ARPA-E Past Grid Hardware Projects and Vision for the Future

Dr. Isik Kizilyalli, Advisor, ARPA-E
Dr. Johan Enslin, Program Director, ARPA-E

2024 DOE Direct Current Circuit Breakers Workshop
Office of Electricity

May 1st, 2024

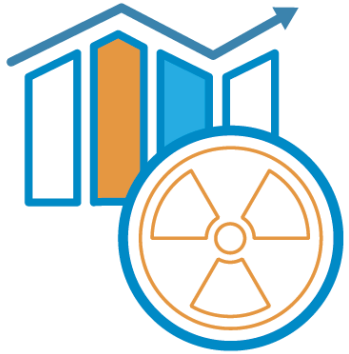
ARPA-E Mission

CHANGING WHAT'S POSSIBLE

REDUCE
imports

REDUCE
emissions

IMPROVE
efficiency



IMPROVE
radioactive waste management

IMPROVE
energy infrastructure resilience

ARPA-E Impact Indicators 2024

CHANGING WHAT'S POSSIBLE

Since 2009
ARPA-E has provided
$3.76 billion
in R&D funding to
more than **1,560 projects**
+ 54 selected projects

230 projects
have attracted more than
$12.1 billion
in private-sector follow-on funding

154 companies
formed by
ARPA-E projects

29 exits
market valuations worth
$21.9 billion
from mergers, acquisitions, and IPOs

340 projects
have **partnered with other government agencies**
for further development

7,318
peer-reviewed
journal articles
from ARPA-E
projects

1,120 patents
issued by
U.S. Patent and
Trademark Office

405 licenses
reported from
ARPA-E projects

As of January 2024

ELECTRICITY GENERATION & DELIVERY

EFFICIENCY

TRANSPORTATION

BLE

Active

CURIE *(new)*
ONWARDS
SHARKS
BETHE
GAMOW
PERFORM
GEMINA
ATLANTIS
DAYS
MEITNER
INTEGRATE
IONICS
GRID DATA
NODES
GENSETS

MINER *(new)*
HESTIA *(new)*
REMEDY
FLECCS
REPAIR
DIFFERENTIATE
BREAKERS
HITEMMP
SENSOR
CIRCUITS
PNDIODES
ENLITENED
ROOTS
SHIELD

EVS4ALL *(new)*
ECOSYNBIO
ULTIMATE
ASCEND
REEACH
SMARTFARM
MARINER
REFUEL
NEXTCAR
RANGE

Alumni

MOSAIC
ALPHA
CHARGES
REBELS
FOCUS
SOLAR ADEPT
HEATS
GENI
GRIDS
IMPACCT

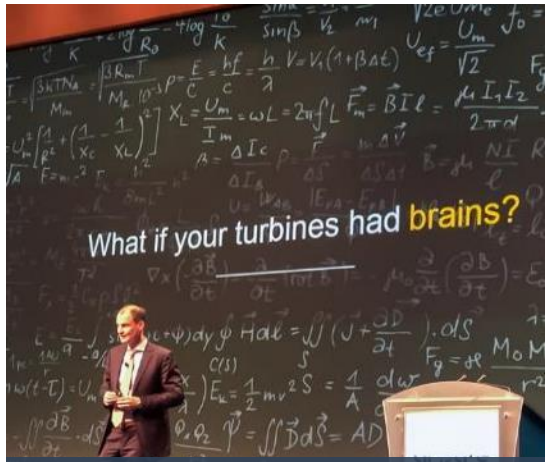
ARID
MONITOR
DELTA
SWITCHES
METALS
REACT
BEETIT
ADEPT

TERRA
REMOTE
TRANSNET
AMPED
MOVE
PETRO
ELECTROFUELS
BEEST

+ OPEN 2009, 2012, 2015, 2018, & 2021 Solicitations
+ Seedlings, Competitions, Complementary Exploratory Topics
+ SCALEUP 2019 & 2021

arpa·e energy innovation summit

Highly Selective Technology Showcase



Inspiring Keynotes

Unparalleled Networking

Fast-Paced Technology Pitches

arpae-summit.com

May 22-24, 2024 | Dallas, Texas

Technology Acceleration Model: Focused Area Program Development

Power Systems for Aviation (CABLES)

Large Power Transformers (INSULATE)

CIRCUITS

SWITCHES

Project Handoff

Transition Toward Market Adoption

PNDIODES

BREAKERS (MVDC) and kV Devices (OPEN2018)

Ongoing Technical Review

EXECUTE

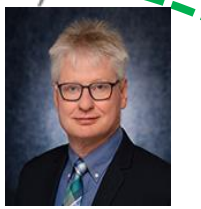
ULTRAFAST GOPHURRS

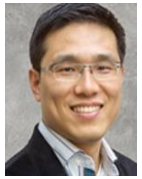
SF6 Replacement In Switchgear

Program Conception (Idea/Vision)

ENVISION

Macro Grid





PROGRAM DEVELOPMENT CYCLE

Workshop

Contract Negotiations & Awards

ESTABLISH

ENGAGE

Program Approval

NSTC

Project Selection

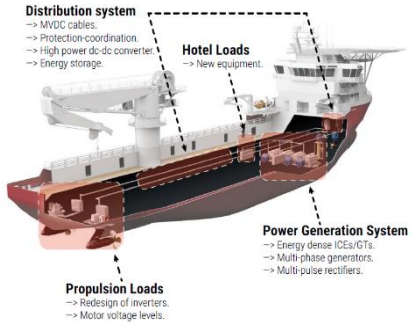
EVALUATE

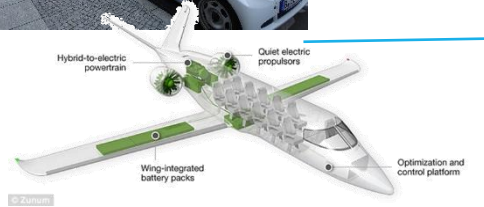
FOA Development & Issuance

Proposal Rebuttal

Merit Review of Proposals

Current and Considered Developments in DC Markets



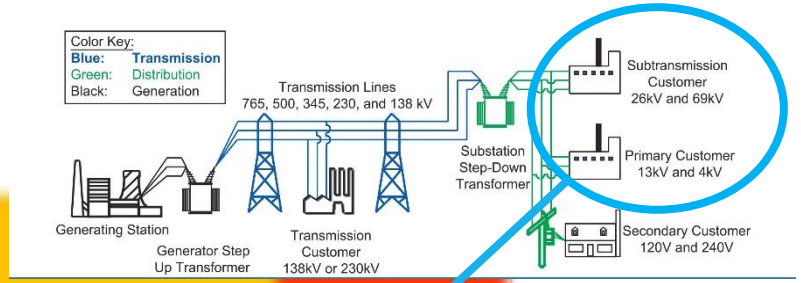


>12GW

Medium Voltage

High Voltage

>1000kV



Low Voltage

SWITCHES

Strategies for Wide-bandgap, Inexpensive Transistors for Controlling High Efficiency Systems

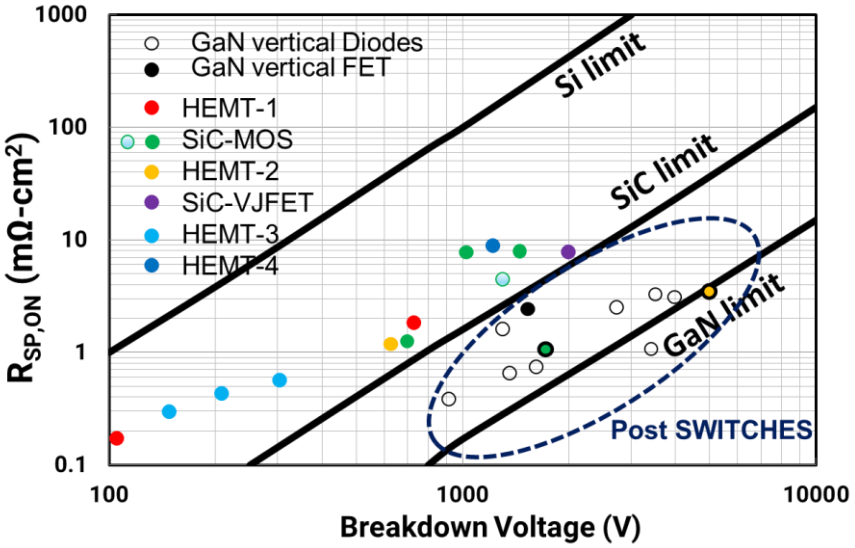
Launched by Timothy Heidel

Program Director: Isik C. Kizilyalli

2014
$34.3 Million
14 projects

Enable the development of high voltage (1200+ V), high current (100+ A), wide-bandgap power semiconductor devices that have the potential for functional cost parity ($/A) with Si devices

Program demonstrated GaN vertical devices approaching 5 kV and their pathway to 20 kV



Monolith Semiconductor, "Advanced Manufacturing for SiC MOSFETS"

- **6" SiC wafers in CMOS Si foundry: Low Cost**
- **Demonstrated**
  - 150 A, 950V SiC Diodes
  - 100 Amp, 15 mΩ, 1200V MOSFETs
  - Device stability of packaged devices at 175°C (and initial on-wafer results at 225°C)

Discrete Device Price	≤ $0.10 /A
Breakdown Voltage	≥ 1200 V

Continuous Drain Current	≥ 100 A
Specific R_{DSON}	< 3 mΩ*cm² @ V_{GS} = 15 V

Link: More about the SWITCHES Program

CIRCUITS

Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors

Program Director: Isik C. Kizilyalli

Use advanced circuit topologies and fundamentally higher performing WBG semiconductor materials to realize efficiency gains both directly and indirectly in electric power conversion

- **Innovate on circuit topology and controls to increase power density**
- **Innovate on packaging and integration to reduce parasitics**
- **Manage conductive and radiative noise (EMI) of fast switching devices**
- **Manage reliability to reduce risk and cost**

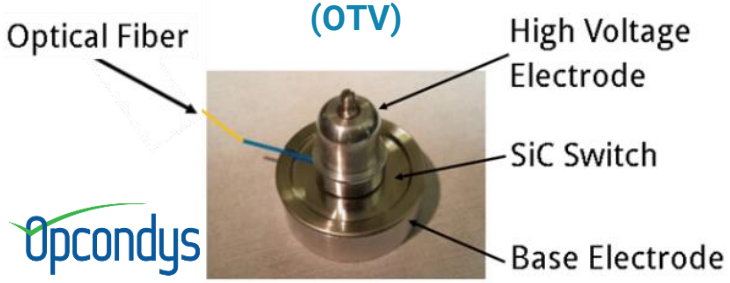
VIRGINIA TECH

2 MW, 24 kV Modular Converter

200 kW SiC Motor Drive

UNIVERSITY OF ARKANSAS

20 kV SiC Optical Transconductance Varistor (OTV)



Power and voltage	≥ 10 kW & ≥ 600 V	Power density	≥ 9.15 kW/l
Efficiency	≥ 97.5% @ rated power	Specific power	≥ 5 kW/kg

Link: More about the CIRCUITS Program

BREAKERS

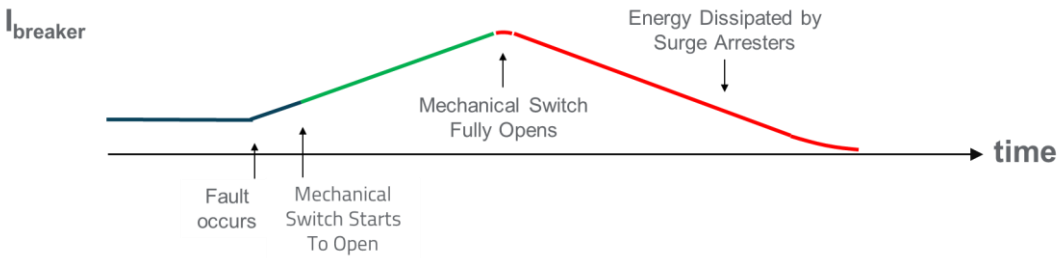
Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

Program Director: Isik C. Kizilyalli

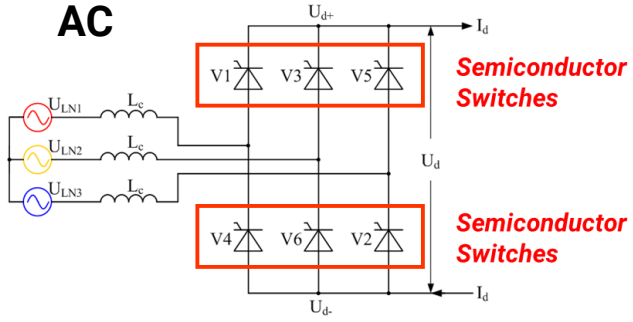
2018
$36.7 Million
11 projects

Enable and create MVDC markets in the range of 1.5 kV – 100 kV by developing novel DC circuit breaker technologies.

DC Has No Zero Crossing Resulting In Persistent Arcs

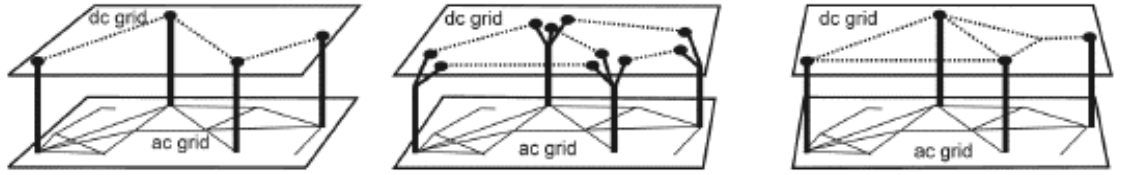


DC Systems Require Faster Breaking Times Compared to AC



Can only handle **2 – 3 times** the nominal current for **<5ms**

MVDC circuit breakers will enable MVDC distribution which can save 1.1 quads of energy per year, reduce U.S. emissions by 3% via electrification of transportation, and lower offshore oil and gas rig costs by 5%.



Point-to-Point → Collection of Point-to Point → Multi-point DC Network Mesh

MVDC Distribution: DC network that delivers medium voltage power across interconnected sources and loads.

BREAKERS

Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

Program Director: Isik C. Kizilyalli

2018
$36.7 Million
11 projects

Program Technical Requirements

ID	Category	Target
1.1	Rated Voltage	1kV DC ≥ V ≥ 100kV DC
1.2	Power*	≥ 1MW
1.3	Efficiency	≥ 99.97%
1.4	Response Time	≤ 500µs
1.5	Lifetime	≥ 30,000 cycles, ≥ 30 years
1.6	Nuisance Trips	≤ 0.1%
1.7	Power Density*	≥ 60 MW/m^3
1.8	Cooling	Passive or Forced Air

**Instantaneous Power*

Link: More about the BREAKERS Program

BREAKERS

Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

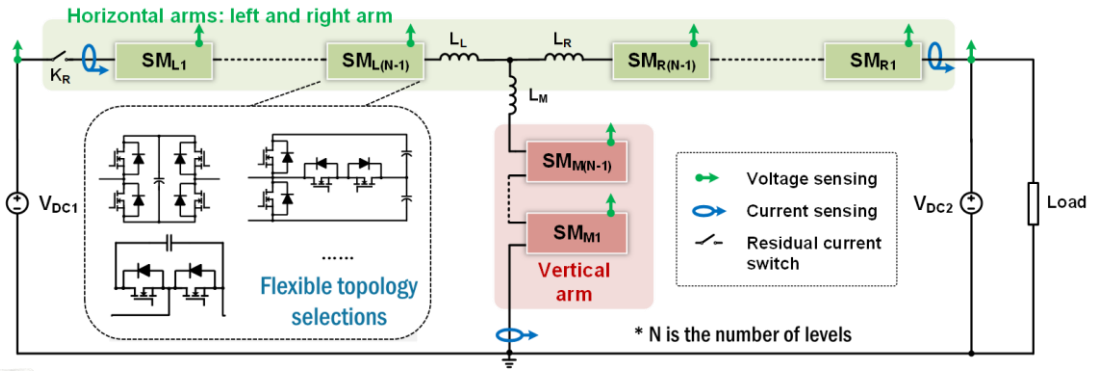
Program Director: Isik C. Kizilyalli

BREAKERS Program Outcomes:
- 116 Publications
- 26 Subject Inventions
- 5 Patents Issued

2018
$36.7 Million
11 projects

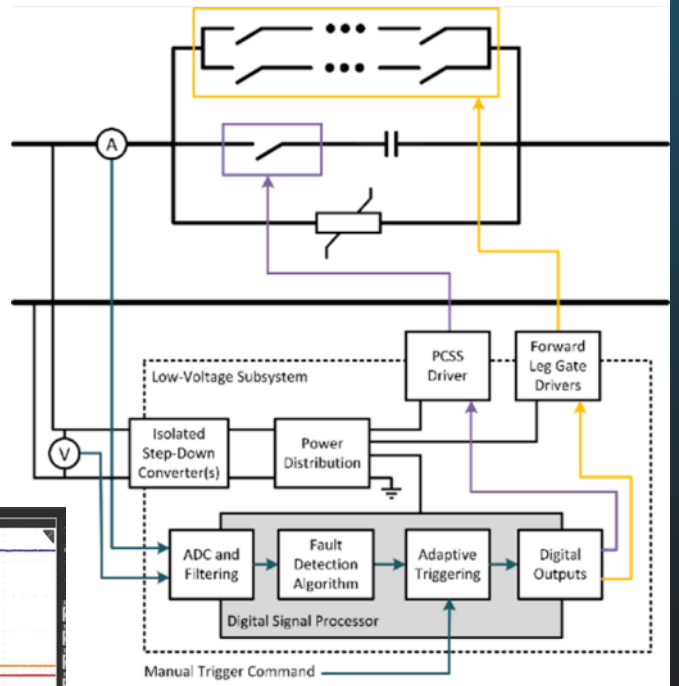
Solid-State Medium Voltage DC Circuit Breakers

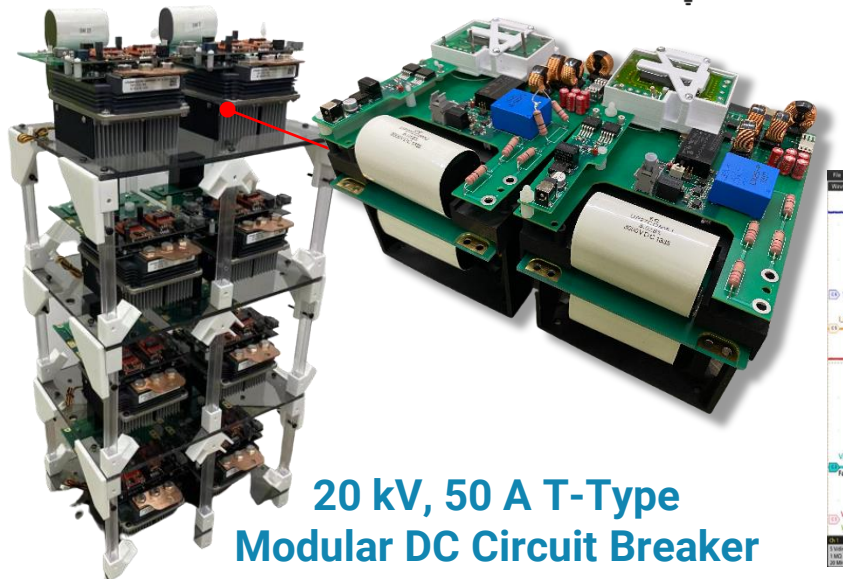
The Ohio State University



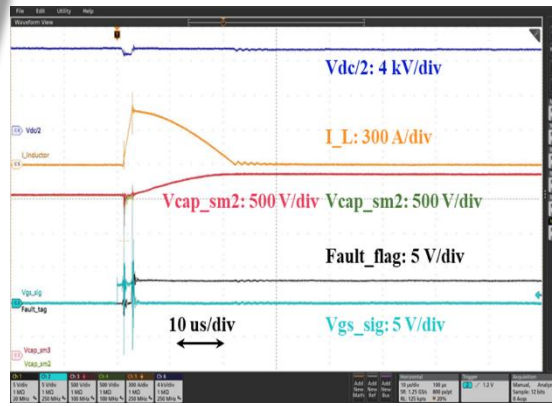
Sandia National Laboratories

SiC JFETs





20 kV, 50 A T-Type Modular DC Circuit Breaker



Drexel University

4 kV, 100 A, <80 µs

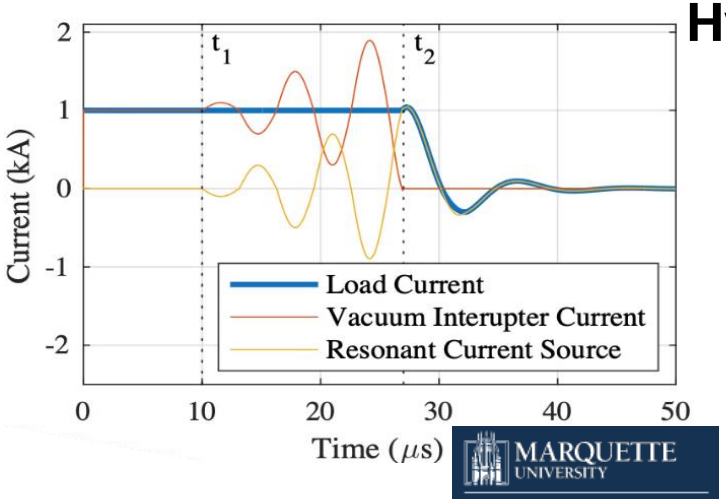
BREAKERS

Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

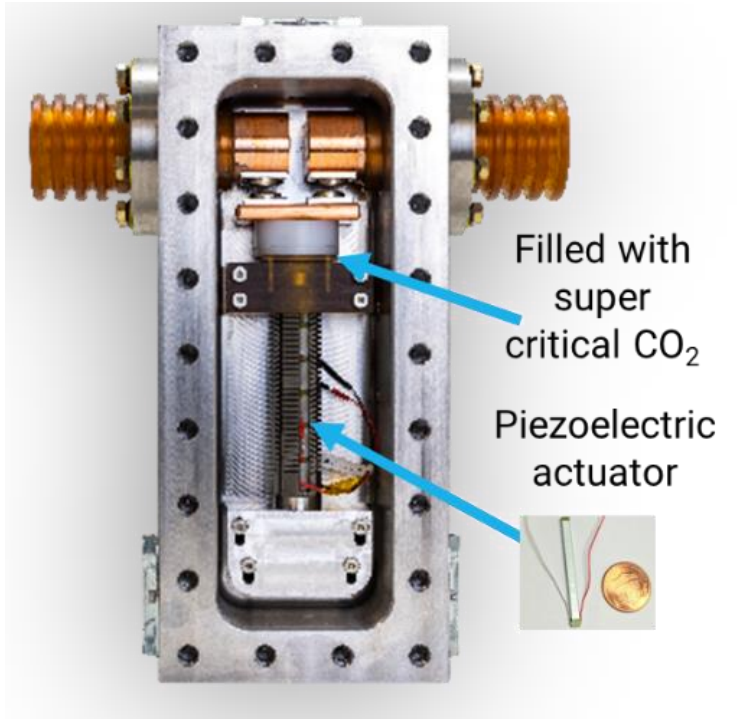
Program Director: Isik C. Kizilyalli

BREAKERS Program Outcomes:
- 116 Publications
- 26 Subject Inventions
- 5 Patents Issued

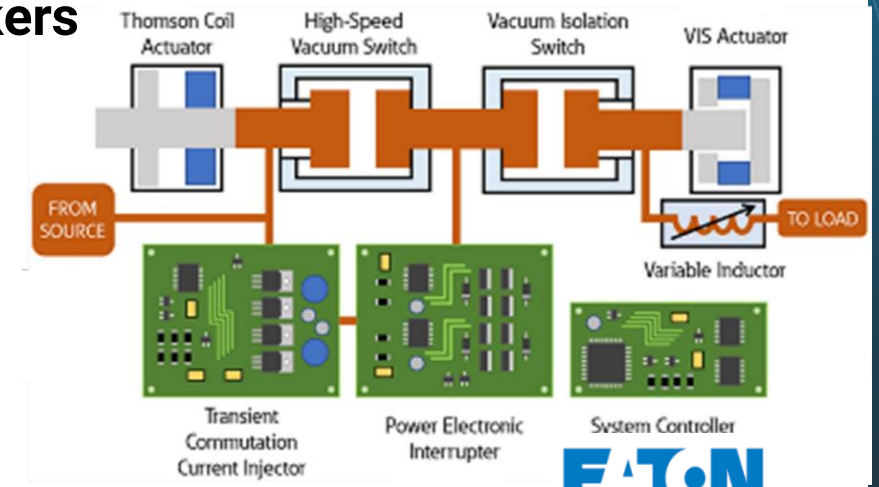
2018
$36.7 Million
11 projects

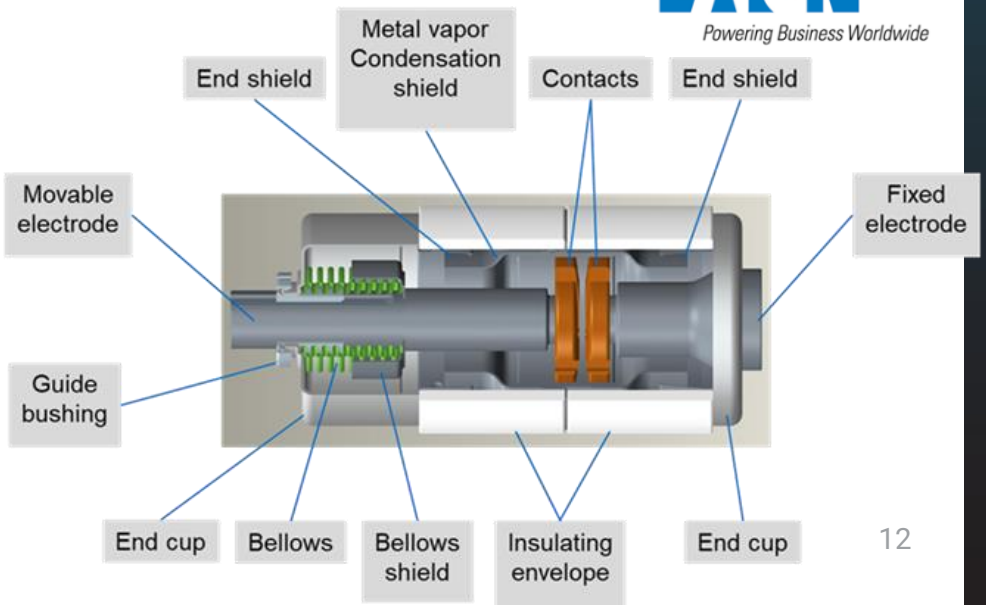


Hybrid Medium Voltage DC Circuit Breakers



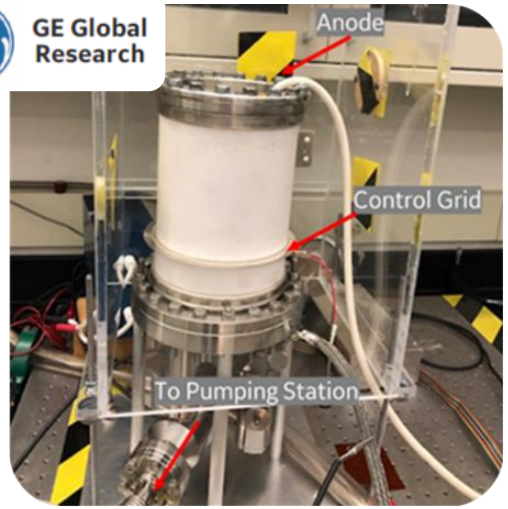
Georgia Institute of Technology



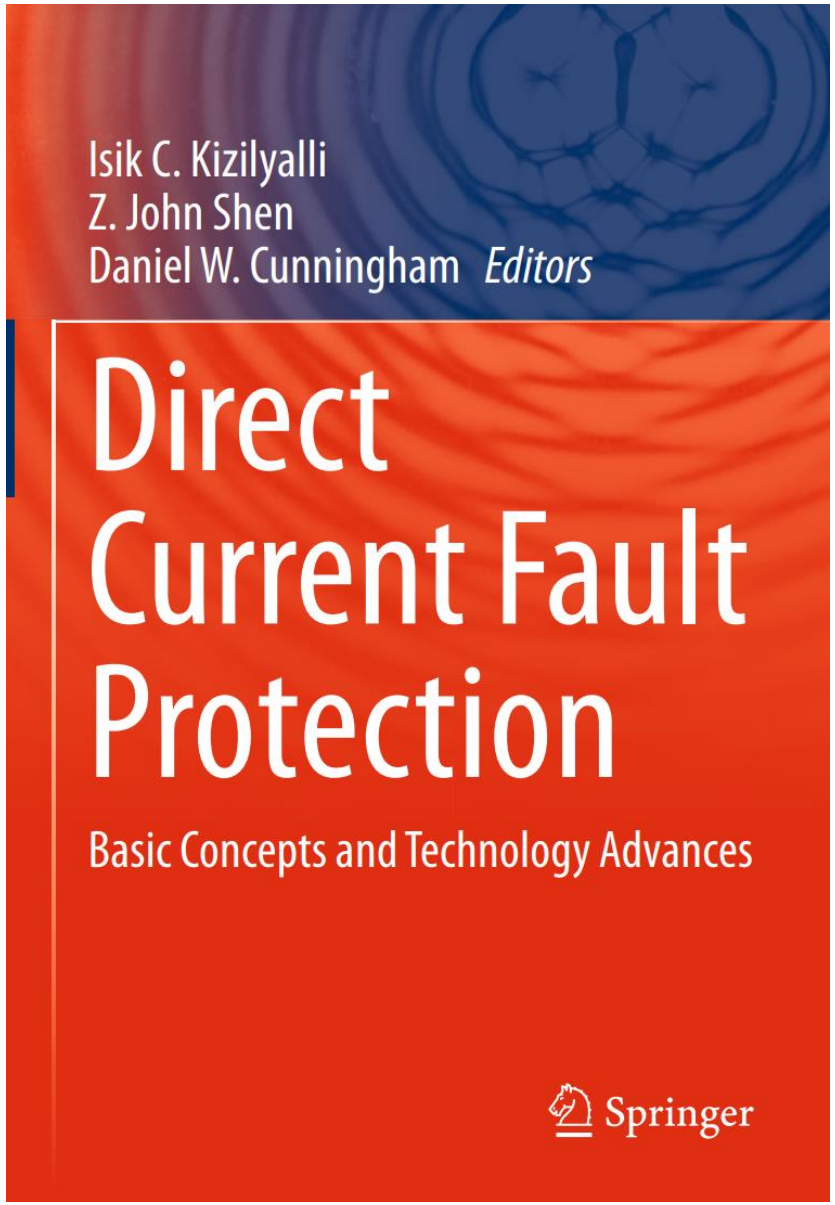


Inline Gas Discharge Tube

GE Global Research



April 2023



Contents

SF6-FREE

SF_6-Free Routes for Electrical Equipment Exploratory Topic

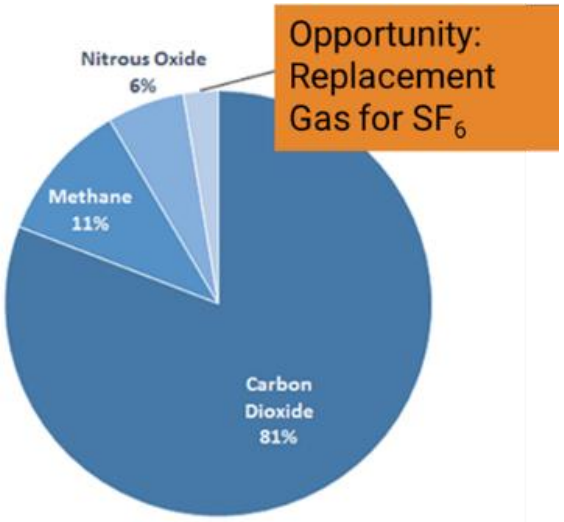
Program Director: Isik C. Kizilyalli

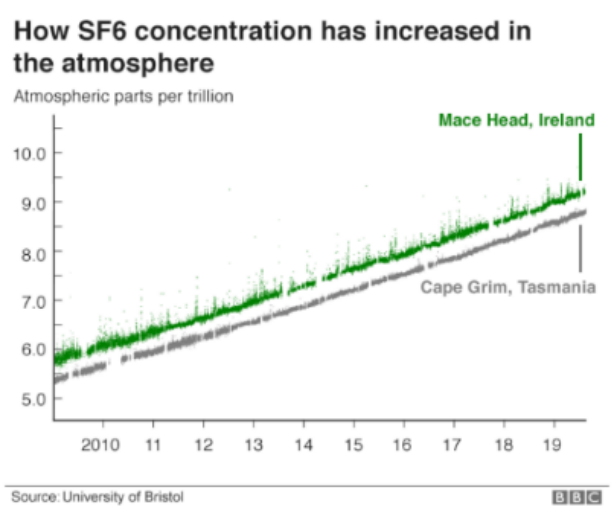
2021
$10 Million
3 projects

Address innovations in low greenhouse gas (GHG) alternatives for gas-insulated equipment in the electric transmission and distribution sector (see AB 32 California)

- High-voltage switchgear rely heavily on SF_6 for electrical insulation, current interruption, and arc quenching - unique dielectric properties
- **SF_6 emissions from the electric T/D sector pose a significant climate risk as a potent and long-lived greenhouse gas (GHG).**

Greenhouse Gas	Global Warming Potential (100 year time span)
SF_6	22,800
HFC	12–14,800
PFC	6,288–17,340





Link: More about the SF6-FREE Exploratory Topic

SF6-FREE

SF_6-Free Routes for Electrical Equipment Exploratory Topic

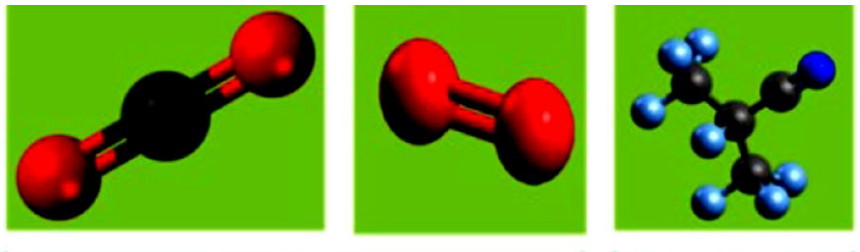
Program Director: Isik C. Kizilyalli

2021
$10 Million
3 projects

245 kV AC outdoor dead-tank power circuit breaker using g3TM gas mixture as the dielectric

GE VERNOVA

AC outdoor dead-tank CB with g3TM gas undergoing dielectric testing as part of ARPA-E project



- ~40% of mass of SF_6 in circuit breaker
- GWP: 300 kg CO_2e, 100y

g3 green gas for grid

Georgia Institute of Technology

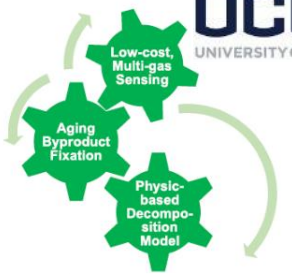
UNIVERSITY of WISCONSIN UWMILWAUKEE

TESLA 245 kV AC circuit breaker using supercritical fluid as the dielectric and arc-quenching medium

SF_6 alternative life-cycle management framework

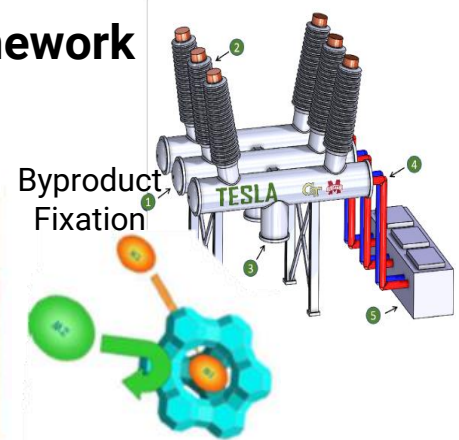
UCONN UNIVERSITY OF CONNECTICUT

GE VERNOVA



Leak Detection
Aging Signature Sensing

Byproduct Fixation



Hermosillo, V., I. Garcia T. Irwin, L. Darles, C. Gregoire, "Desarrollo de un Interruptor de Tanque Muerto de 145 kV Aislado con una Mezcla de Gases Compuesta de $CO_2/O_2/C_4FN$", IEEE RVP, August 8th, 2023, Acapulco, MX

INSULATE

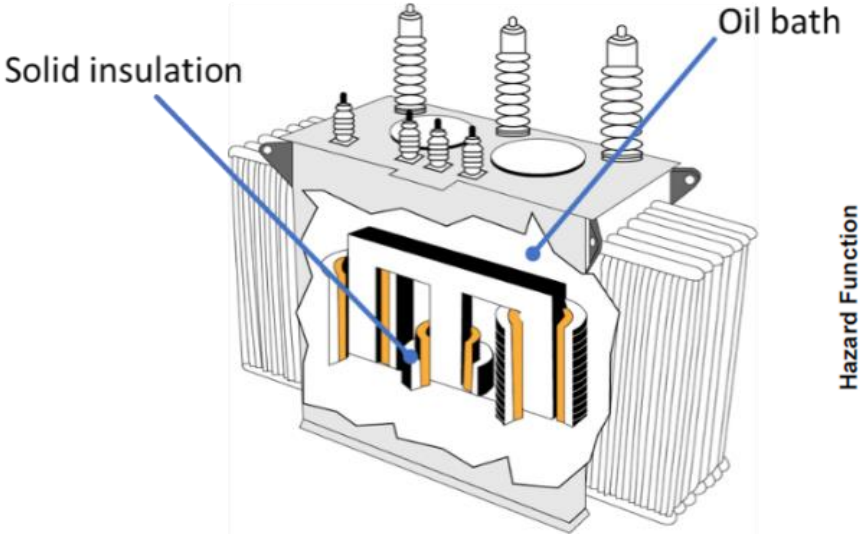
Program Director: Isik C. Kizilyalli

Insulating Nanofluids and Solids to Upgrade our Large Aging Transformer Equipment Exploratory Topic

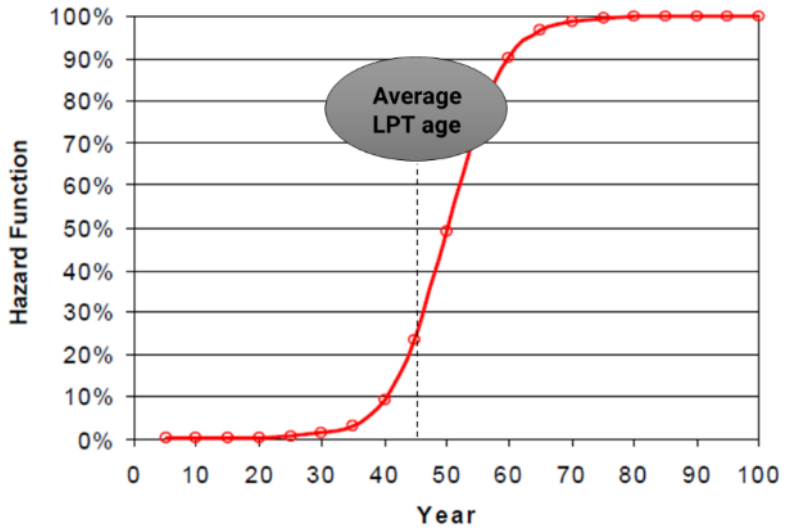
2021
CHANGING WHAT'S POSSIBLE
$3.5+1.8 Million
3+1 projects

Increase the durability, reliability, and resilience of large power transformers through improvements in the vital solid and oil insulating elements

Large Power Transformers (LPTs) carry > 90% of the Nation's power



70% are 25+ years old



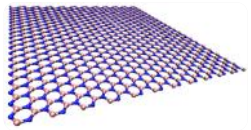
2015 CIGRE survey of 964 prominent transformer failures found the major reason for transformer collapse was dielectric (i.e., insulation failure).

Bartley, William H. "An Analysis of Transformer Failures." *Hartford, CT* (1997).
DOE. Large Power Transformers and the Electric Grid. 2012.

Link: More about the INSULATE Exploratory Topic

INSULATE program goal is to double transformer lifetime

Functionalized 2D hexagonal boron nitride nanoparticles



Commercial Transformer Mineral Oil

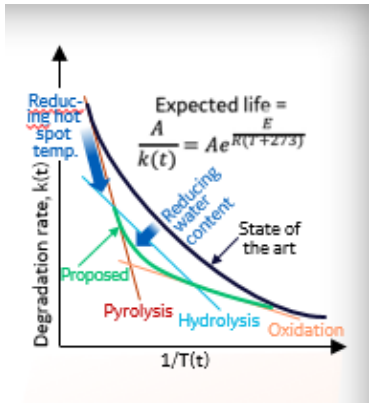
Nanofluid with suspended h-BN

Thermal Conductivity (W/mK)	Viscosity (cp)
0.193	10.5

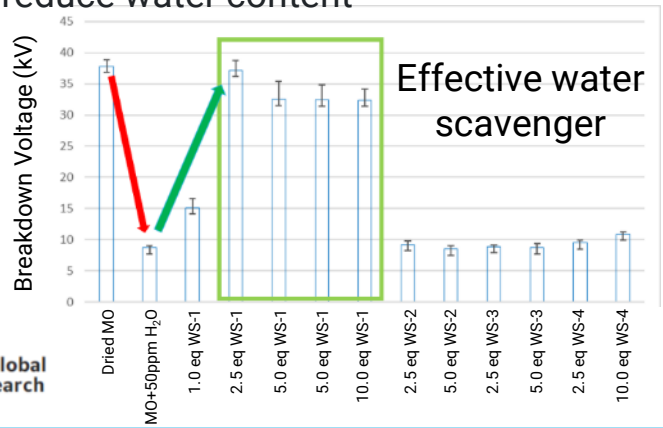
h-BN: excellent electrical insulator, high temperature resistance, high chemical inertness, and superhydrophobicity

C-Crete TECHNOLOGIES

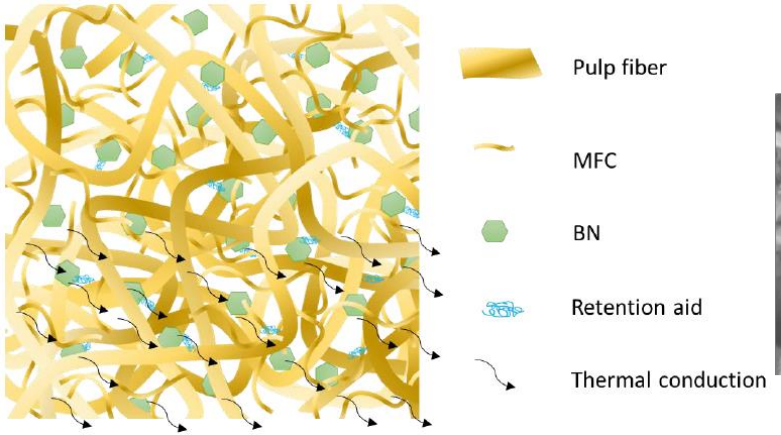
- TiO_2-based nanofluid to improve thermal conductivity and enhance dielectric strength
- Soluble water-scavenger to reduce water content



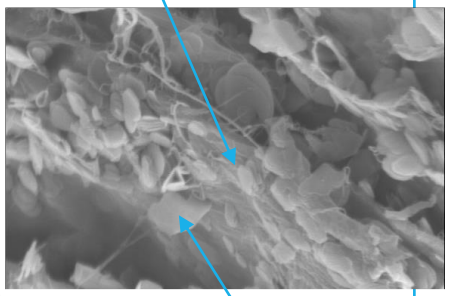
GE Global Research



Effective water scavenger



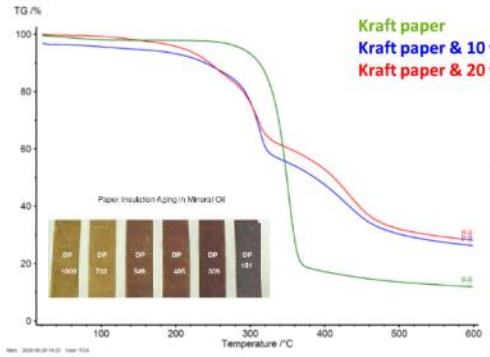
Microfibrillated cellulose (MFC) + pulp fiber

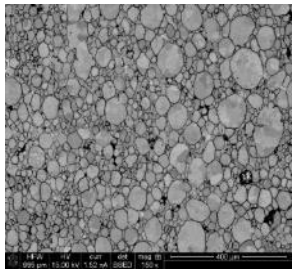


Boron nitride particle nano-additive

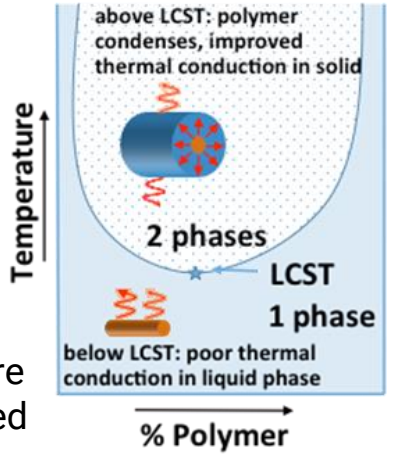
TEXAS The University of Texas at Austin

h-BN has high thermal conductivity and high dielectric constant





- Kraft paper remediation process
- Efficient CoFe/insulating shell transformer core
- Phase changing polymer additives for improved transformer oil heat transfer



Sandia National Laboratories

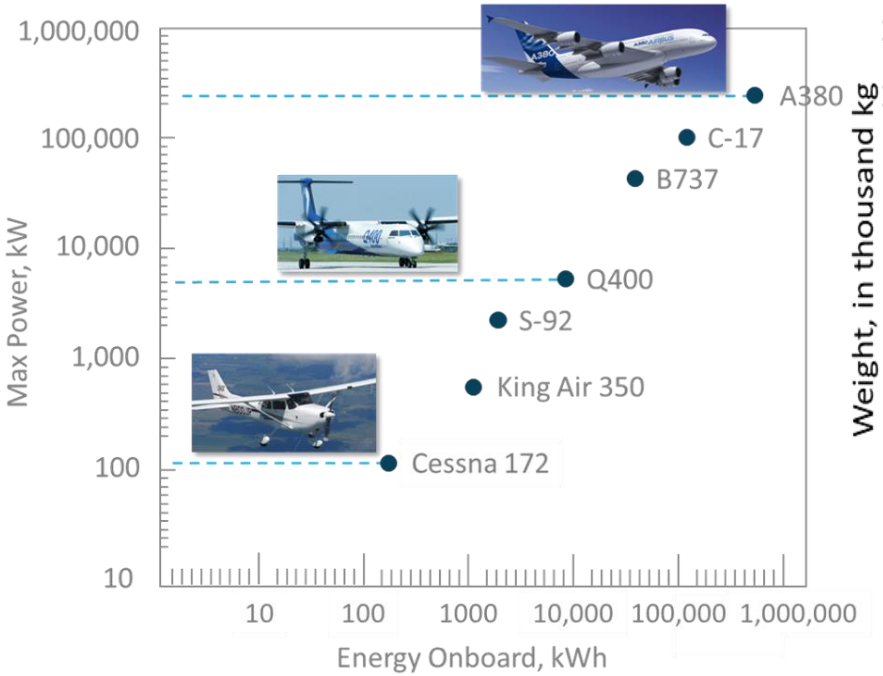
CABLES

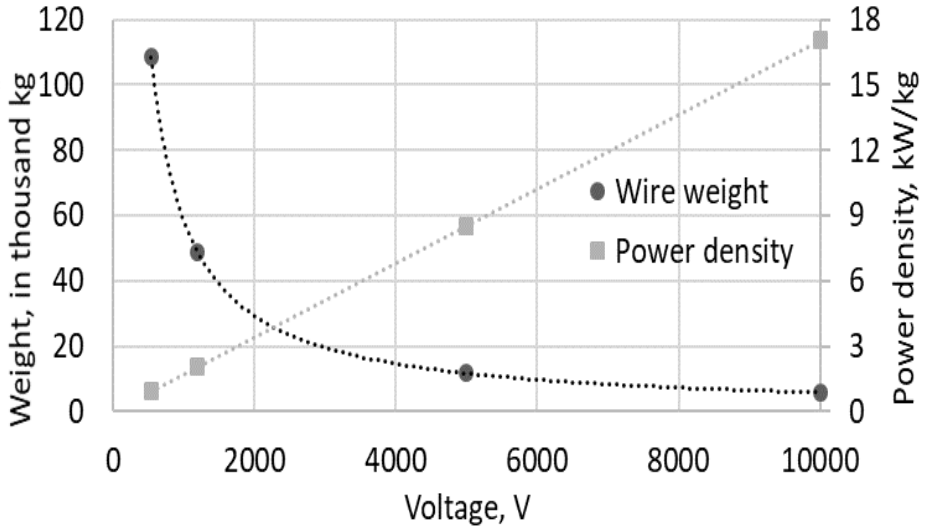
Connecting Aviation By Lighter Electrical Systems
Exploratory Topic

Program Director: Isik C. Kizilyalli

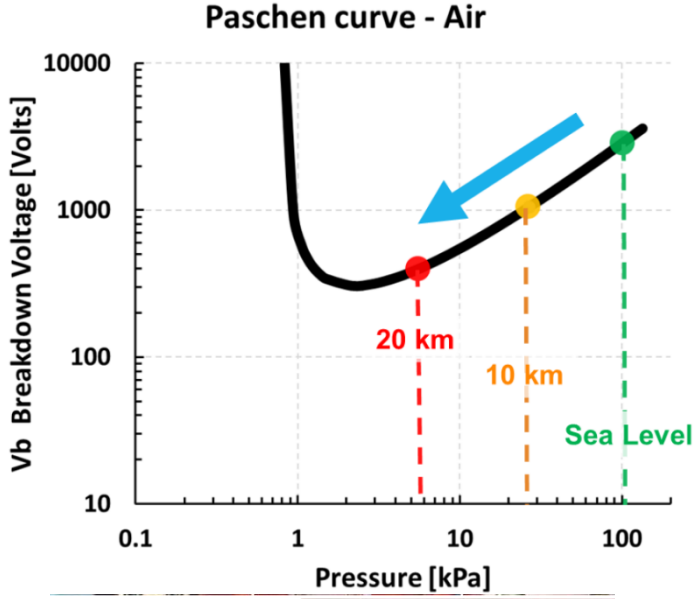
2021
$12 Million
7 projects

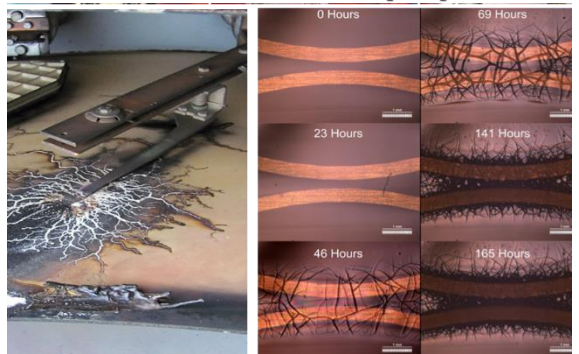
Develop technologies for medium-voltage (>10 kV) power distribution cables, connectors, and circuit breakers for fully electric aviation applications to enable megawatt scale distribution with minimal impact on weight while maintaining the high reliability and safety requirements of aviation.





Voltage *vs.* copper wiring weight (no insulation) and power density





Partial discharge leads to failure

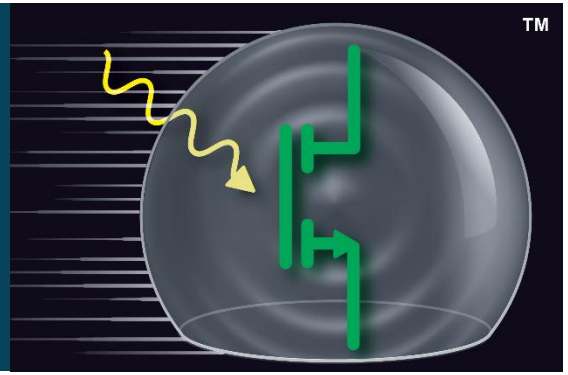
Source: National Academies of Sciences, Engineering, and Medicine. 2016. *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. Washington, DC: The National Academies Press.

Link: More about the CABLES Exploratory Topic

ULTRAFAST

Program Director: Olga Spahn

Unlocking Lasting Transformative Resiliency Advances by Faster Actuation of power Semiconductor Technologies

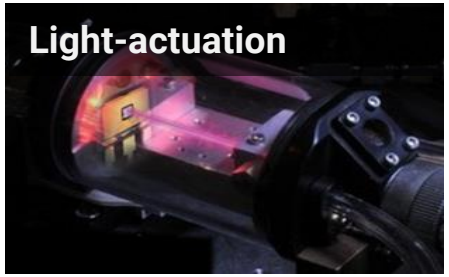


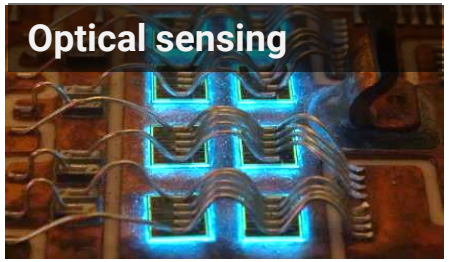
CHANGING WHAT'S POSSIBLE

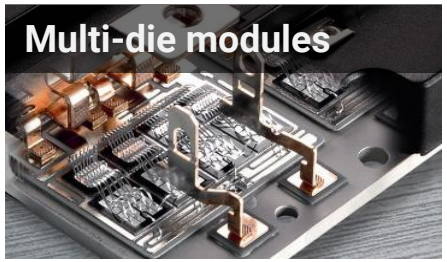
Kickoff Year	2024
Projects	15
Investment	$42M
Duration	36 months

Next generation material, device and module technologies for improved power distribution and control in future grid applications

- **Ultra-wide Bandgap materials for higher power individual devices and modules**
  [protection > 20 kV, > 250 A | continuous switching > 3.3 kV, > 10 A]
- **EMI mitigation for improved stacking reliability**
  [wireless/optical actuation, control and sensing]
- **Faster actuation – improved protection, better control, lower losses**
  [1-100 kHz | > 250 V/ns, > 100 A/ns | > 99% efficiency]
- **Better Size Weight and Power (SWaP)**
- **Supporting enabling technology – sensing, passives, packaging, gate drive technology**

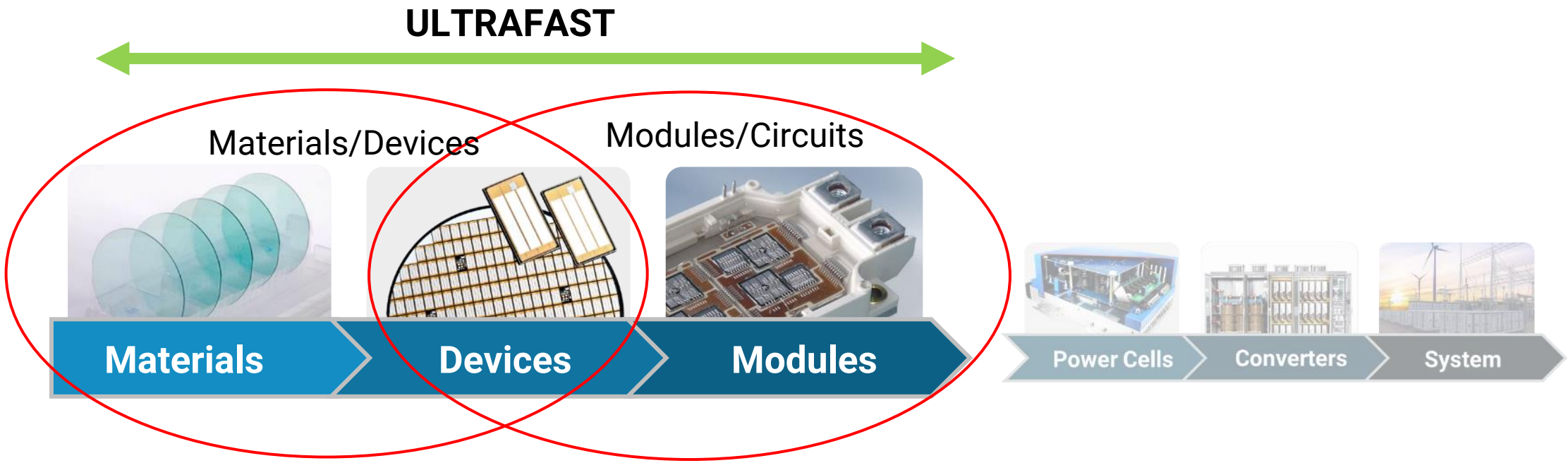




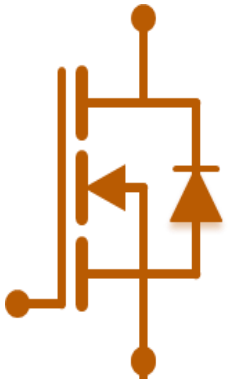


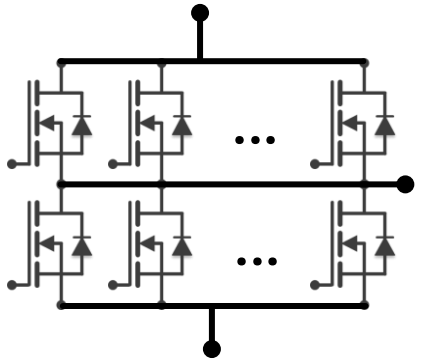
Link: ULTRAFAST Program Announcement Link: Power Magazine News Link: ARPA-E Website Info

ULTRAFAST Project Types



Risk: novel material/devices





Risk: integration complexity

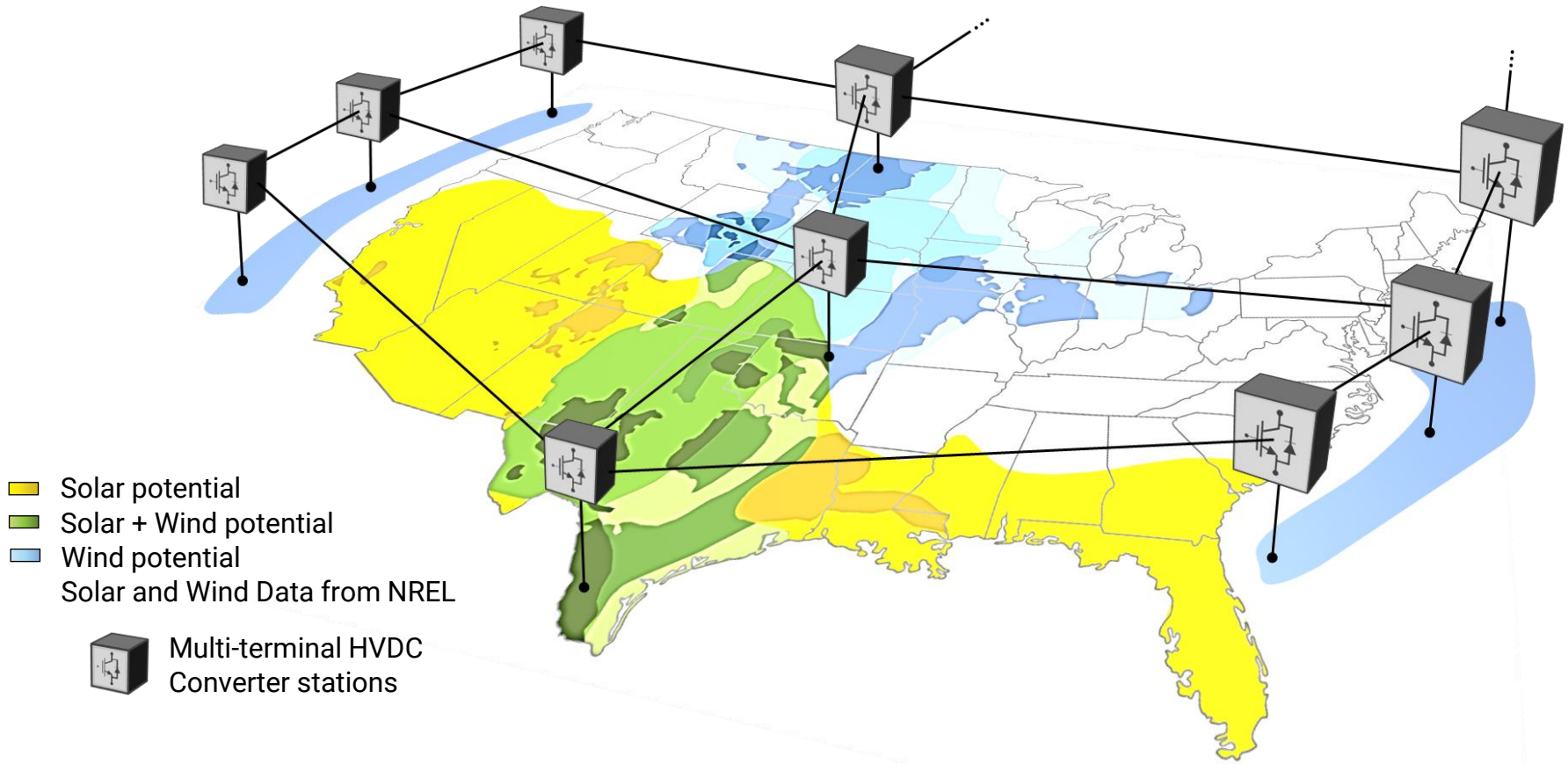
Program Director: Johan Enslin

CHANGING WHAT'S POSSIBLE

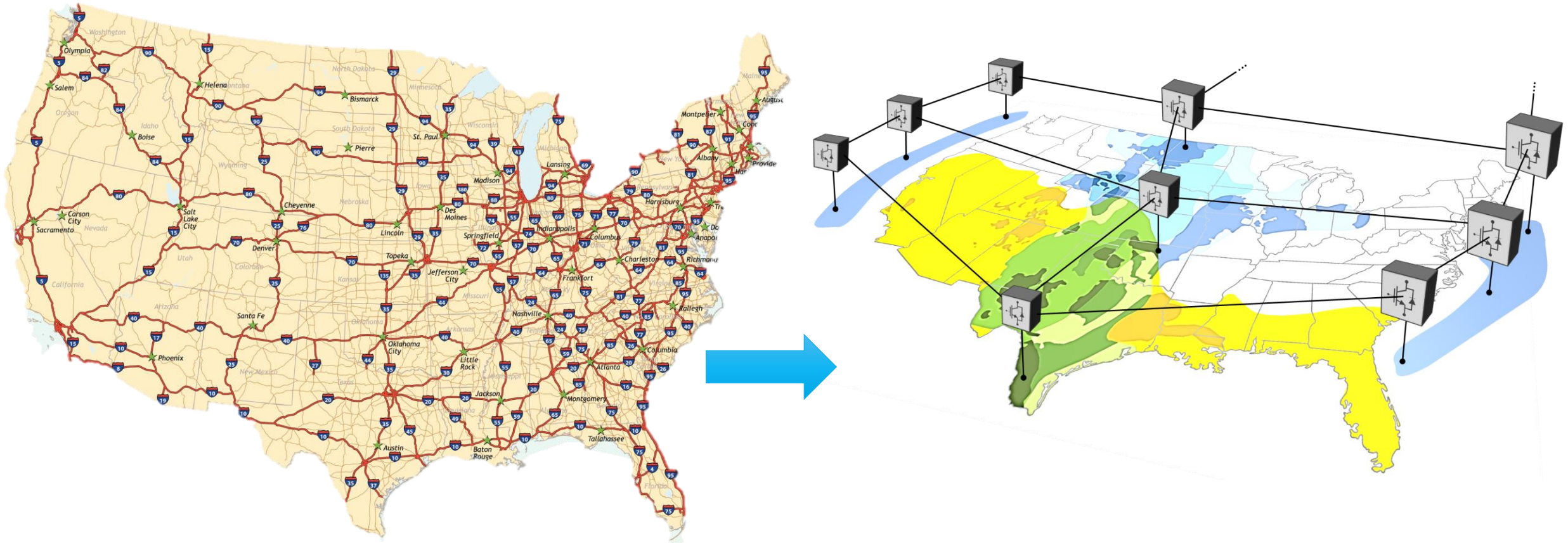
Potential New Program

MTDC Network to Support Grid Capacity for Carbon-free Generation

Kickoff Year	2025
Projects	TBD
Investment	TBD
Duration	TBD



Super Electronic Highway Grid is Needed!



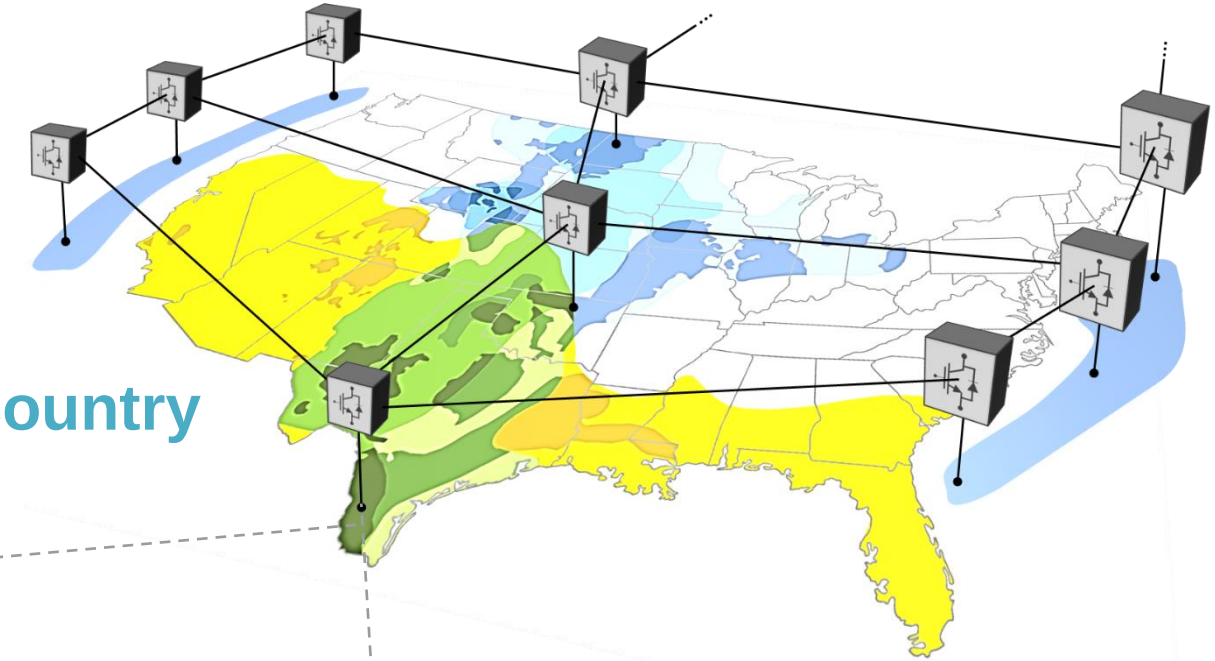
US Transportation Highway System and Transporting to an Electric Super Highway

Why do we need to Modernize the Power Grid?

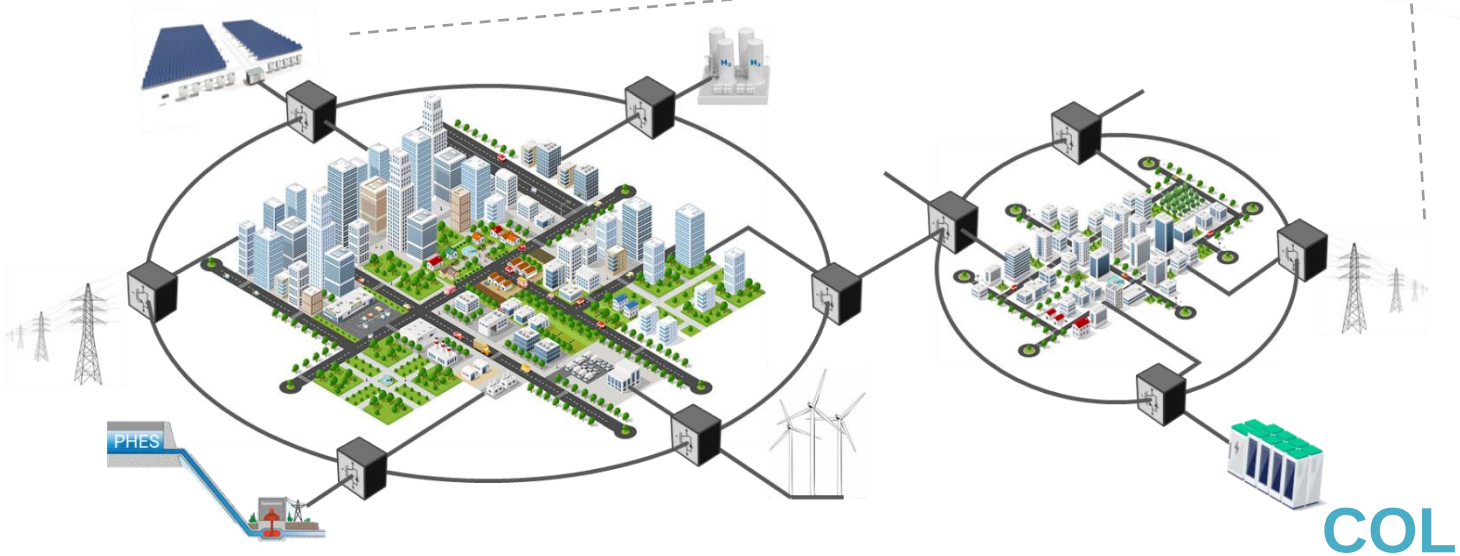
- 100 years old centralized T&D infrastructure for centralized plants
- Incompatible with carbon-neutral power generation integration
- Net-zero carbon goals by 2050 – Urgency for new technology

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

How are the grid's *architecture* evolving?



CONNECT Resources Across Country



COLLECT from Virtual Power Plants

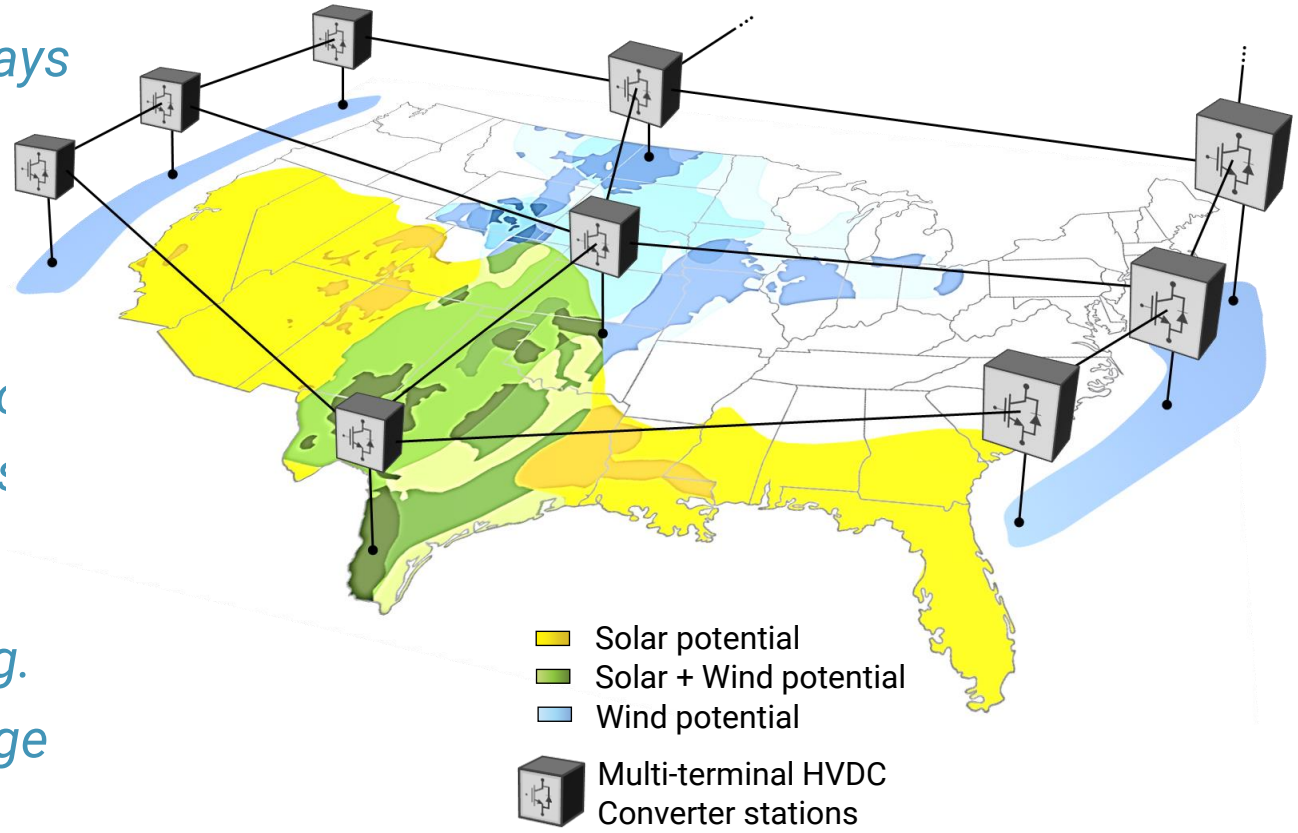
Designing tomorrow's Super Integrated Grid NOW!

CHANGING WHAT'S POSSIBLE

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

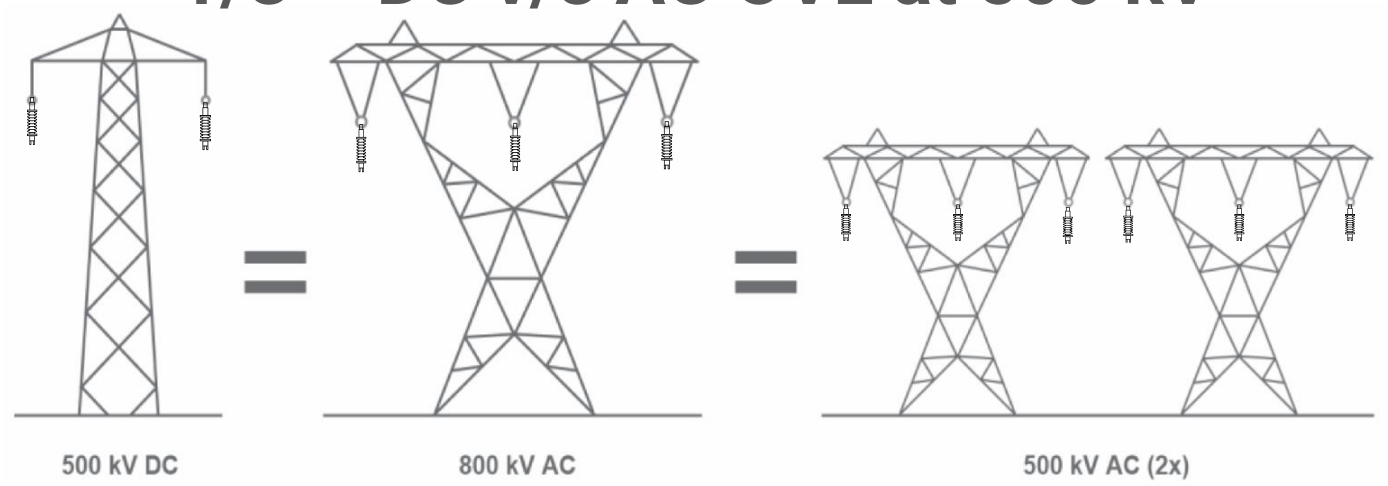
2. **Transform Integrated System Operations**
   - *Hybrid AC&DC Solid-state Substations*
   - *Release existing AC-Grid Capacity -2-3x*
   - *Provide Diversity and Equity in Interconnecti*
   - *Increase Distributed Resiliency through VPPs*

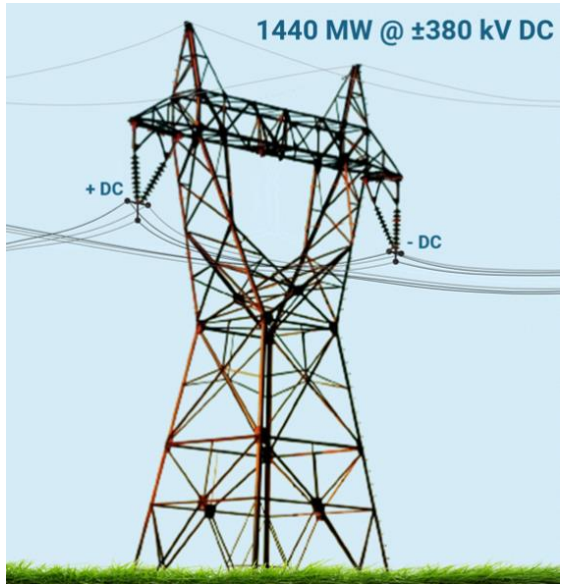
3. **Balance Energy Storage with Time Shift**
   - *Seasonable & daily renewable energy shifting.*
   - *Interconnecting Dynamic Pump-Hydro Storage*
   - *Power-2-X with H2 Storage*
   - *Integration of Chemical and Thermal Energy Transfer Networks*

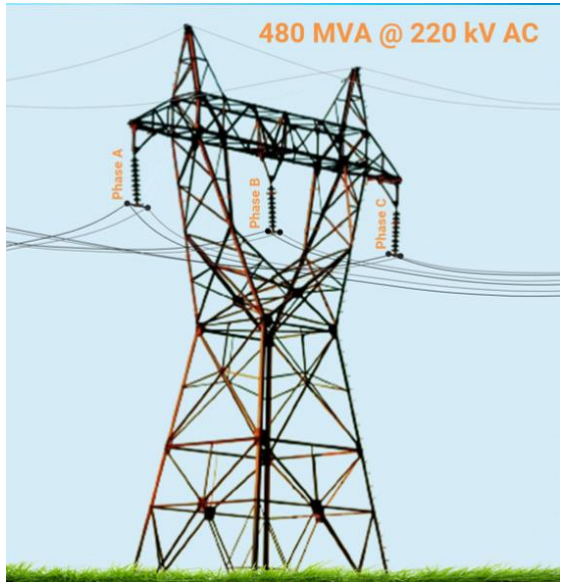


Utilizing Existing Grid Infrastructure – HVAC v/s HVDC

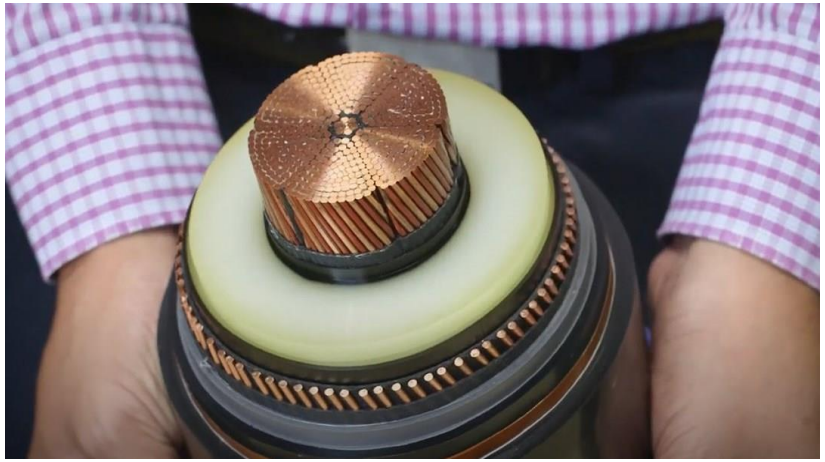
1/3 – DC v/s AC OVL at 500 kV







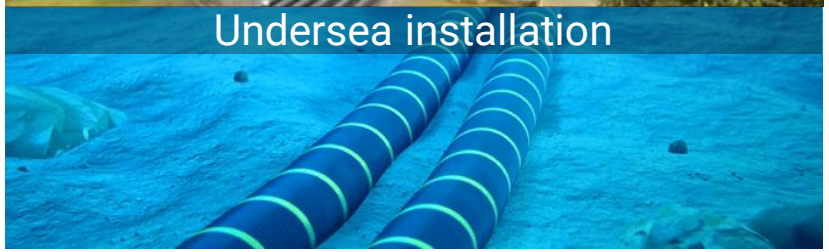
DC Enables Fully Imperceptible Infrastructure



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

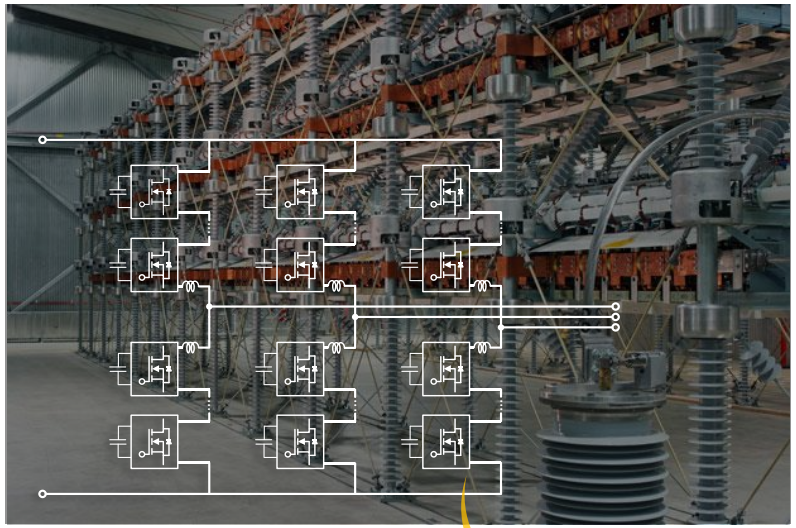


Technology Gaps

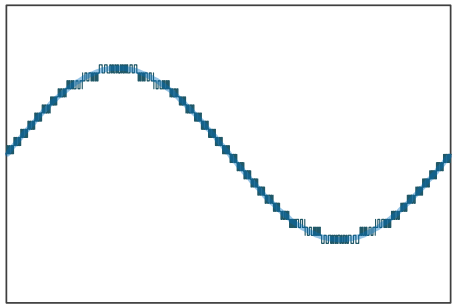
CHANGING WHAT'S POSSIBLE

- **New HVDC Converter Topologies**

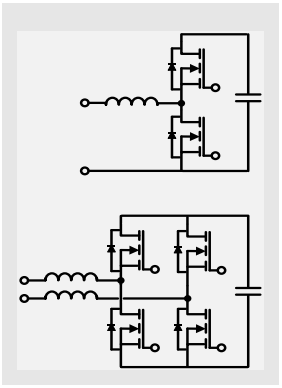
(Beyond state-of-the-art Modular Multi-level Converter)



n-level

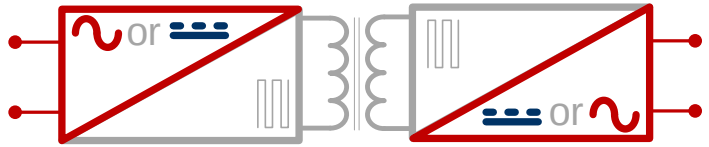


Power Cell

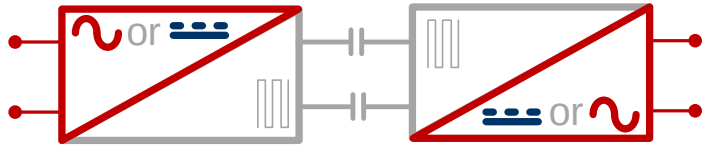


Now utilizing inductively or capacitively coupled power cells for significantly higher flexibility, modularity, and reliability

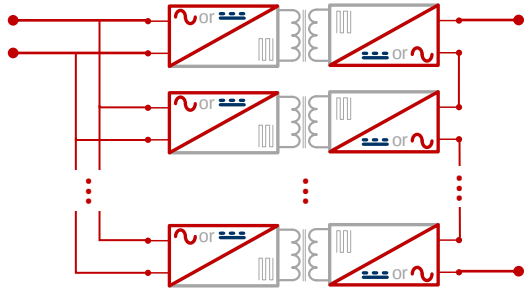
Inductively coupled power cells



Capacitively coupled power cells



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

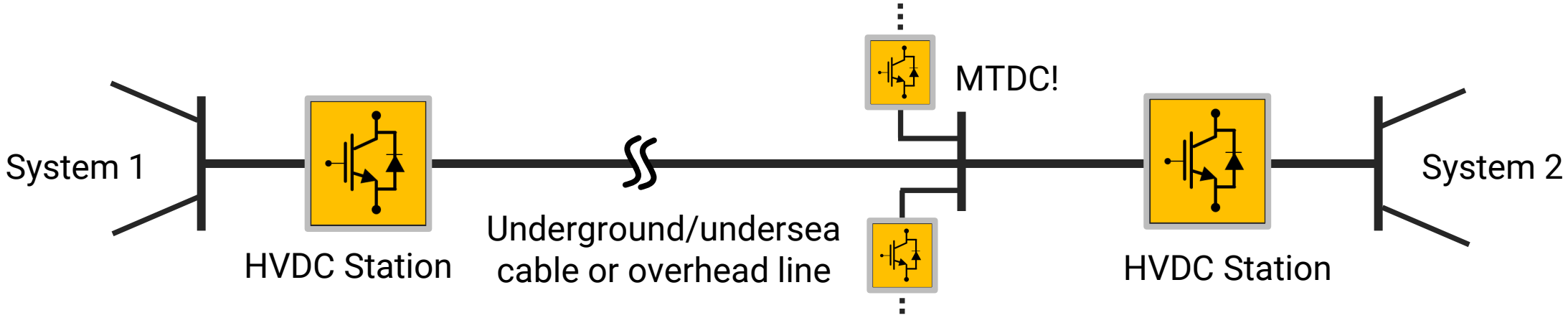


Experimentally validated with scaled-down hardware and P-HIL simulations

HVDC Stations

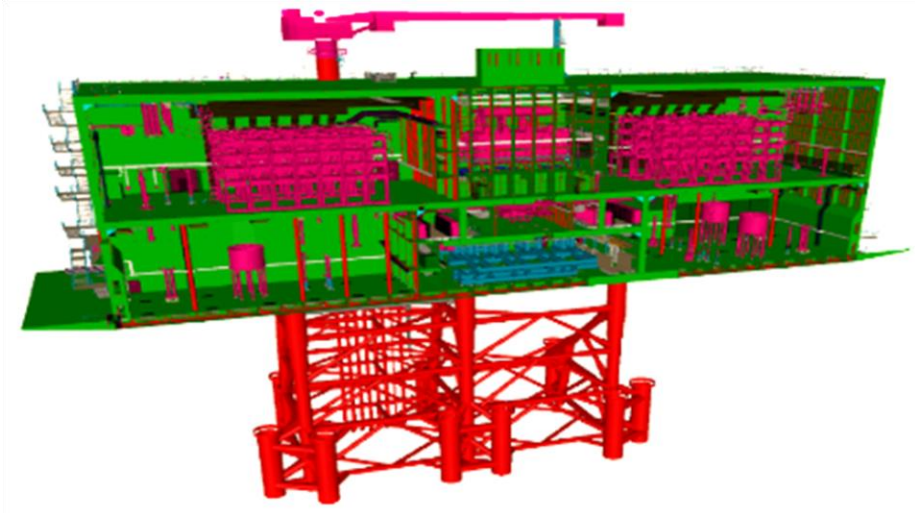
On-shore HVDC Station

Off-shore HVDC Station



Example: Dolwin 3 Offshore Platform (SOA)

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



Valve Hall

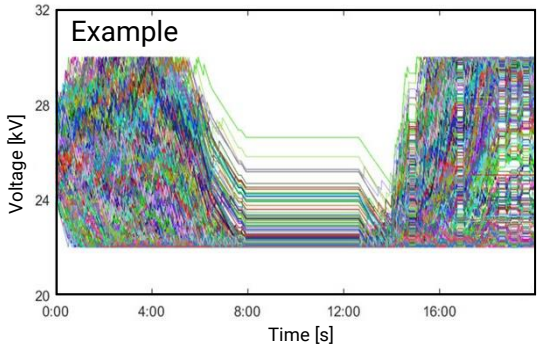
Images by GE Vernova

System-Level EMT Modeling for Planning and Operations

CHANGING WHAT'S POSSIBLE

Example: Simulated system

Converter station



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

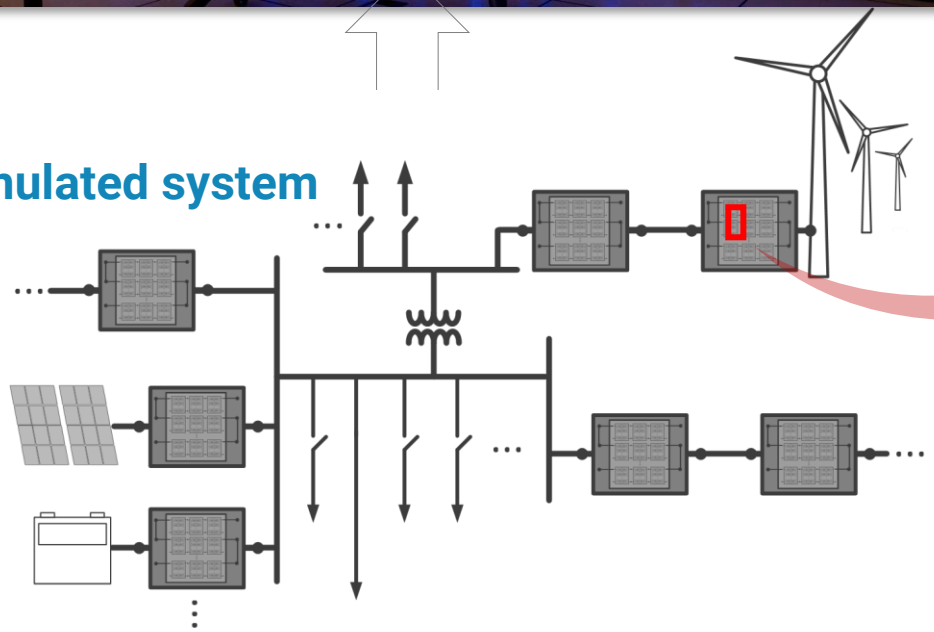
Component	Model
Power Module	
Power Cell/ Sub-module	
Converter "Valve" or DC Breaker	
Converter Station	

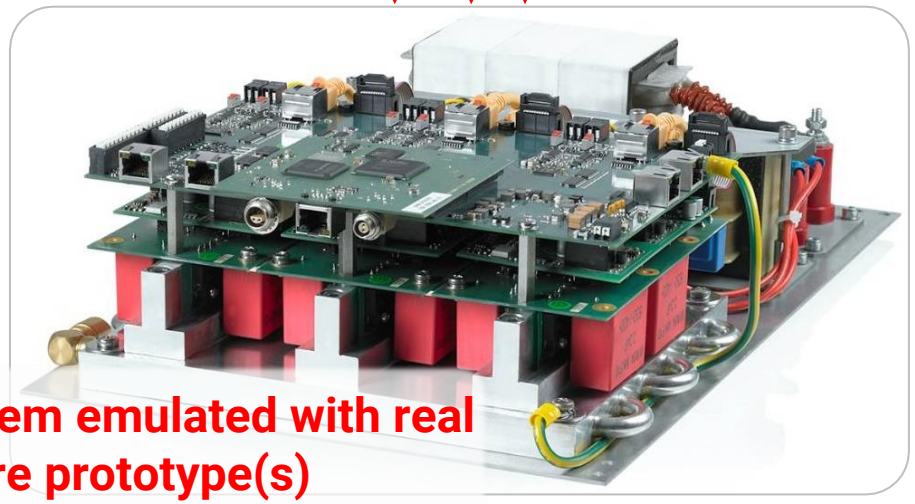
System-Level Emulation in Real-Time Environment, with P-HIL

Data

Power

Simulated system





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

Program Director: Johan Enslin

CHANGING WHAT'S POSSIBLE

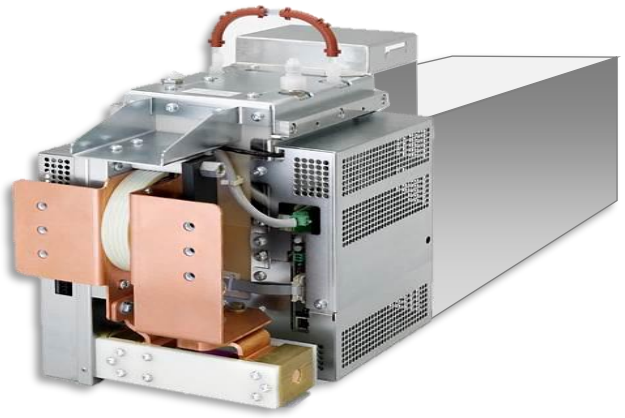
Potential New Program

MTDC Network to Increase Grid Capacity for Carbon-free Generation and Active Loads

Kickoff Year	2025
Projects	TBD
Investment	TBD
Duration	TBD

New Power Electronic Building Blocks for HVDC submodules

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

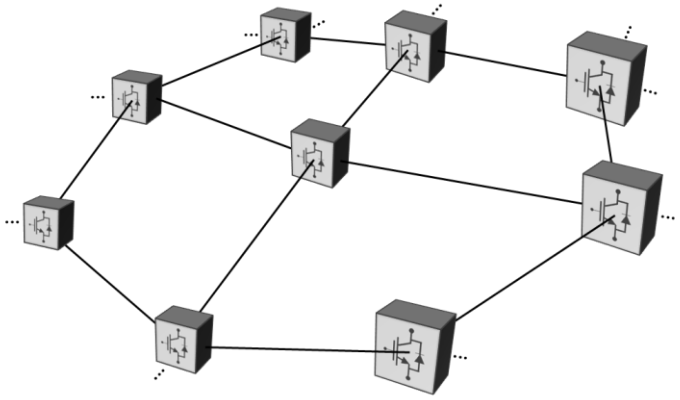


New Multi-Terminal HVDC Converter Station Design

5-fold power density and cost reduction (**from 250 m³/MW and $250 k/MW**)

System Integration and Operation

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



Thank you

Questions / Comments / Suggestions ?

Ask us about the Upcoming MTDC Workshop June 6/7 in DC

Johan Enslin, Program Director, ARPA-E, johan.enslin@hq.doe.gov

Isik Kizilyalli, Advisor, ARPA-E, isik.kizilyalli@hq.doe.gov