Super Electronic Highway Grid

COLLECT Active Loads and Carbon-free Generation!

MTDC Workshop Presentation

COmpacting muLti-terminaL dirEct Current Technology

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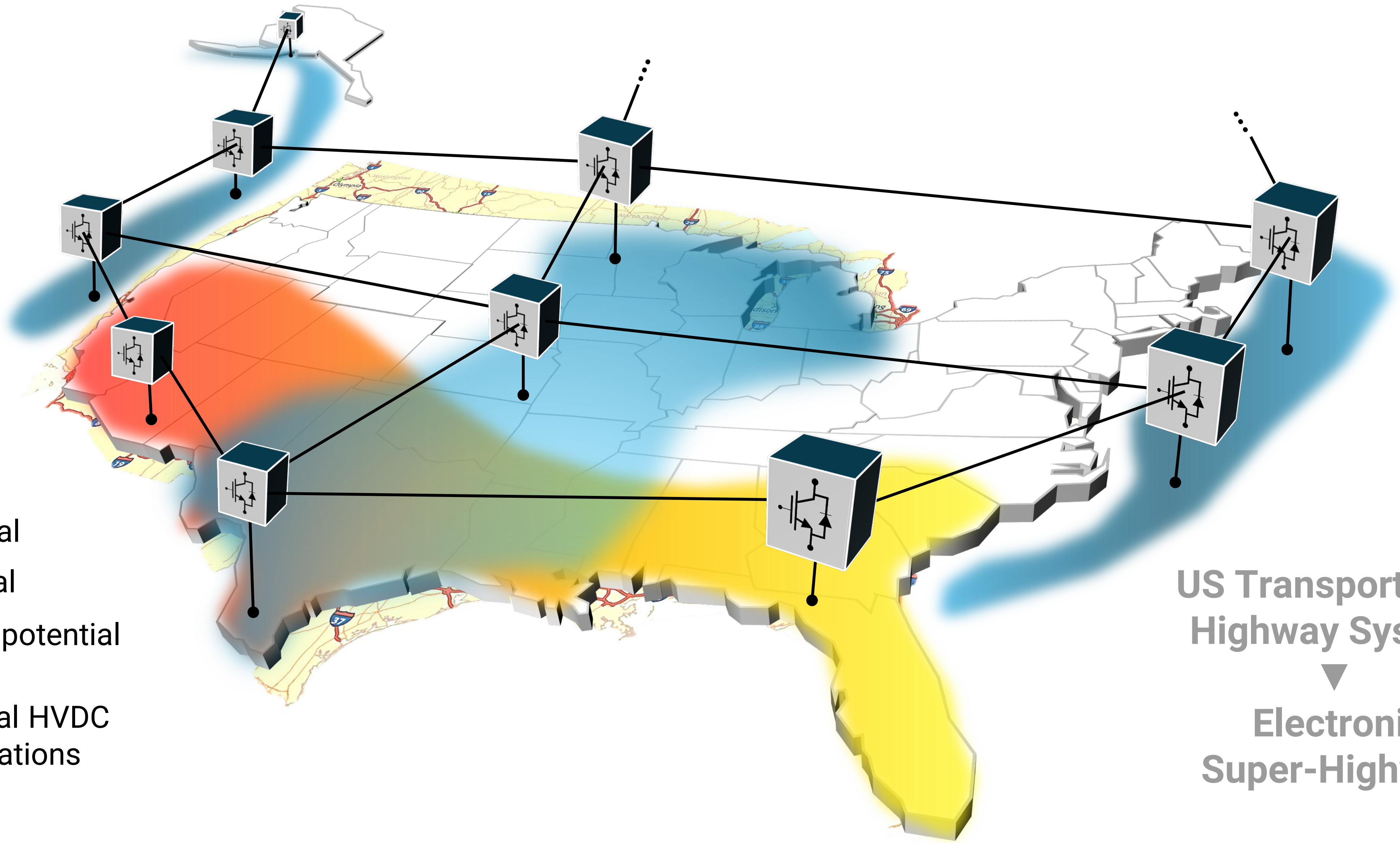
A Macro Super-Highway Grid is Needed!



Solar potential

Wind potential

Solar + Wind potential

Multi-terminal HVDC Converter stations

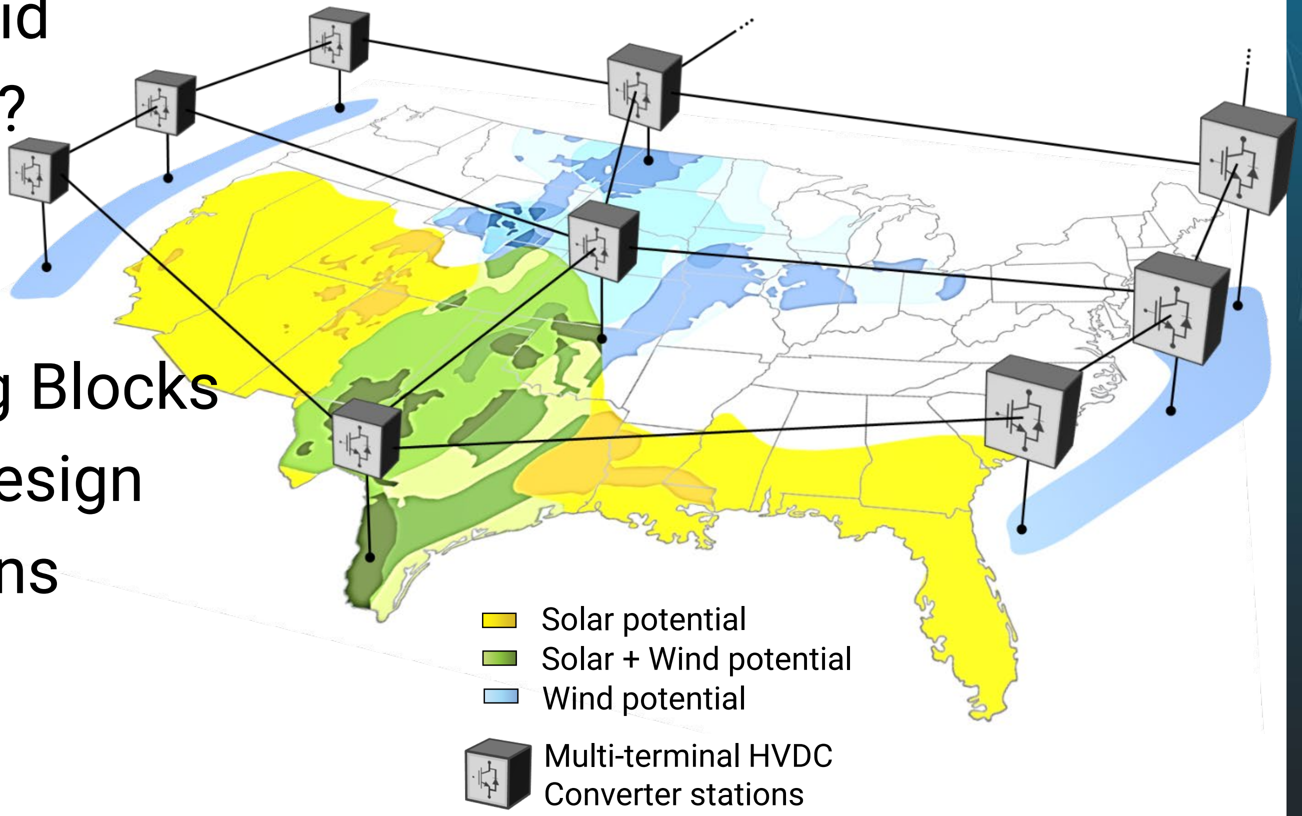
US Transportation Highway System

▼

Electronic Super-Highway

Outline

- Need for a Super Electronic Highway Grid
- Why HVDC and MTDC Interconnections?
- Converter Station SOA Challenges
- Proposed Whitespaces
  - Integrated Power Electronic Building Blocks
  - Converter Topologies and Station Design
  - Integrated AC - DC System Operations
  - Utilizing existing Infrastructure
- Summary of Focus Areas and Metrics



Why do we need to Modernize the Power Grid?

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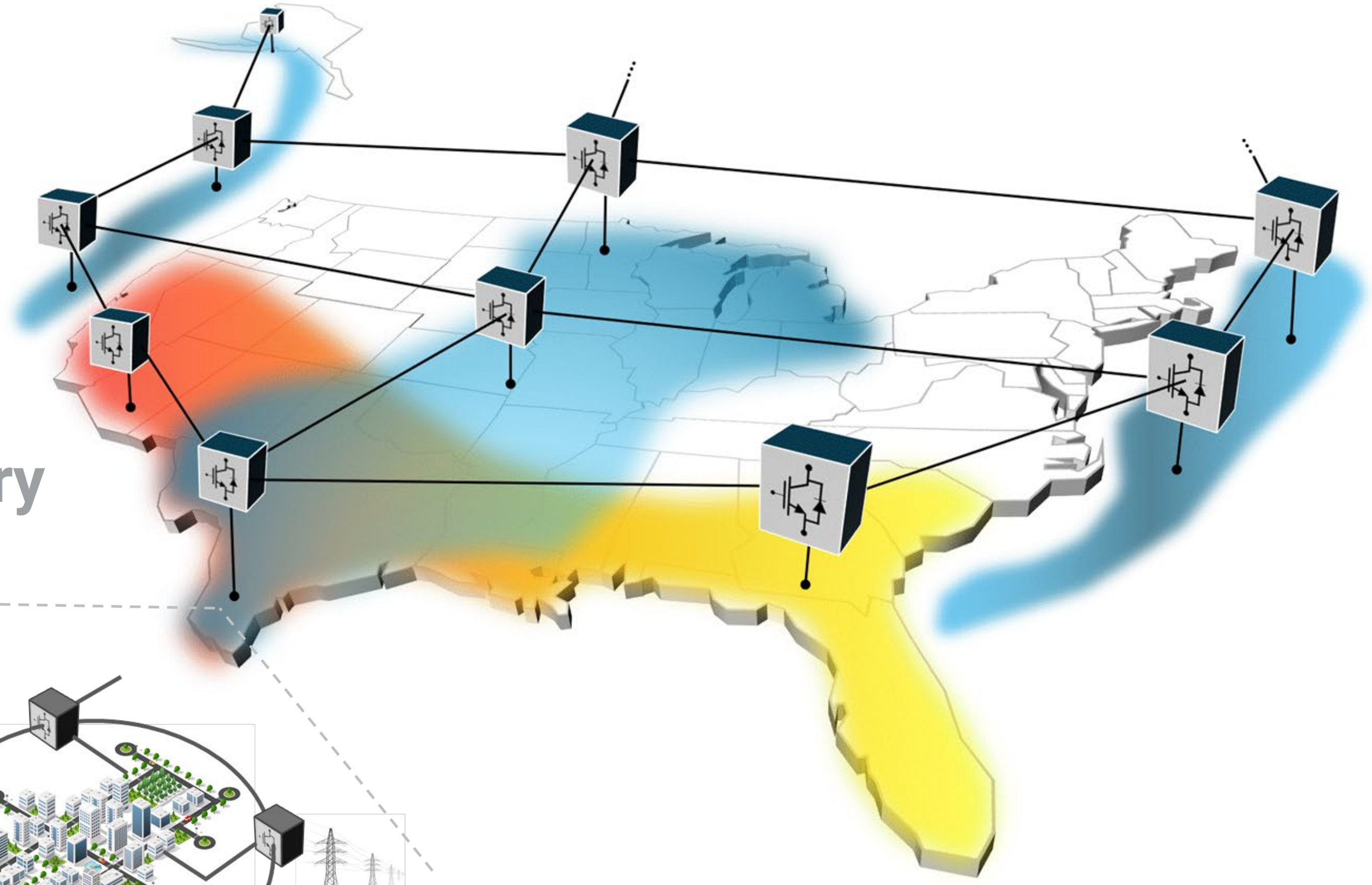
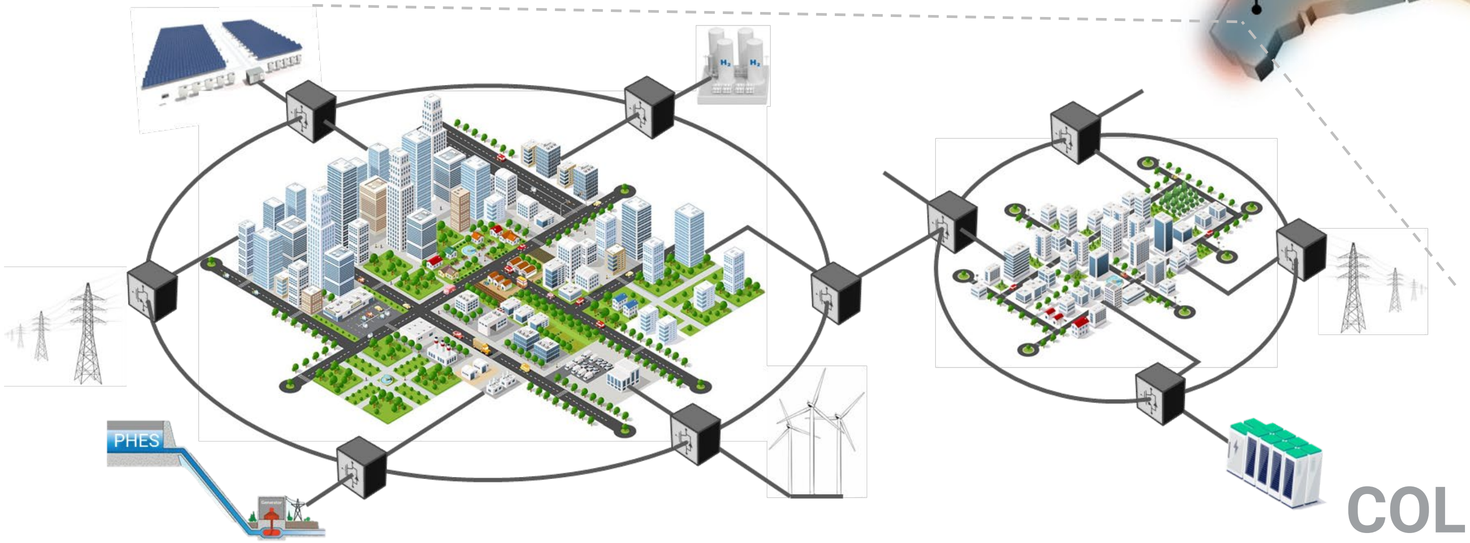
- 100 years old centralized T&D infrastructure for centralized plants
- Incompatible with carbon-neutral power generation integration
- Net-zero carbon goals by 2050 – **1.3 TW New Generation waits to interconnect**

- > 3x Electrical load growth by 2050 (3-4 TW) [EIA]
- Hybrid electrical, thermal and hydrogen energy networks
- Large-scale hydro, battery and hydrogen storage

How is the grid’s *architecture* evolving?



CONNECT Resources Across Country



COLLECT from Virtual Power Plants

Designing tomorrow's Super Integrated Grid NOW!

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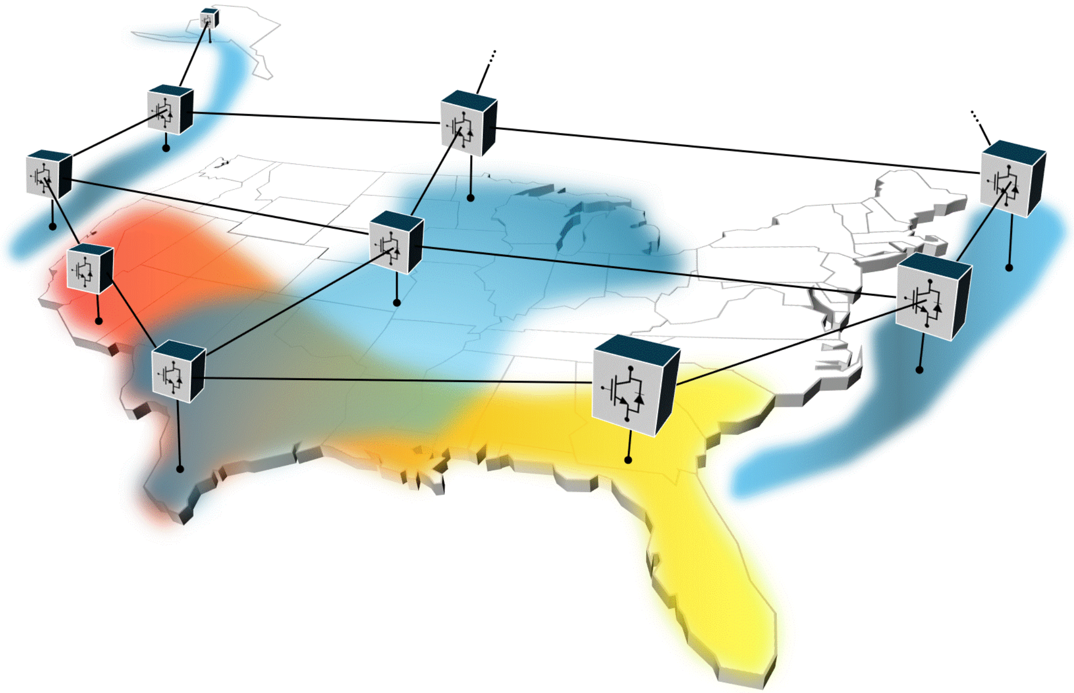
1. **Super Electronic Highway Grid**
   Connect HVDC Electronic Grid-of-Grids
   Release Capacity from "Regional AC Grids"
   Collect from MicroGrids and Active Loads
   Build on Existing Infrastructure & Right of Ways

2. **Transform Integrated System Operations**
   Hybrid AC&DC Solid-state Substations
   Release existing Grid Capacity - 1.5-2x
   Provide Diversity and Equity in Interconnections
   Increase Distributed Resiliency through VPPs

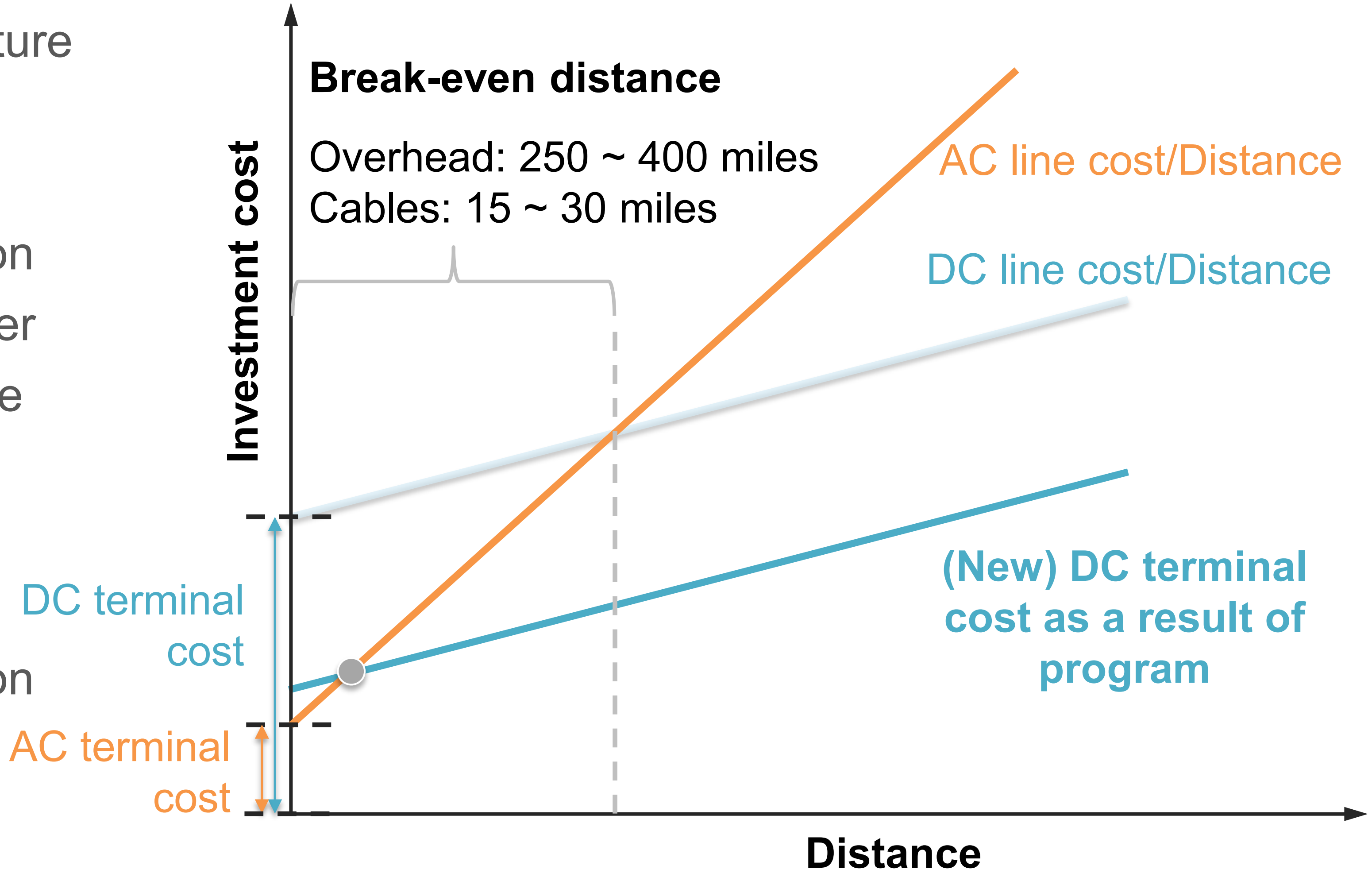
3. **Balance Energy Storage with Time Shift**
   Seasonable & daily renewable energy shifting.
   Interconnecting Dynamic Pump-Hydro Storage
   Power-2-X with H2 Storage
   Integration of Chemical, Gas and Thermal Energy Transfer Networks



COLLECT and CONNECT – 360
Day / Night Solar & Wind Utilization

• Why High Voltage DC in Multi-terminals (MTDC)?

- ✓ 3x power transfer on same infrastructure
- ✓ Controlled power flow
- ✓ Underground (cable) friendly
- ✓ No need for frequency synchronization
- ✓ Efficient way of electric energy transfer
- ✓ No reactive power – Power X1.4 more
- ✓ No skin effect in cable
- ✓ No proximity effect
- ✓ No harmonic resonances
- ✓ No need for frequency synchronization
- ✓ Fewer conductors
- ✓ Dynamic decoupling
- ✓ Renewable energy sources integration

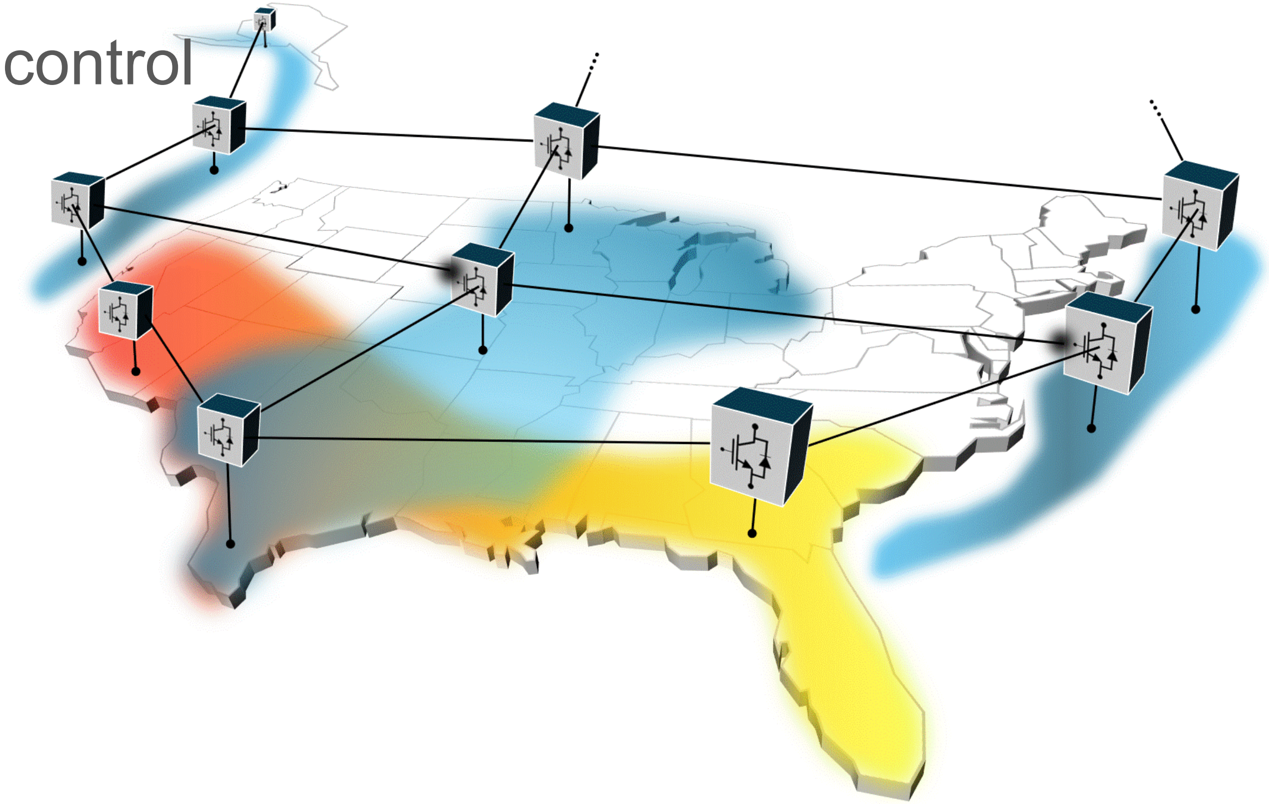


DC terminal cost significantly shortens the break-even distance

Why Operating a Multi-Terminal HVDC (MTDC) Grid?

- ✓ Higher reliability, flexibility, balanced and coordinated power dispatch
- ✓ Managed power-flow control with improved resiliency
- ✓ Energy equity for all technologies, vendors and geographical areas
- ✓ Better protection AC & DC coordination
- ✓ HVDC nodes feature integrated fast control that reduces “human-in-the-loop”

Incorrect decisions can cause a blackout!



Cahora Bassa:- Mozambique to South Africa (1977)
First commercial semiconductor LCC HVDC System

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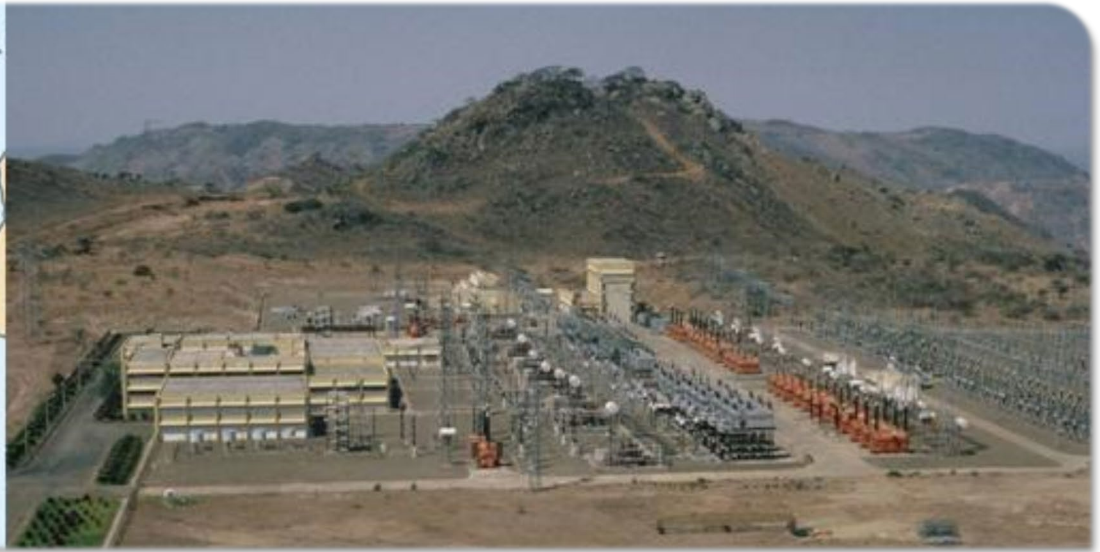
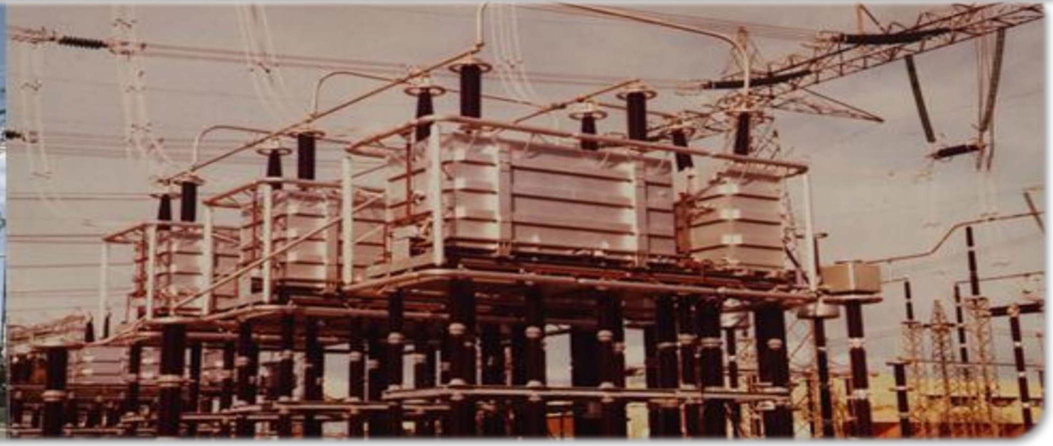


1,920 MW; ± 533 kV; 1,420 km

Songo, Mozambique to **Apollo,** South Africa – 1977



Outdoor Oil Insulated and Cooled Converter Station

Radisson Quebec to Sandy Pond LLC MTDC System

- Sandy Pond Converter Station

- Converter Hall

5 Terminal HVDC System (Operating as 3 since 1990)

+/- 450-kV, 960-mile, 2,000 MW bi-pole HVDC line

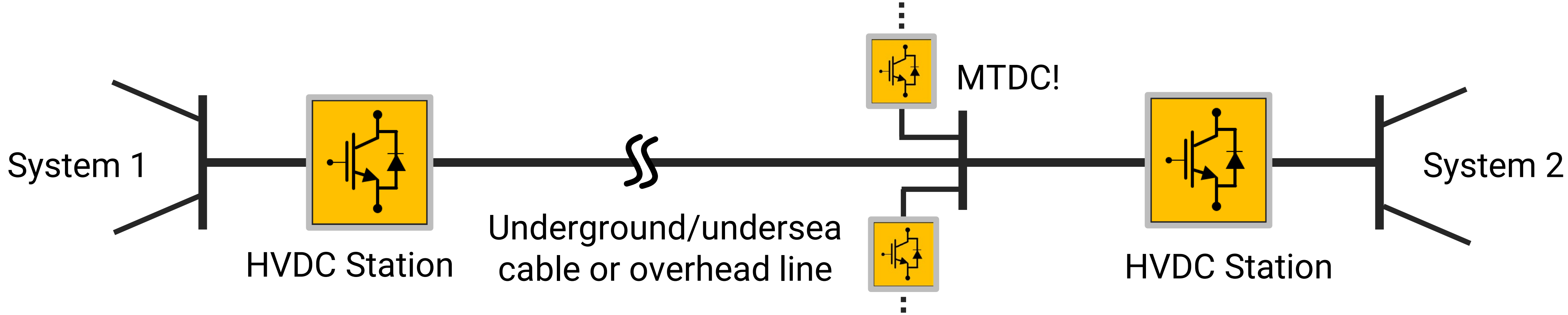
(Images: T&D World / ABB)

Yunnan-Guangdong, China – ±800 kV LCC HVDC Converter
2010; 5 GW; 1418 km

VSC HVDC Stations SOA

Trans Bay On-shore HVDC Station (2010)

Dolwin-3 Off-shore HVDC Station (2017)

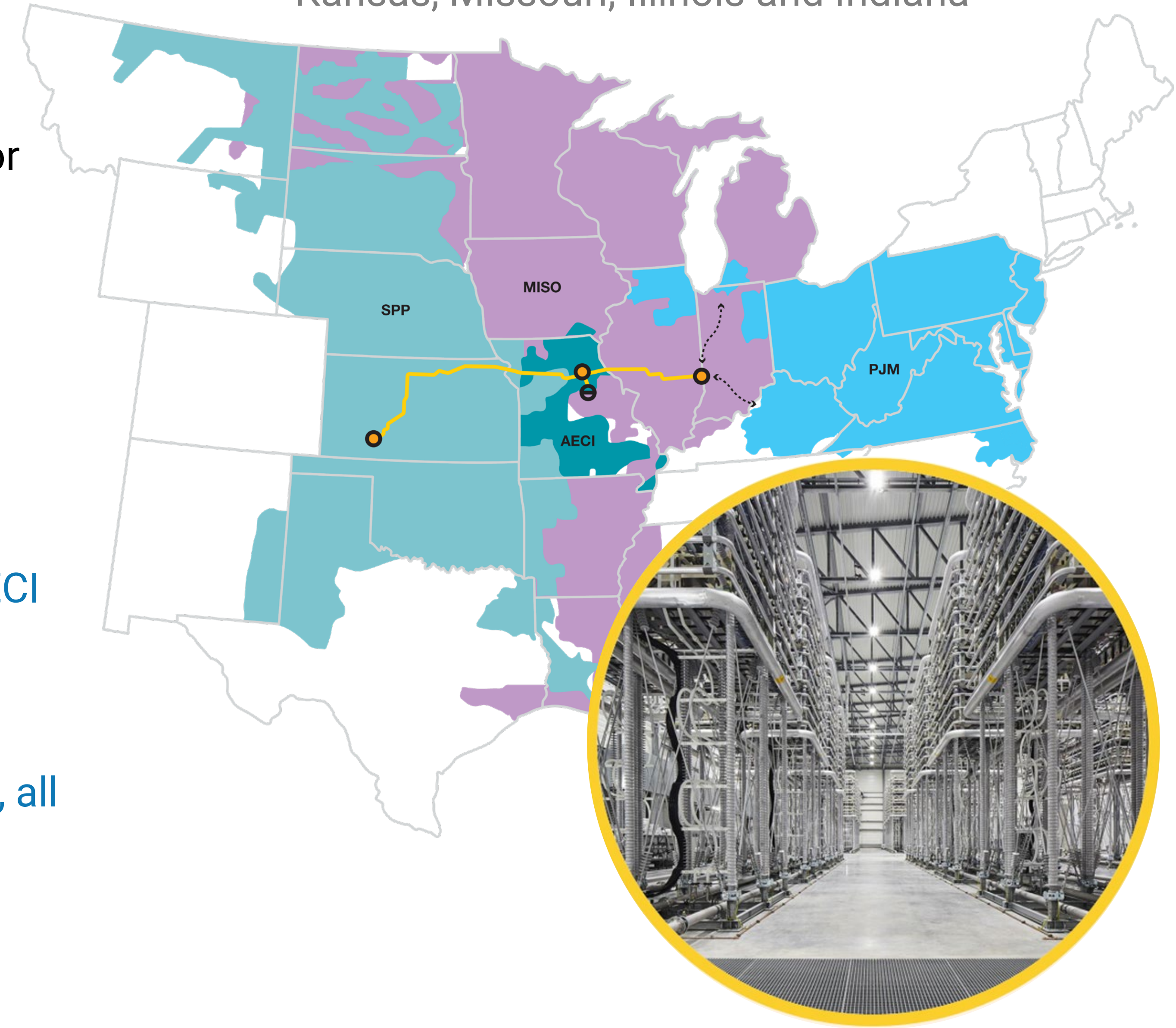


Grain Belt Express HVDC Project – Commissioning 2025 - 2029

Invenergy

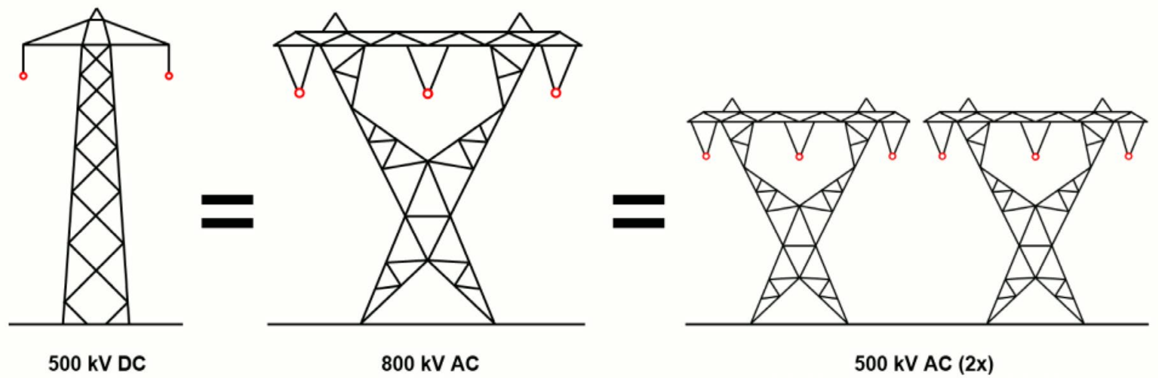
- **$20B** Total Investment: $7B transmission; $13B for new renewables enabled
- **5,000** Megawatts: Highest capacity U.S. transmission project
- **800** Miles: Second-longest U.S. transmission line
- **436M** Tons CO_2 reduced
- Interconnection positions filed with SPP, MISO, AECI and PJM
- Two-way, bi-directional power flow control
- Smaller footprint, fewer structures, and lower cost, all for equal power capacity
- “Blackstart” capability to jumpstart grid outages

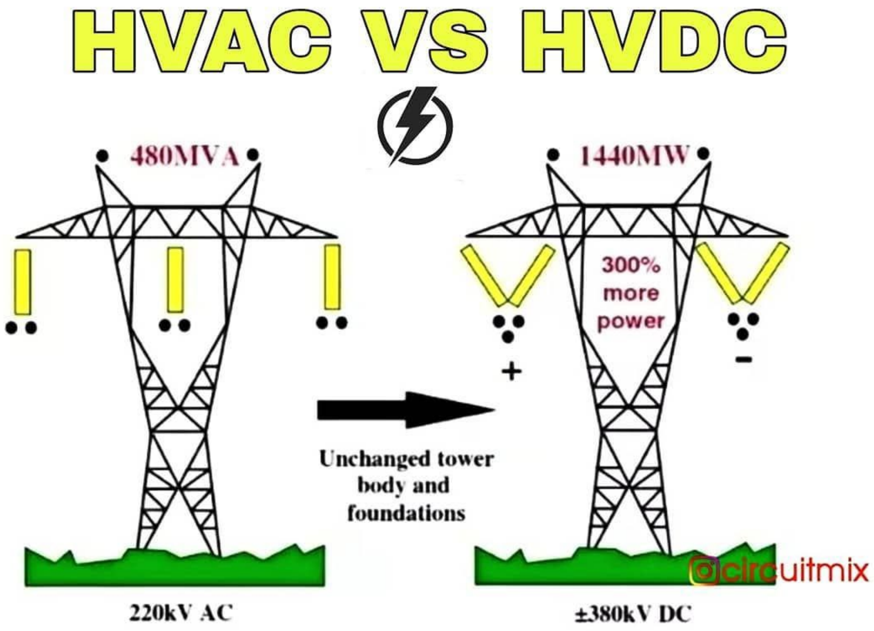
Kansas, Missouri, Illinois and Indiana

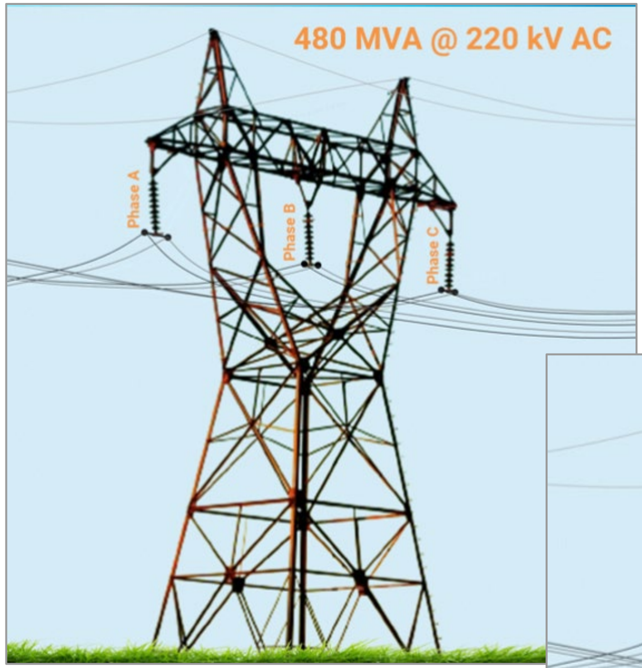


Utilizing existing Right of Way – HVAC v/s HVDC

- 3x ROW comparison – DC cable and DC OVL v/s AC OVL at 500 kV



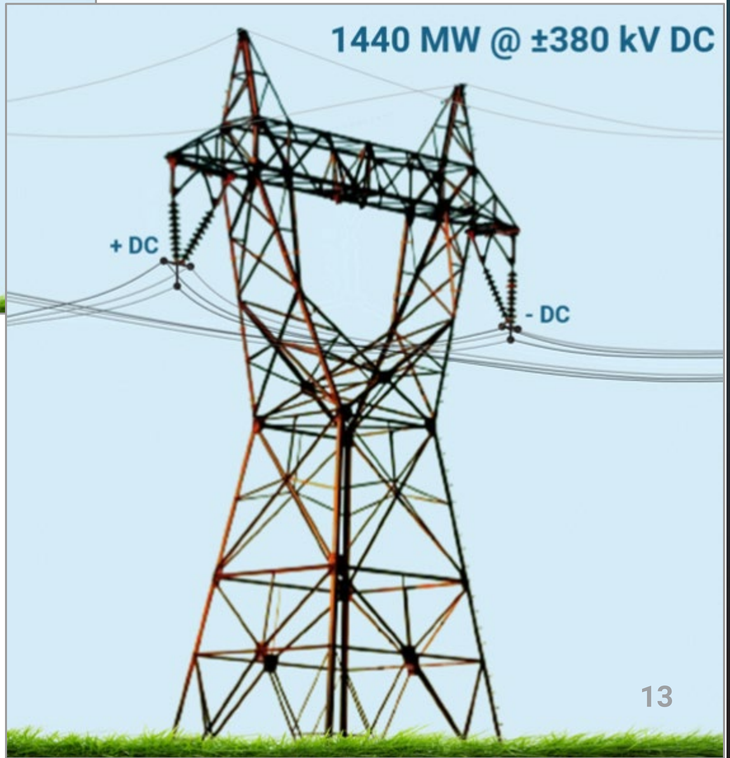




Unchanged tower body,

Existing Right of Way

But 300 %
more power



DC Enables Fully Imperceptible Infrastructure

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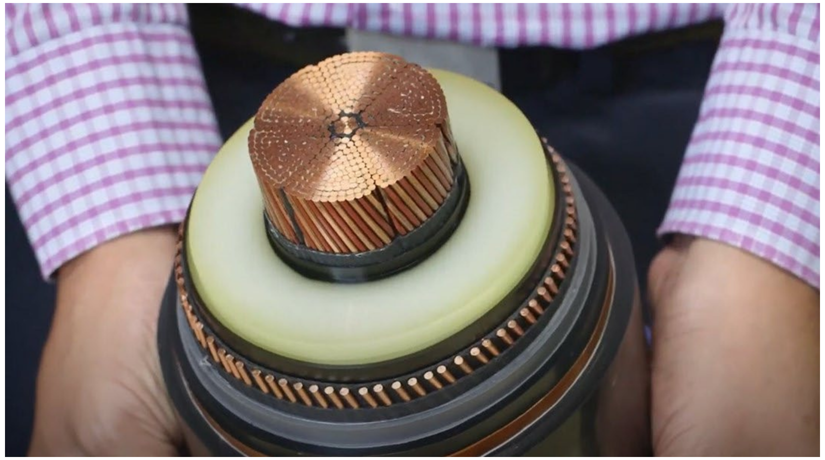

525 kV Cable, >2 GW
The whole conductor cross-section utilized

Can either repurpose existing transmission (300 % capacity increase) or go underground:

Or utilize highway medians for cable installation

Example: Dolwin 3 Offshore Platform (SOA)

(HB MMC Topology - < 1 GW / 325 kVdc)

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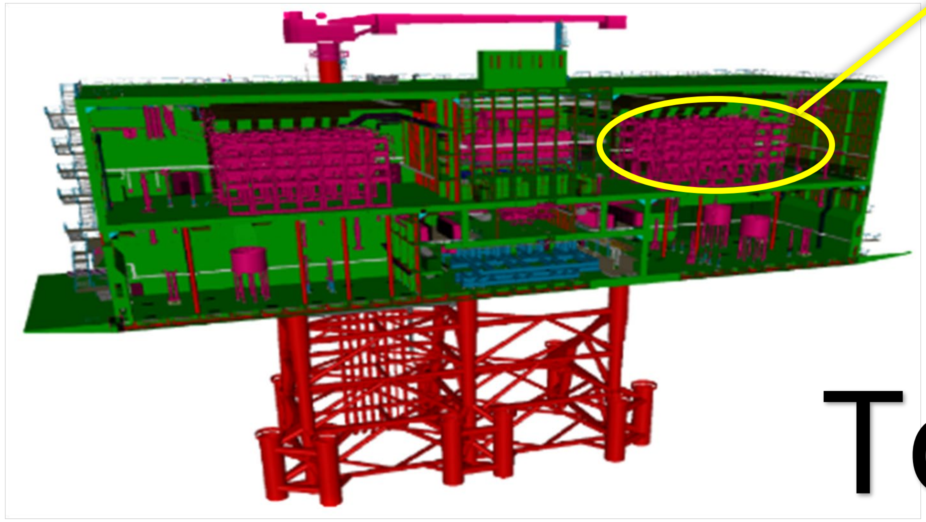

Valve Hall

Too Large!

A Unique Opportunity to Utilize Past and Current ARPA-E Programs

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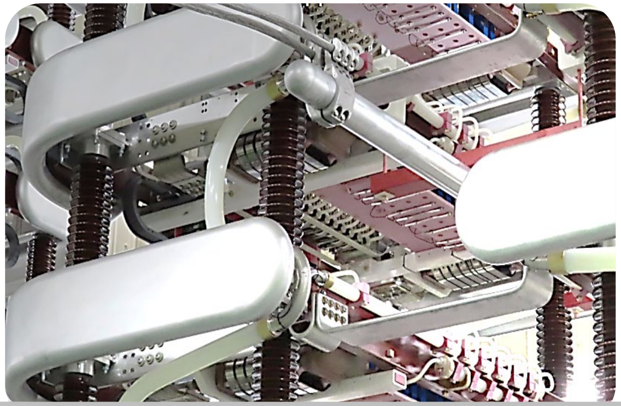
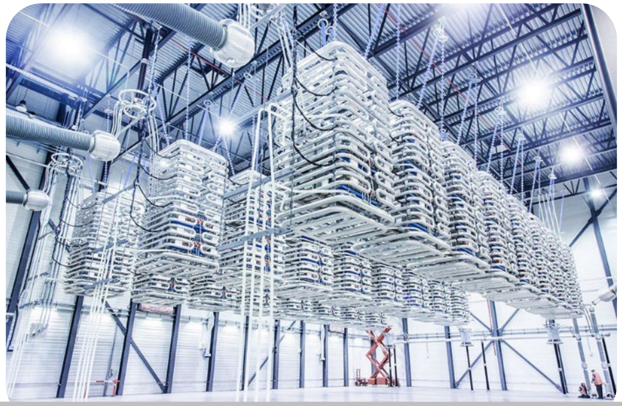




Power Modules → **Power Cells** → **Valves** → **HVDC Converter**

ULTRAFAST

BREAKERS

CIRCUITS

SWITCHES

ADEPT

OPEN 2015, 2018, 2021

GENI

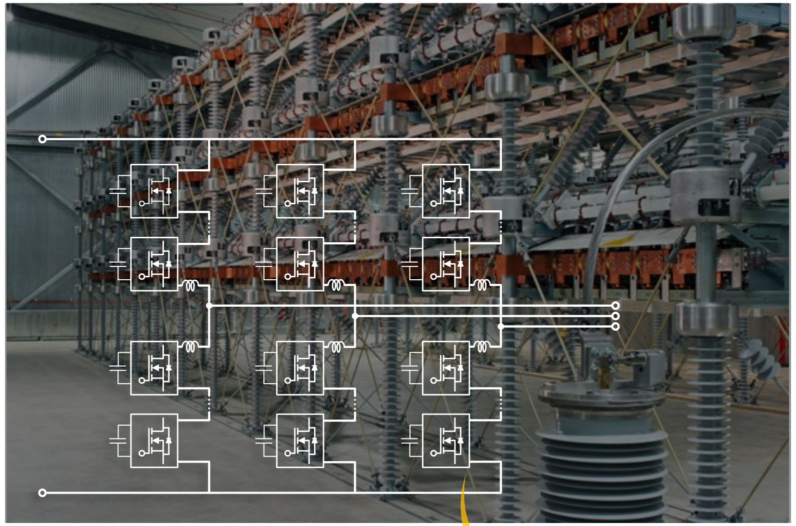
GOPHURRS

Building upon current and past ARPA-E programs!

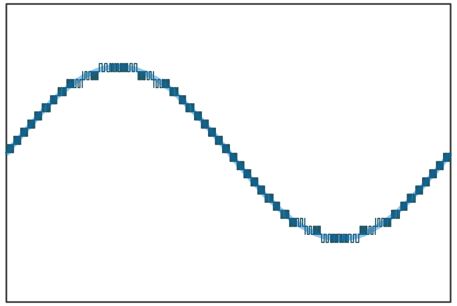
Technology Gaps for COLLECT Program
***CO**mpacting mu**L**ti-termina**L** dir**E**ct **C**urrent **T**echnology*

- **New HVDC Converter Topologies**

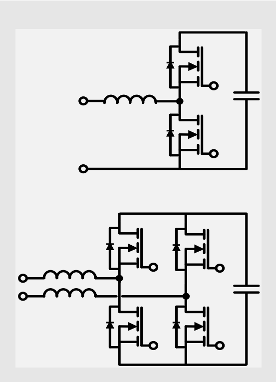
(Beyond state-of-the-art Modular Multi-level Converter)



n-level

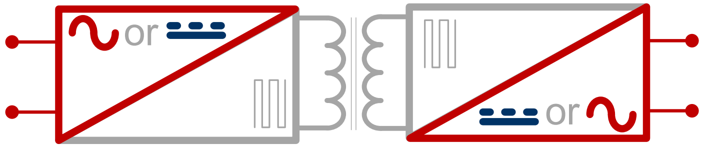


Power Cell

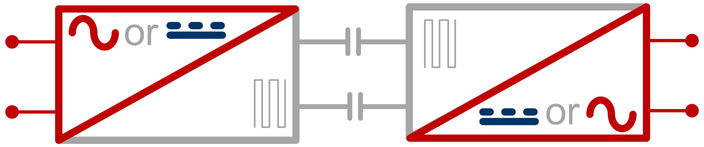


Now utilizing inductively or capacitively coupled power cells for significantly higher flexibility, modularity, and reliability

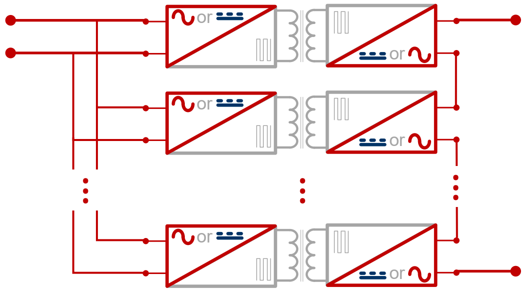
Inductively coupled power cells



Capacitively coupled power cells

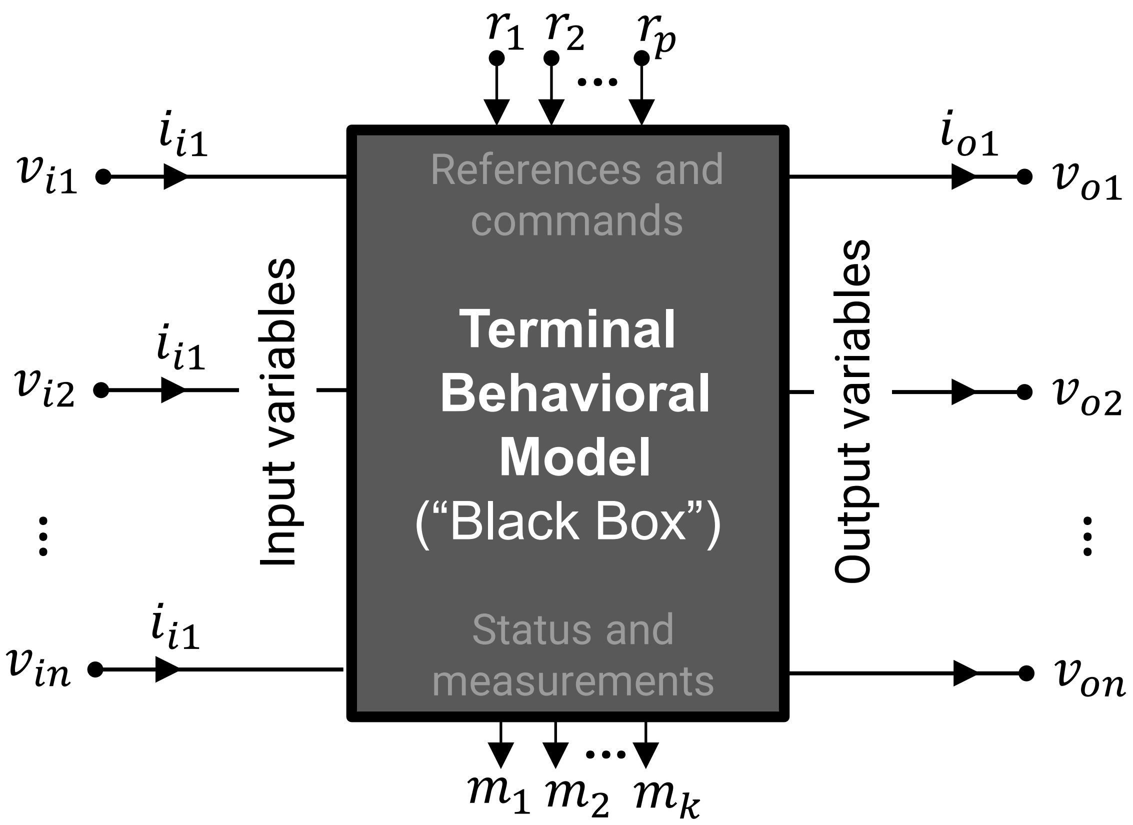


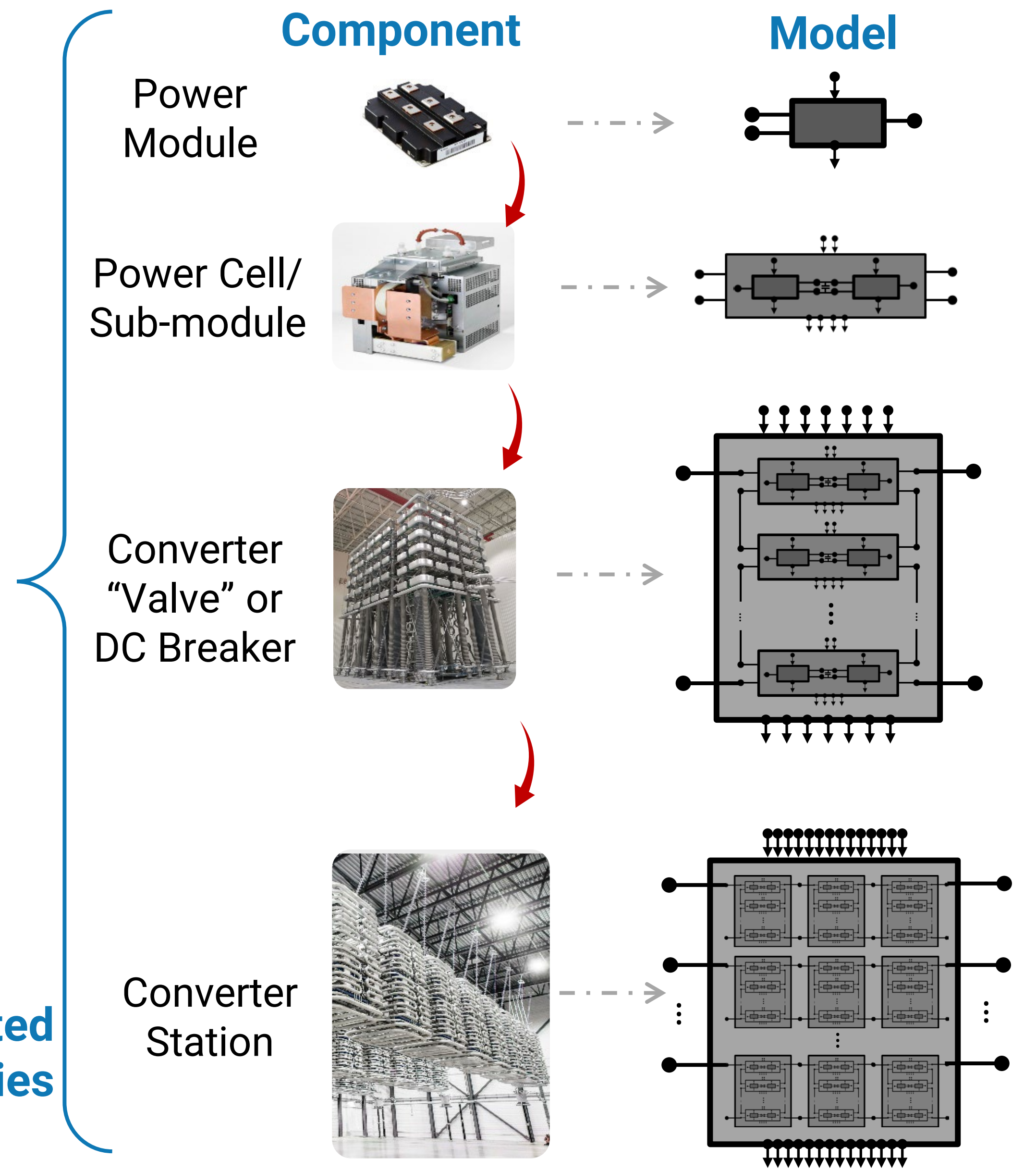
Independent series/parallel connection of galvanically isolated power cells for high voltage and high current design



Experimentally validated with scaled-down hardware and P-HIL simulations

Generic Dynamic Models of System Components at Different Levels of Abstraction





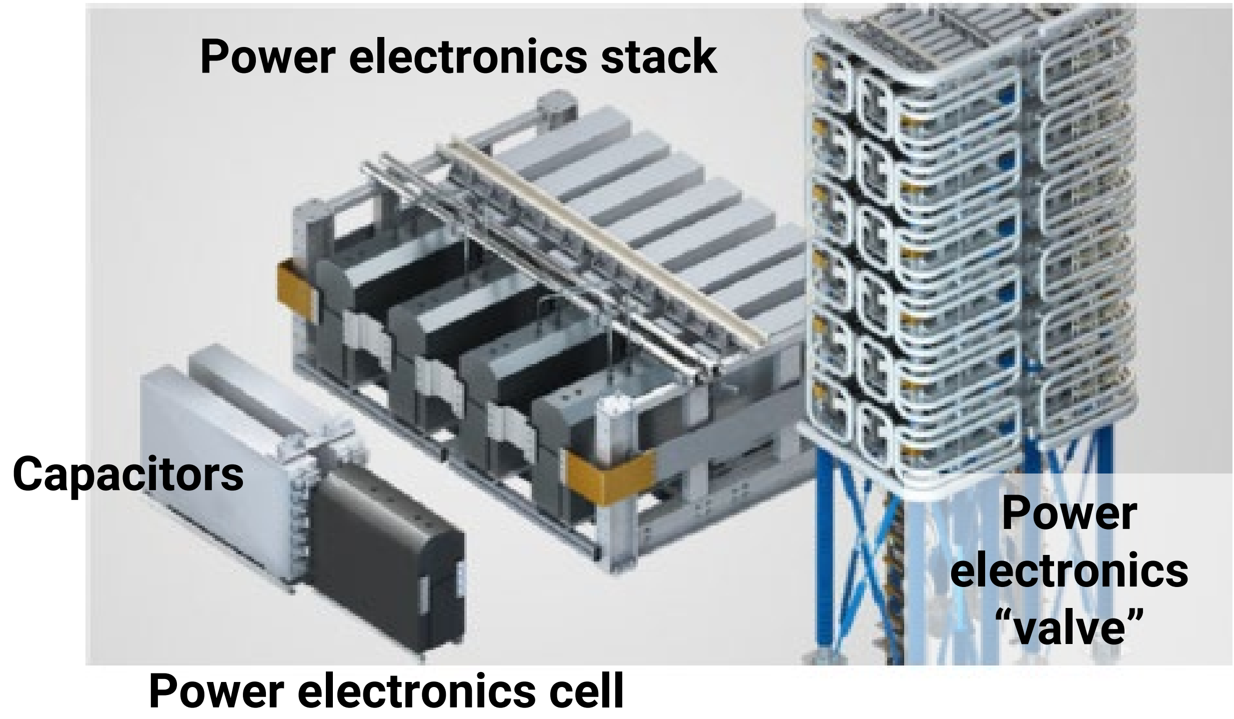
Component models represented with minimal relevant dynamics for system-level studies

Technology Gaps for COLLECT Program

- **Advanced Station & System Control Strategies**

Low-, medium-, and high-level control

Up to 75% of power cell occupied by capacitors (due to line cycle balancing strategy). **Faster low-level control can shrink capacitors 100+ times.**



Low-level Control

- PWM modulation/switching cycle control
- Zero-voltage switching
- Overmodulation
- Active slew-rate control
- Fast overcurrent protection
- Reduce parasitics, etc…

Medium-level Control

- Capacitor voltage balancing control
- Circulating current control
- Bypass/shunt protection
- Inductive/capacitive inter-bridge control
- Bipole / station operations for reliability

High-level System Control

- Multi-terminal power flow control
- Voltage/current/frequency regulation
- Active/reactive power control
- Design Standards
- Protection Coordination
- Grid Forming / Blackstart

Technology Gaps for COLLECT Program

System-Level Modeling for Planning and Operations

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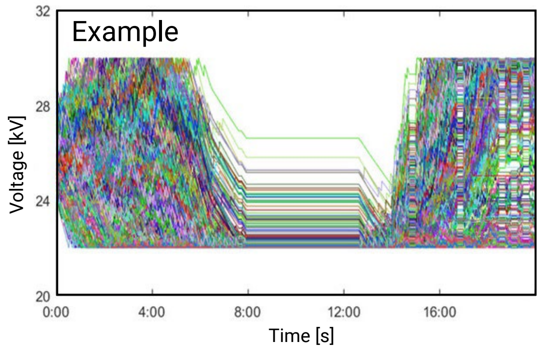
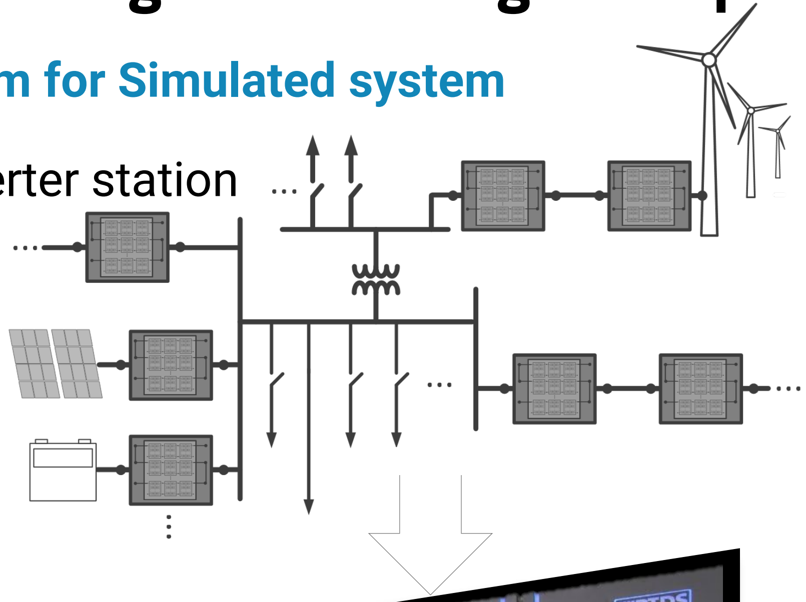
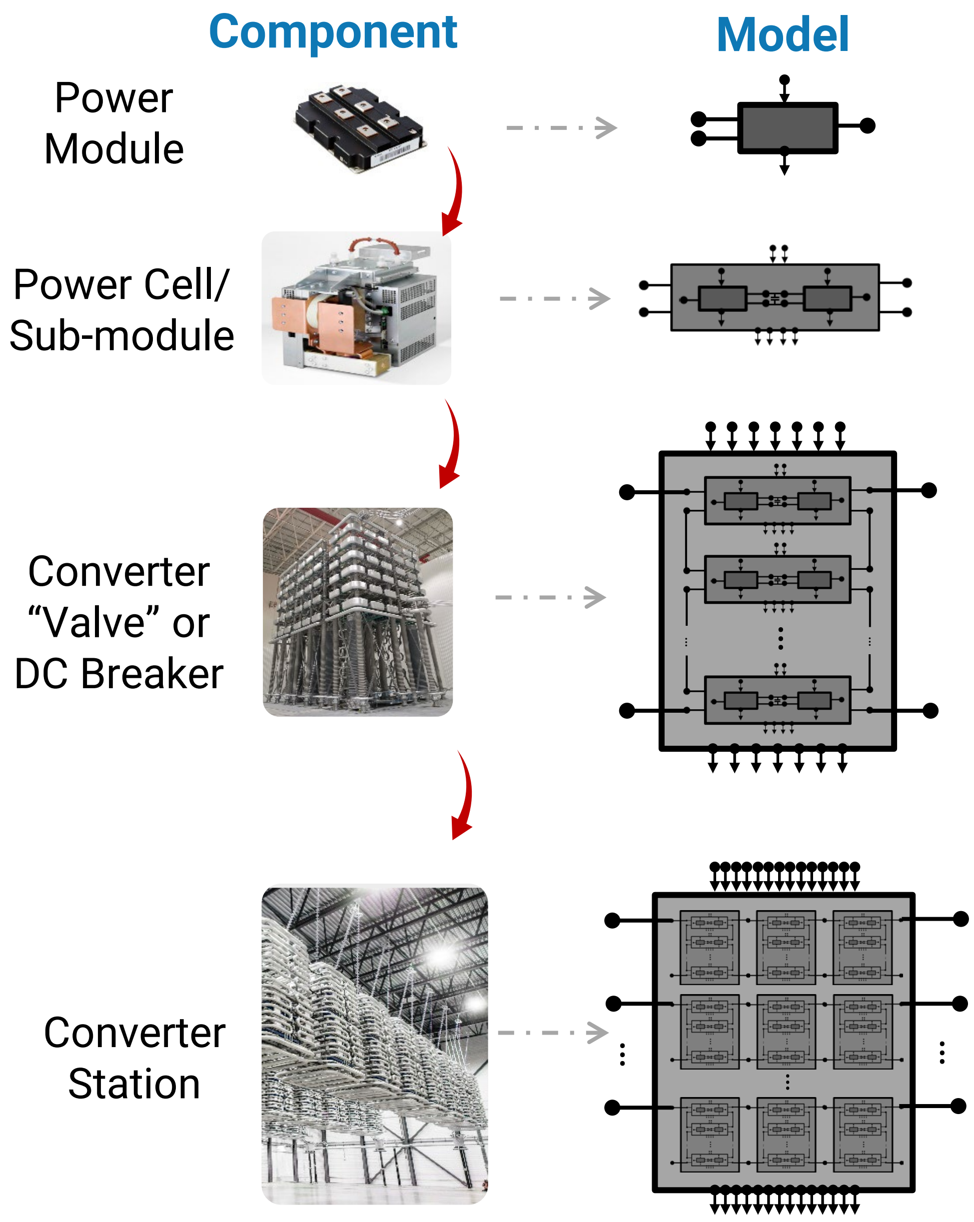
Capabilities Team for Simulated system

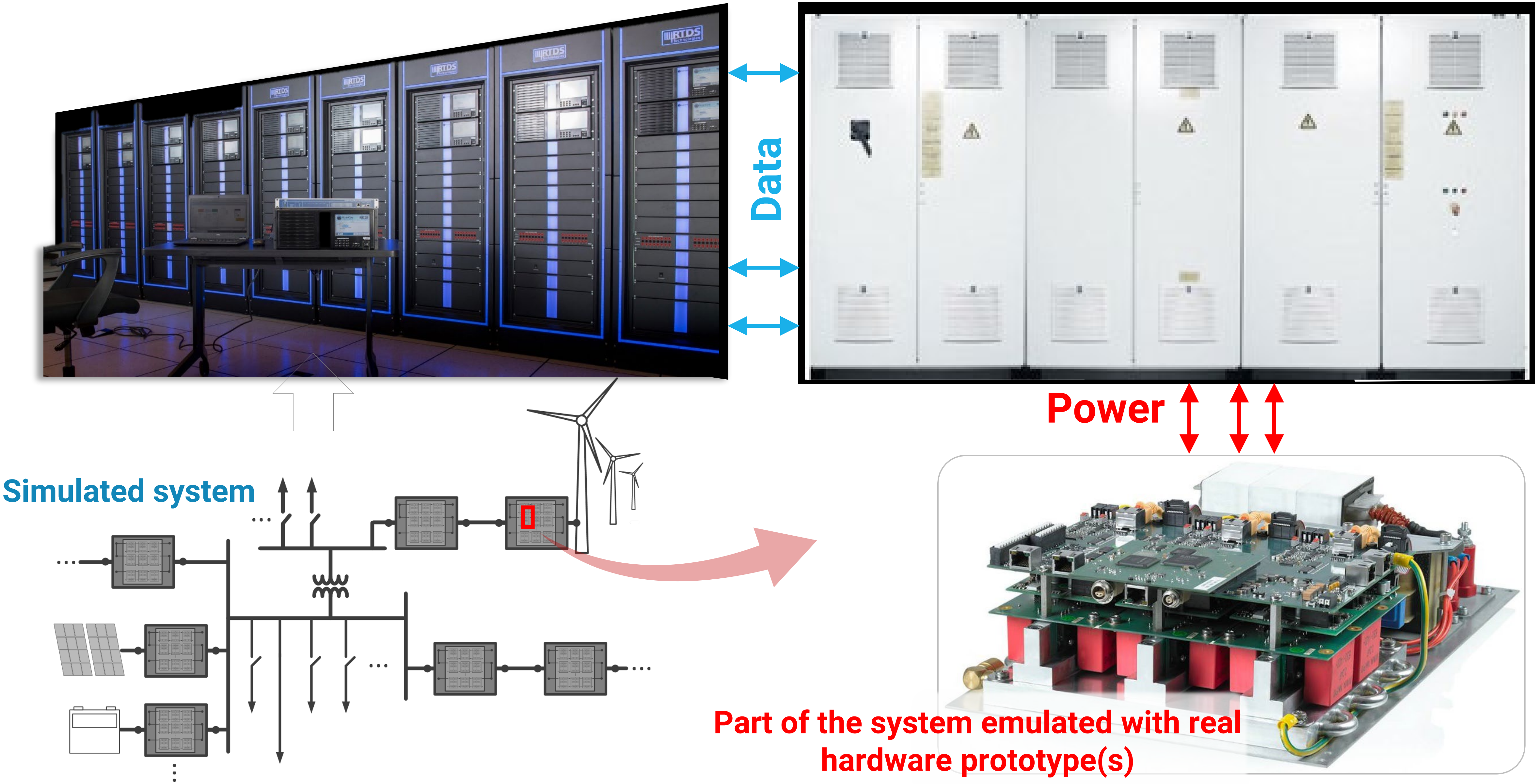




Real-Time Hardware-in-the-Loop (HIL)



System-Level Emulation in Real-Time Environment, with P-HIL



Part of the system emulated with real hardware prototype(s)

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Program Focus Areas

New Power Electronic Building Blocks for HVDC submodules

50 kV, 2000 A, PEBB Sub-Modules featuring **> 50%** higher power density

New Multi-Terminal HVDC Converter Station Design

5-fold power density and cost reduction

(**250 m^3 to 50 m^3/MW offshore**

100 m^2 to 20 m^2 / MW on-shore)

System integration and Operation – Capabilities Team

Multi-terminal HVDC system operation and protection in P-HIL for **> 9 terminals**

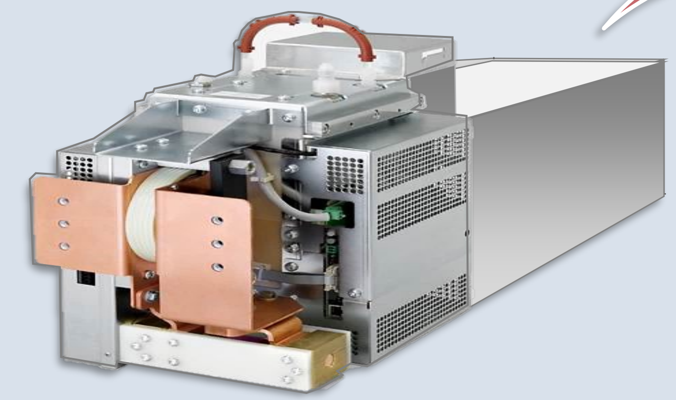

Image by SIEMENS Energy

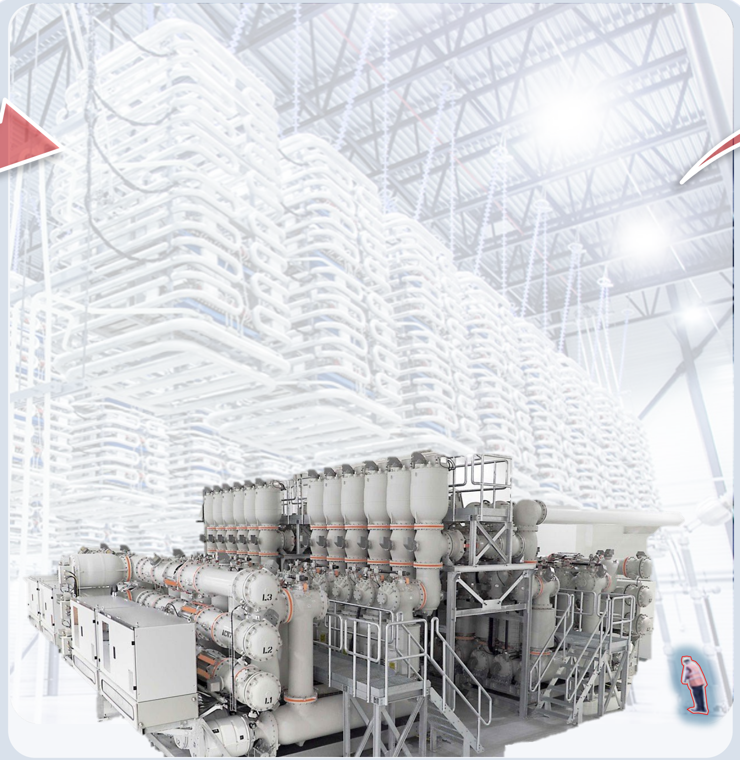

Image by HITACHI Energy / APP

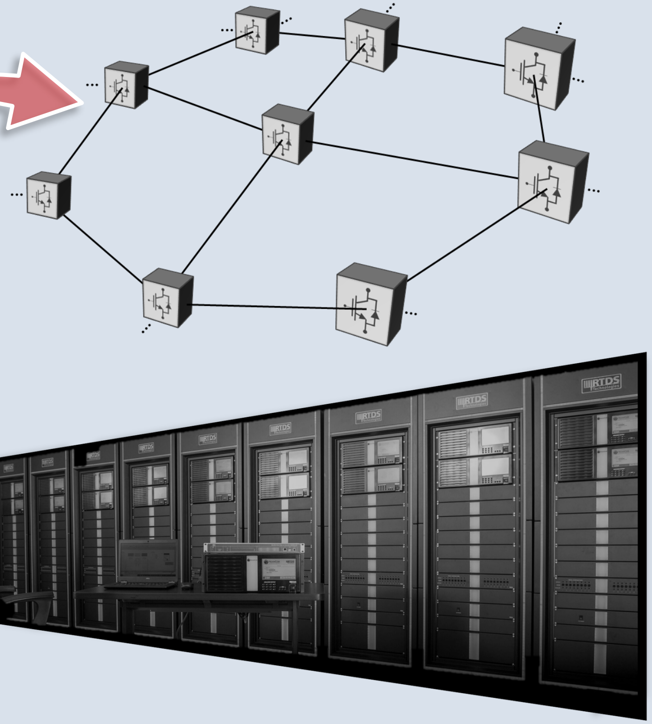

Image by AMETEK

Summary of New Program Metrics

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Category 1

- **New Power Electronic Building Blocks for HVDC submodules (DAB, LLC resonant, etc.):**
  - **50 kV, 2000 A**, PEBB Sub-Modules featuring **> 50%** higher power density compared to SOA (MMC submodules)
  - High-density integration with partial discharge **< 10 pC @ V_{nom}**
  - Bypass protection design with **< 1 μs** reaction time
  - Experimentally shown with **1-2 submodules** built and tested in the lab

Category 2

- **New Multi-Terminal HVDC Converter Station Design:**
  - **5-fold** power density reduction compared to MMC (**from 250 m^3/MW to 50 m^3/MW and 100 m^2 to 20 m^2 / MW on-shore**)
  - **10-fold** cost reduction of converter stations (**< 150 k$/MW offshore and 30 k$/MW**)
  - Nominal voltage **≥ ± 525 kV** and 2X power **≥ 4 GW**
  - Efficiency **> 98%**
  - Availability **>99.9%**
  - Insulation (non-greenhouse gases, solid-state materials, etc.)
  - HF Transformers and Capacitors
  - Validated in a real-time simulation environment

Category 3

- **System Integration and Operation Capacity (Using Hybrid Emulation with P-HIL):**
  - Multi-terminal HVDC operation in P-HIL for **> 9 terminals**
  - Station bypass protection design with **< 5 ms** reaction time
  - Multi-terminal HVDC power flow control with coordinated protection
  - Voltage/current/frequency regulation
  - Active/reactive power management
  - Validated EMT system models in a real-time simulation environment
  - Show multi-vendor / agnostic operation.

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