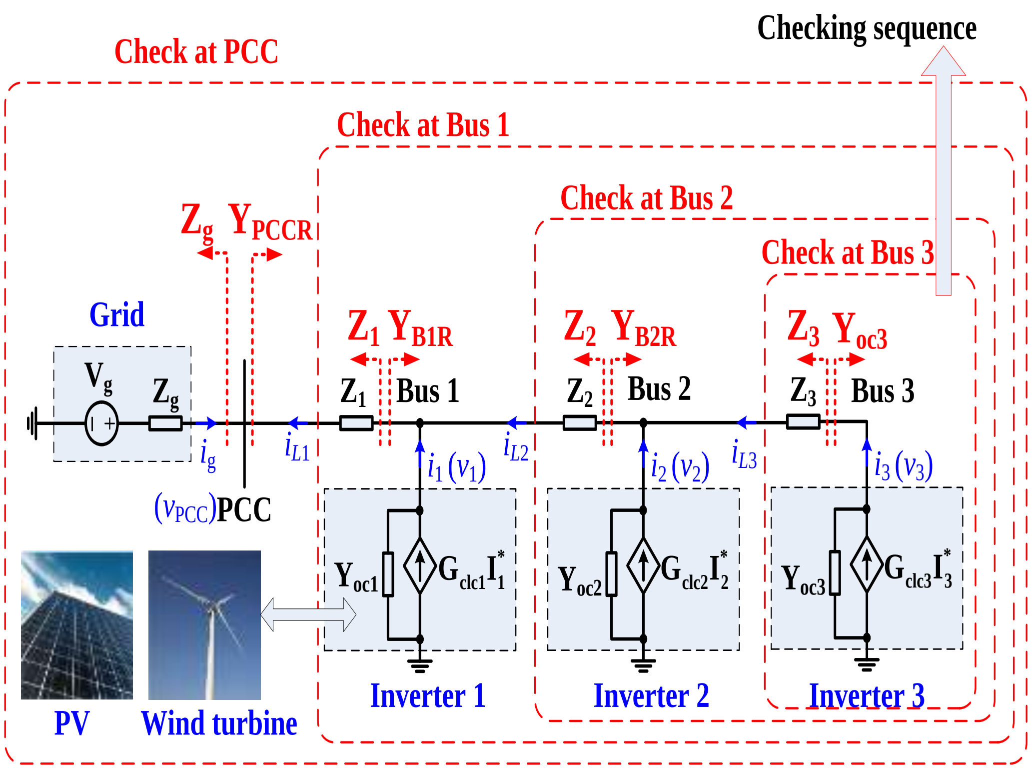
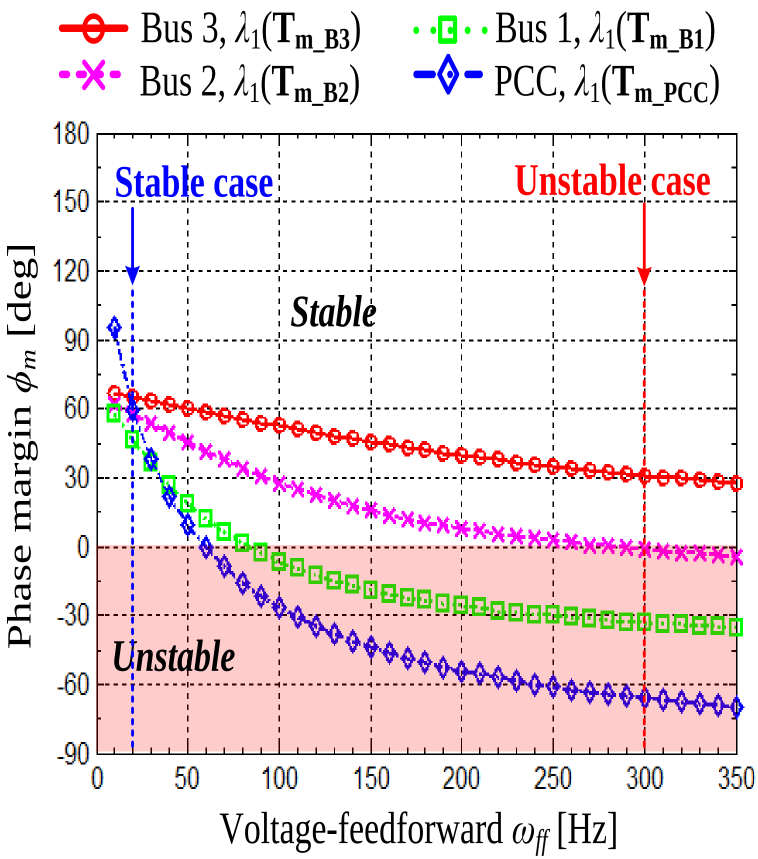
Design of Renewable Interface Converters Considering Stability

Objective: Develop stability criterion and design methodology of renewable interface converters to ensure stable operation of multi-bus systems with renewable energy sources.

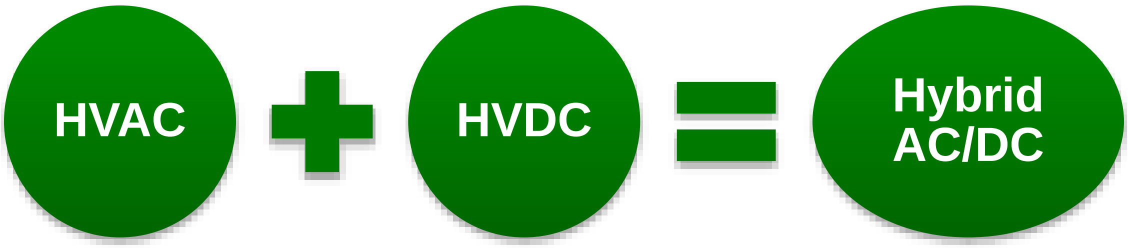
Grid-Connected Radial-line Renewable System Stability

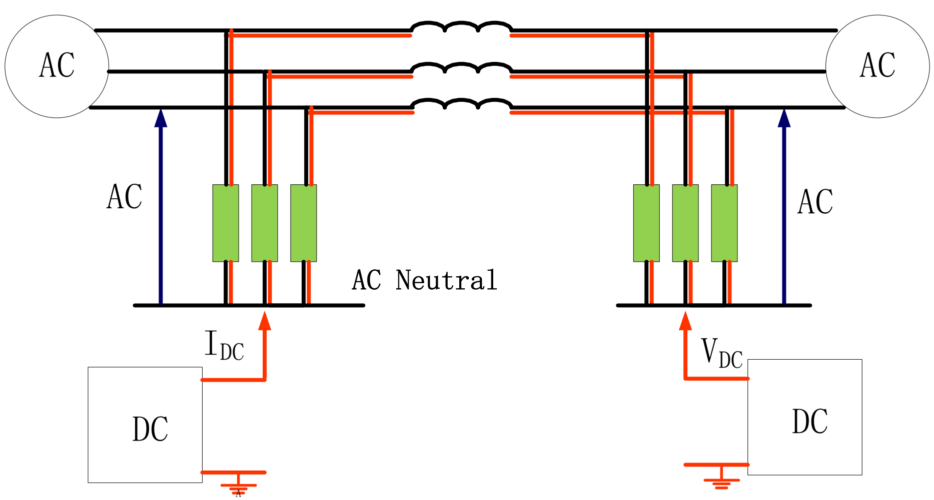


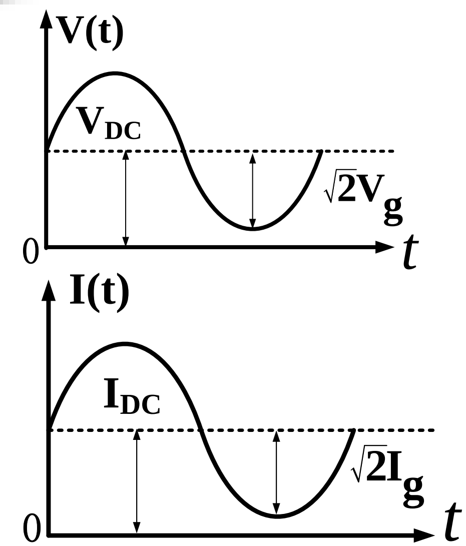


Hybrid AC/DC Transmission

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

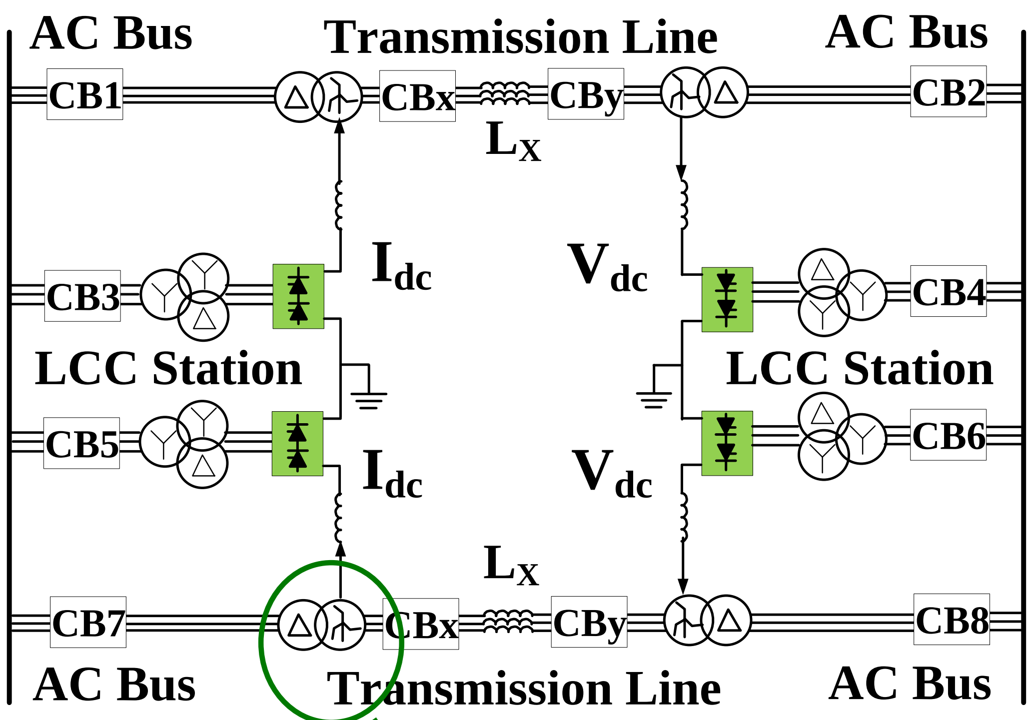




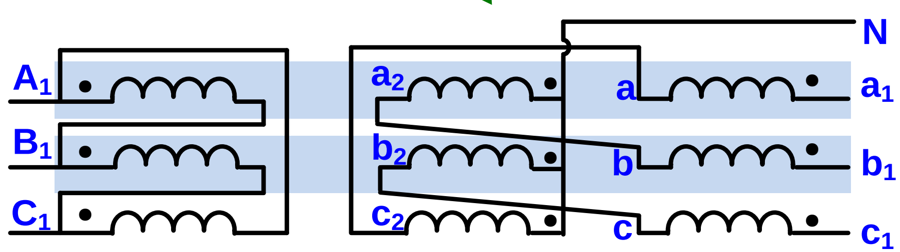


Basic Concept of Hybrid AC/DC System

System topology:



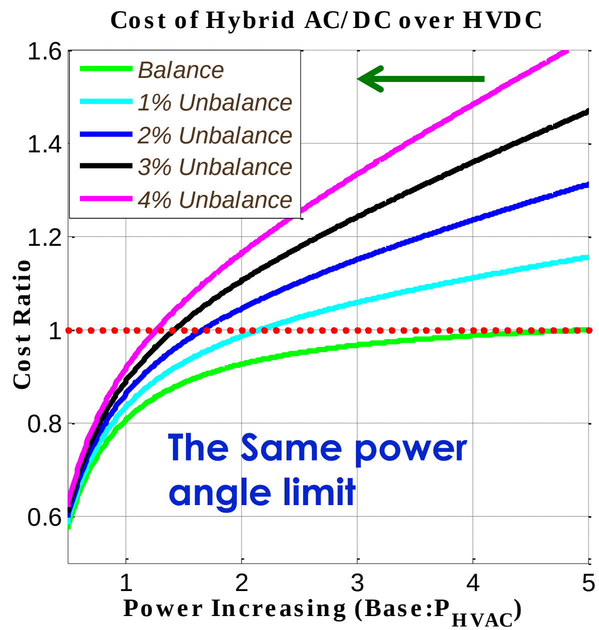
DC injection link: zigzag transformer

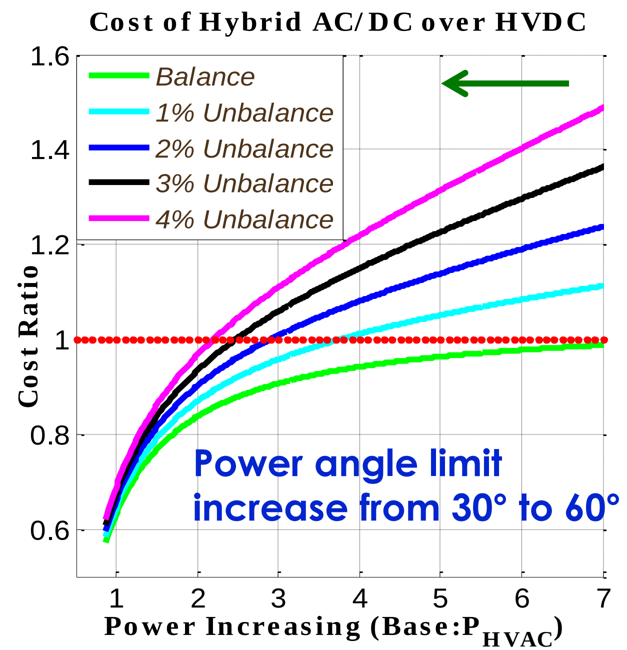


Benefits and Issues

Benefits:

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





Issues:

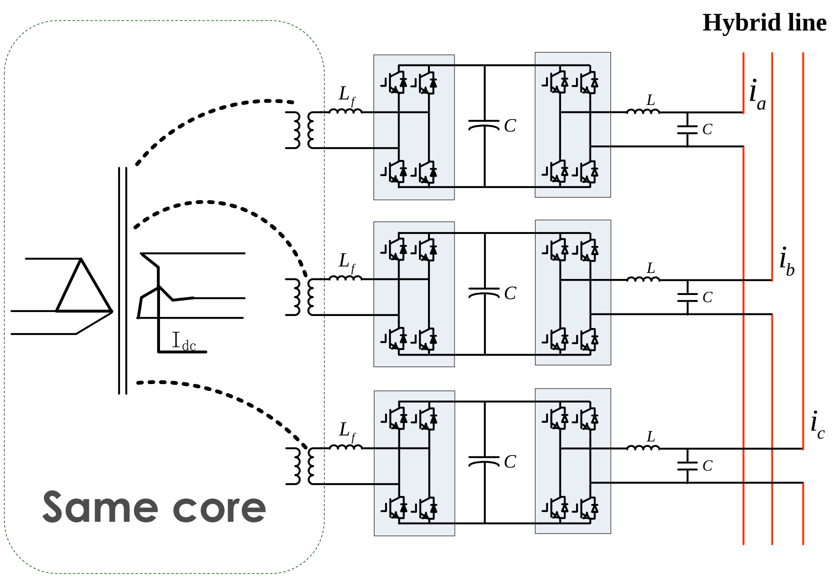
- Zigzag transformer may be saturated with unbalanced AC line resistance, due to the uncanceled DC flux within zigzag windings.
- Neutral point of zigzag transformer needs extra insulation to withstand dc bias voltage

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)

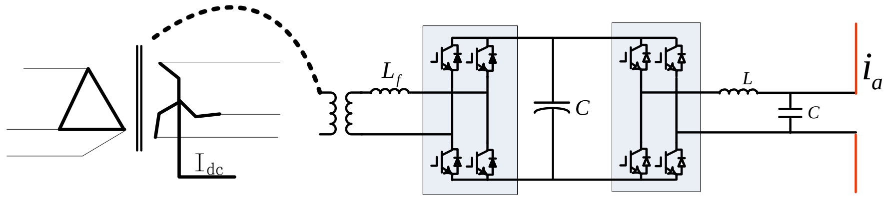
Adjust the line resistance by phase.

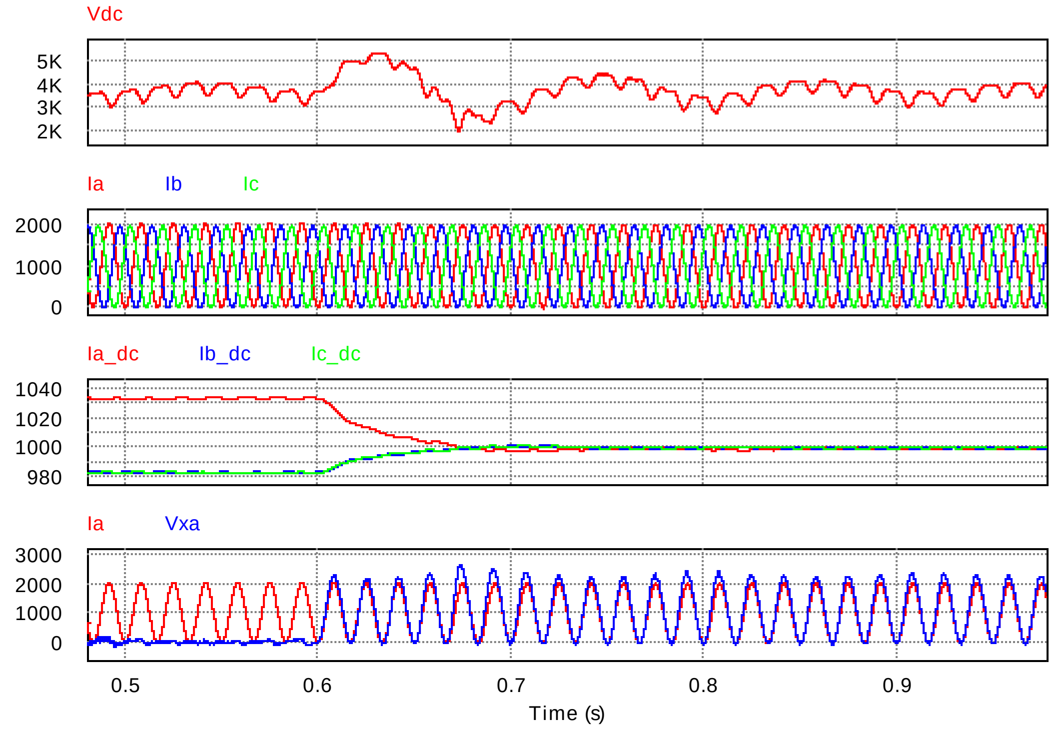
Can be enabled or bypassed

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

Impedance Conditioner Design and Simulation

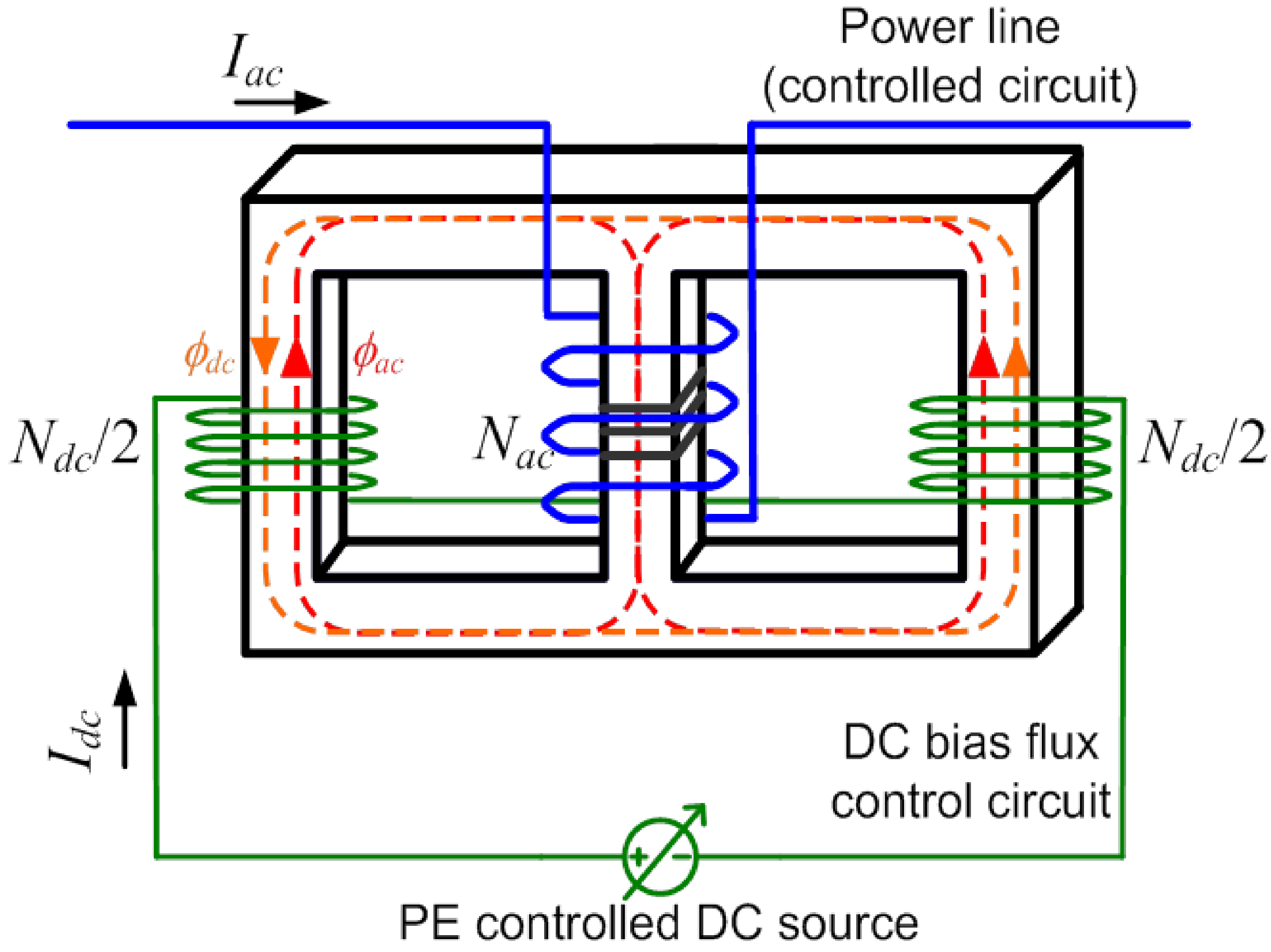
System Parameters	
Line Length	650km
Impedance	0.035Ohm/km+ 0.9337mH/km
Unbalance	**5%**
Line voltage (phase)	AC: 115 kV; DC 180 kV
Line current	AC: 612A, DC: 1000A
Transmission Power	729 MW (189 AC and 540 DC)
Inverter AC voltage	3.183kV(peak)
DC link voltage	3.617kV
DC link Capacitance	**3300uF**
Rectifier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

Magnetic Amplifier Controller



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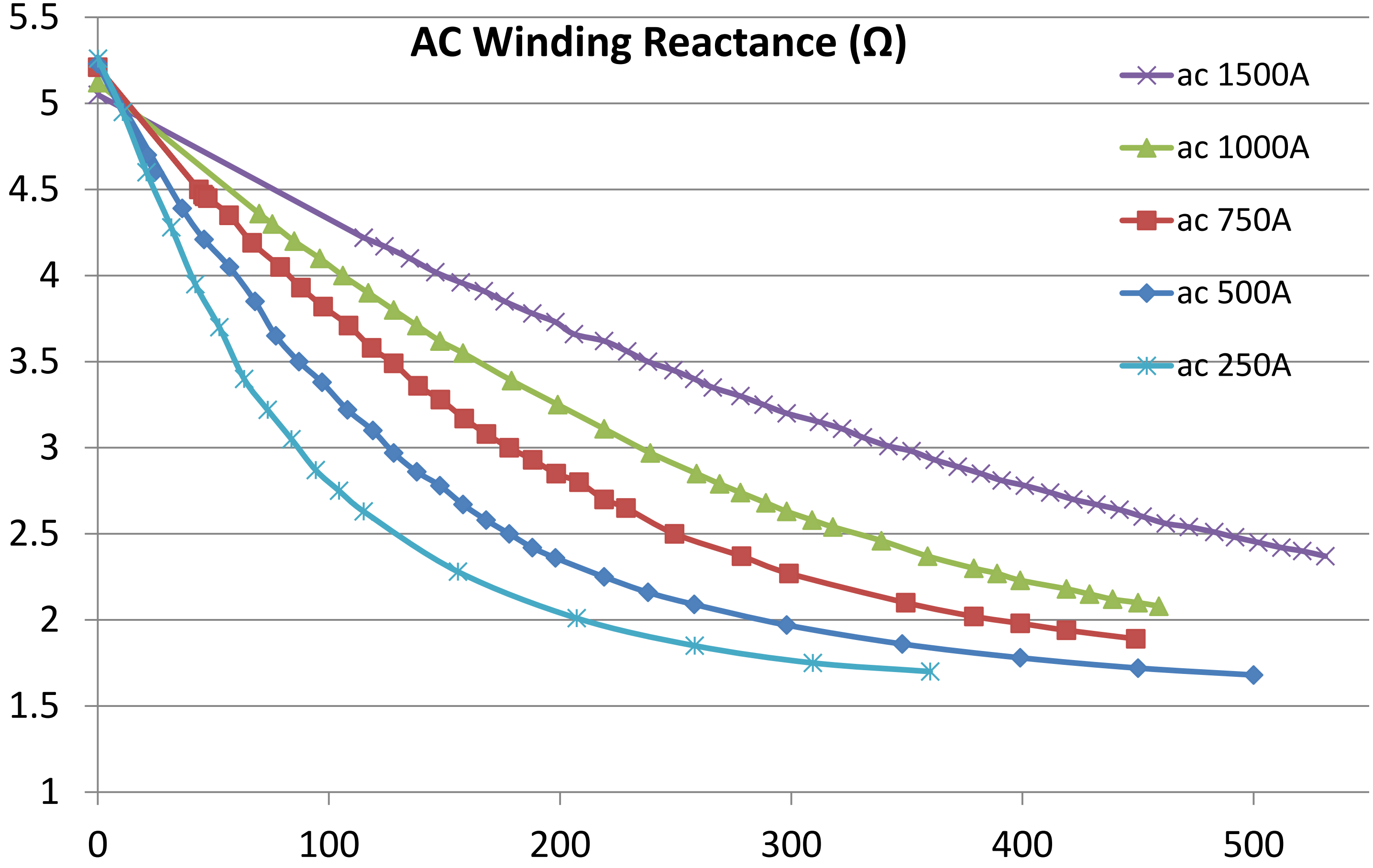
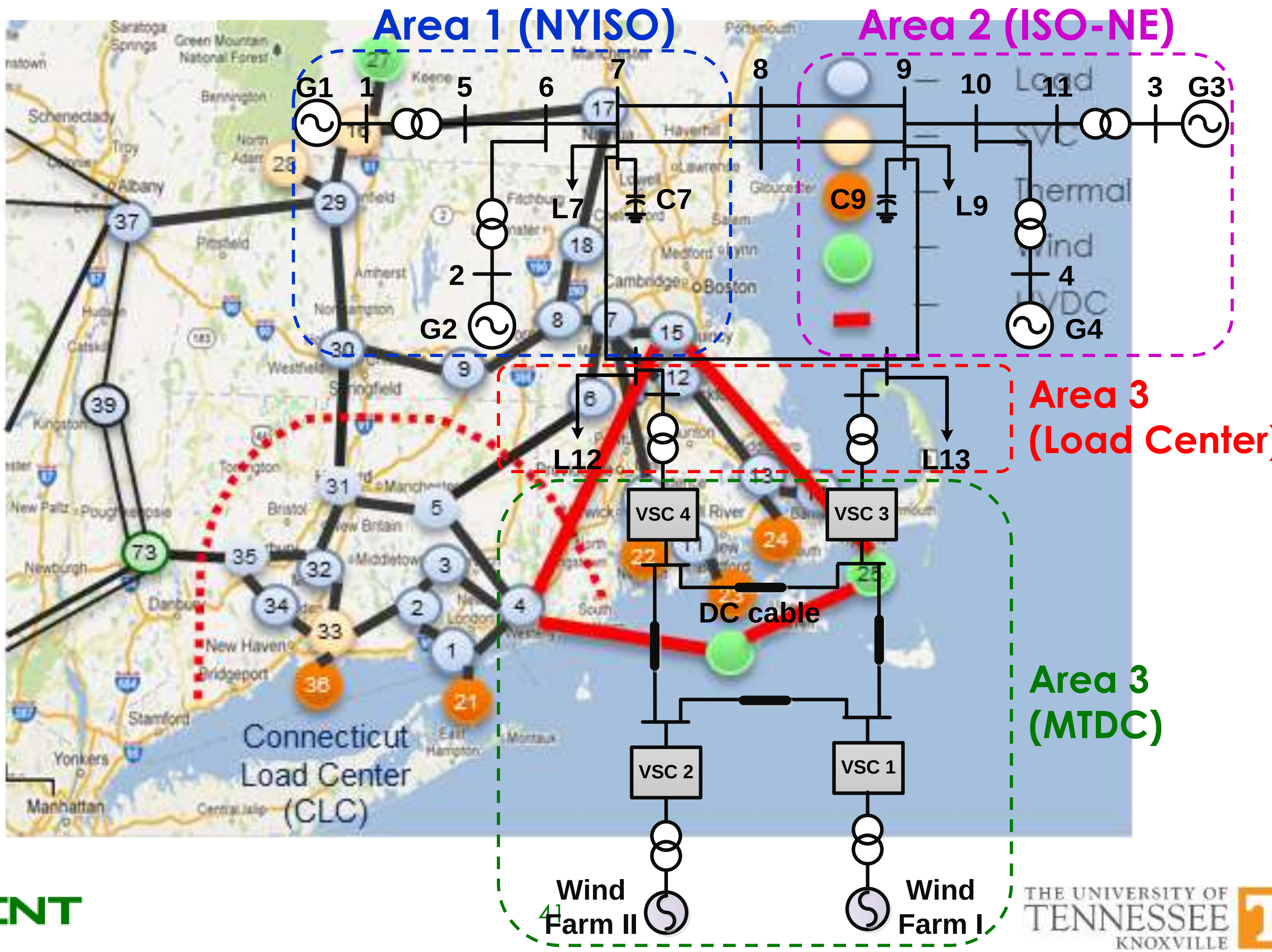
Magnetic Amplifier Controller

Magnetic Amplifier Controller



Multi-terminal HVDC Modeling & Control



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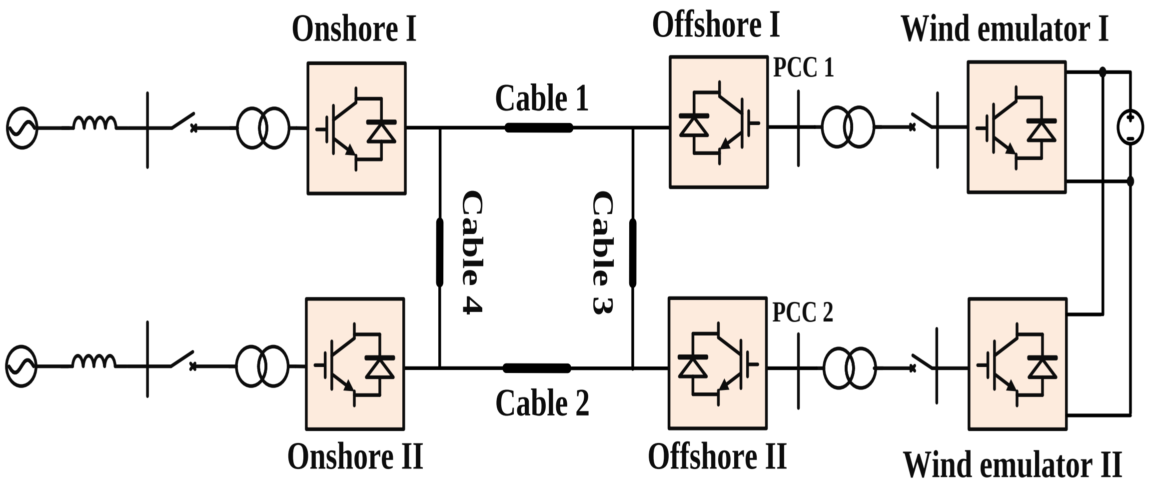
Multi-Terminal HVDC Testbed

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

System Structure

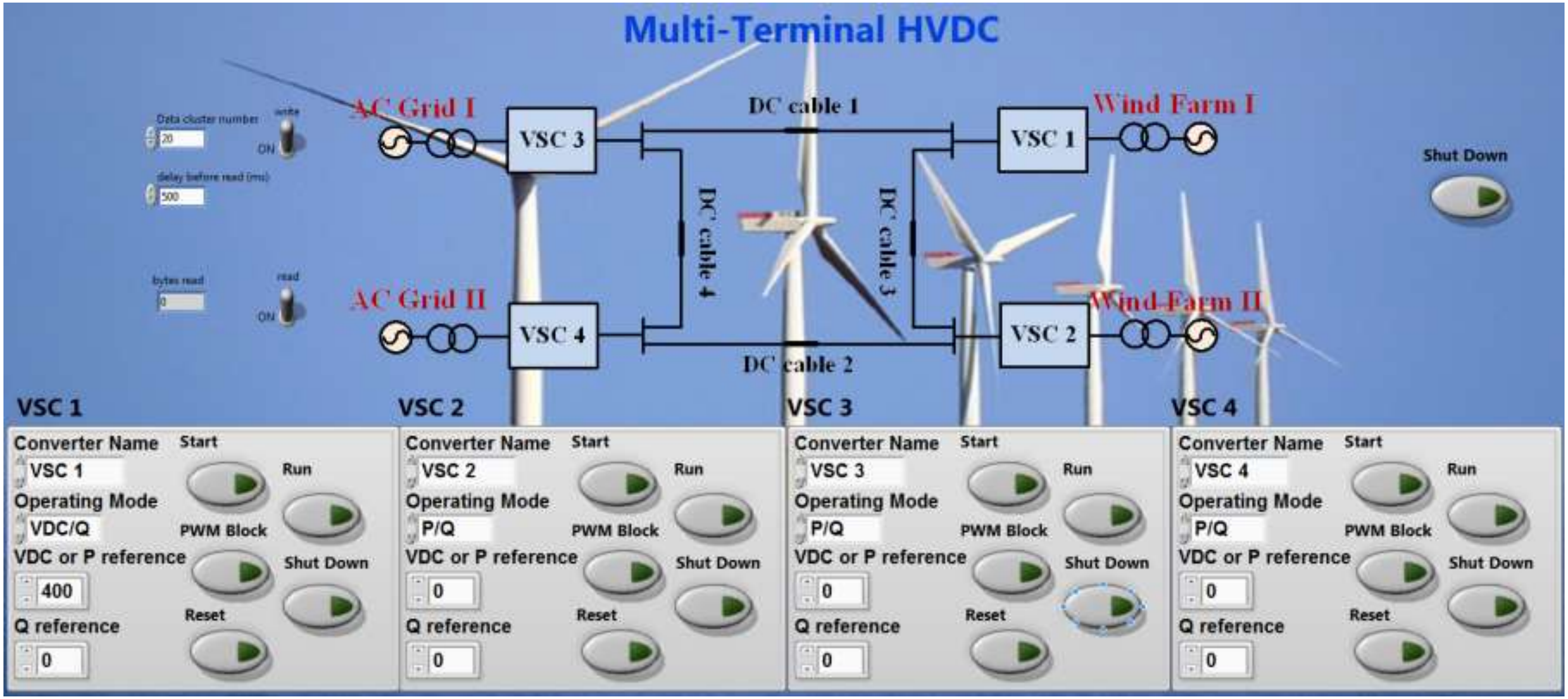


MTDC Testbed Hardware

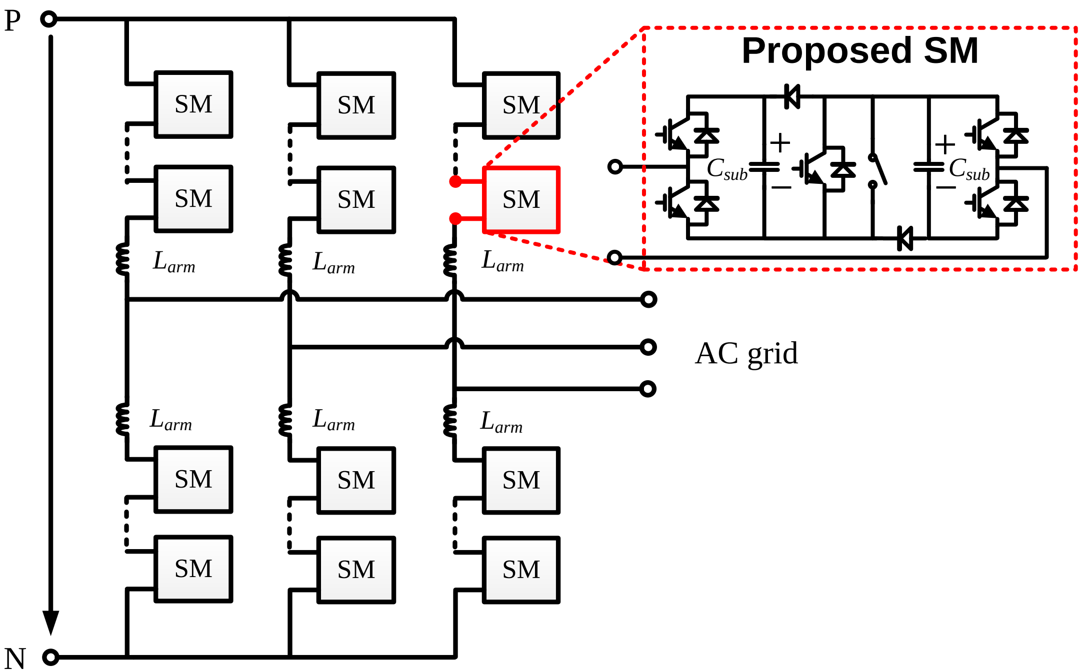
Testbed Capability on Scenario Emulation:

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

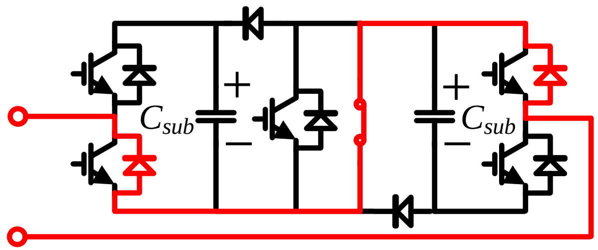
MT-HVDC Testbed Interface



VSC HVDC DC Fault Protection – A CURENT Proposed Solution



❖ In case of DC short circuit fault



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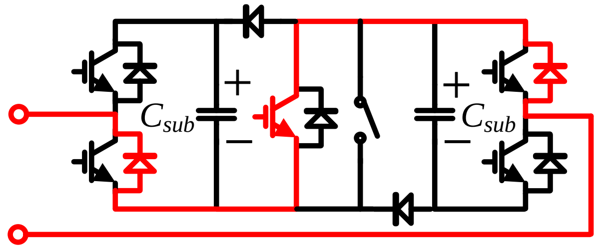

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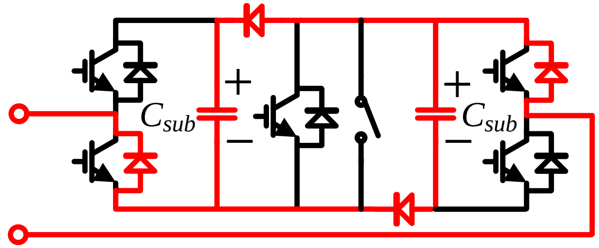
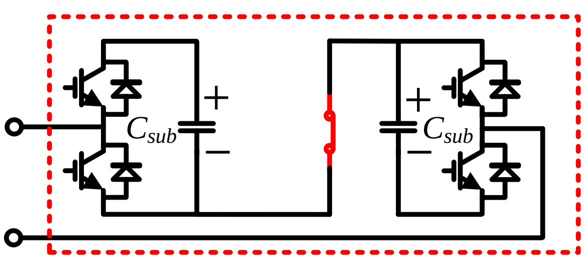


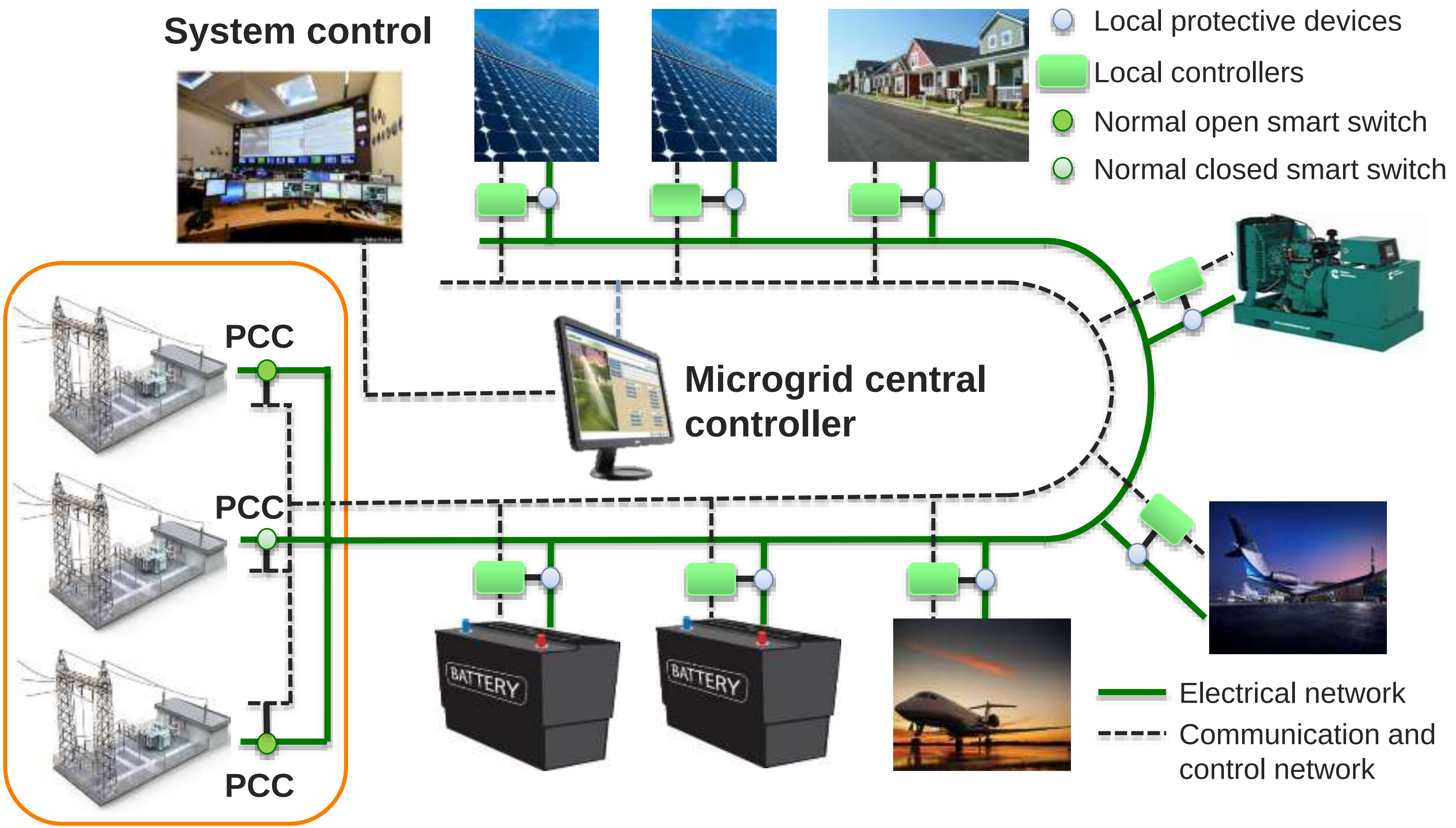
(c)

❖ Normal operation



Two half-bridge sub-modules

Smart and Flexible Microgrid



Conclusions

- Actuation thrust provides essential technology for wide-area coordinated control, and directly supports the CURENT systems.
- Thrust research focuses on multifunctional actuators and flexible architecture.