DOE Office of Electricity TRAC

Peer Review

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

PROJECT SUMMARY

DEMONSTRATION OF A 5 MVA MODULAR CONTROLLABLE TRANSFORMER (MCT) FOR A RESILIENT AND CONTROLLABLE GRID

The project team will design, build, and test a 5 MVA 24 kV/12 kV modular controllable transformer (MCT) and demonstrate its functionality, which includes modularity, interoperability through variable impedance and connection of multiple voltage levels, power flow control, and fail-normal design.

PRINCIPAL INVESTIGATOR

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WEBSITE

https://cde.gatech.edu/

The Numbers

DOE PROGRAM OFFICE:
OE – Transformer Resilience and Advanced Components (TRAC)

FUNDING OPPORTUNITY:
DE-FOA-0001876

LOCATION:
Atlanta, GA

PROJECT TERM:
06/01/2019 to 05/30/2022

PROJECT STATUS:
Current Awardee

AWARD AMOUNT (DOE CONTRIBUTION):
$1,798,315

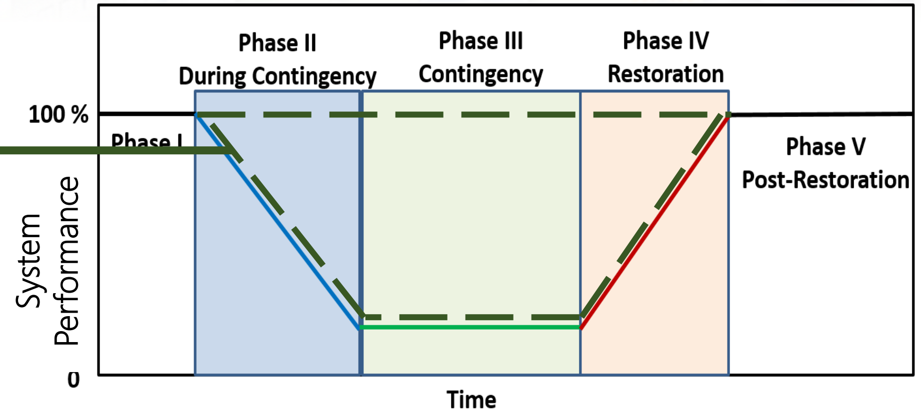
AWARDEE CONTRIBUTION (COST SHARE):
$495,032

Introduction: Grid Resiliency

- Key concerns of modern day grid:
  - Grid Resiliency
  - Cyber-Physical Security
  - Rapid restoration following extreme events
  - Dynamic Balancing of Load and Generation volatility.
- What is Grid Resiliency?
  - The ability of a system to return to an optimal/sub-optimal state following disturbances.
- The current infrastructure is not equipped to handle High Intensity Low Probability (HILP) events:
  - Weather-related emergencies (Hurricanes, Lightning Strikes)
  - Physical damage through terrorist attacks
  - Cyber-physical attacks
  - EMP bursts
- Critical Infrastructure sustaining damage:
  - Generators,
  - Transmission Line Network,
  - Substations and
  - Large Power Transformers (LPTs)

Resiliency Metric

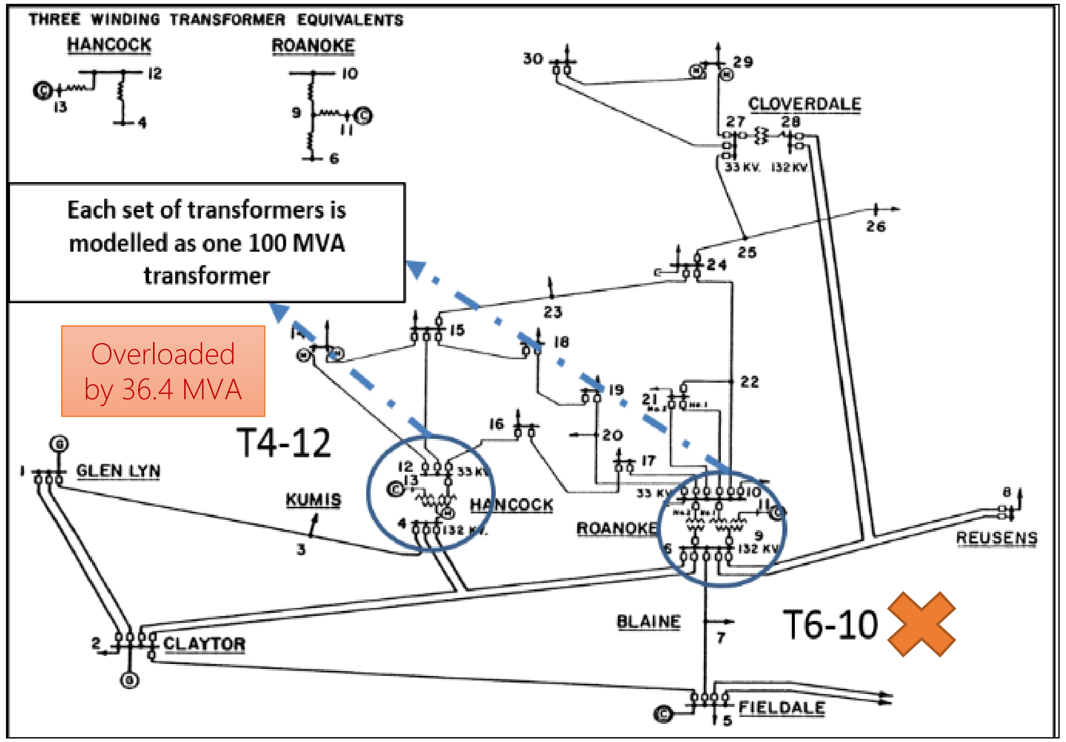
Smaller Trapezoid -> More Resilient



MVA-months lost could serve as a measure for resiliency

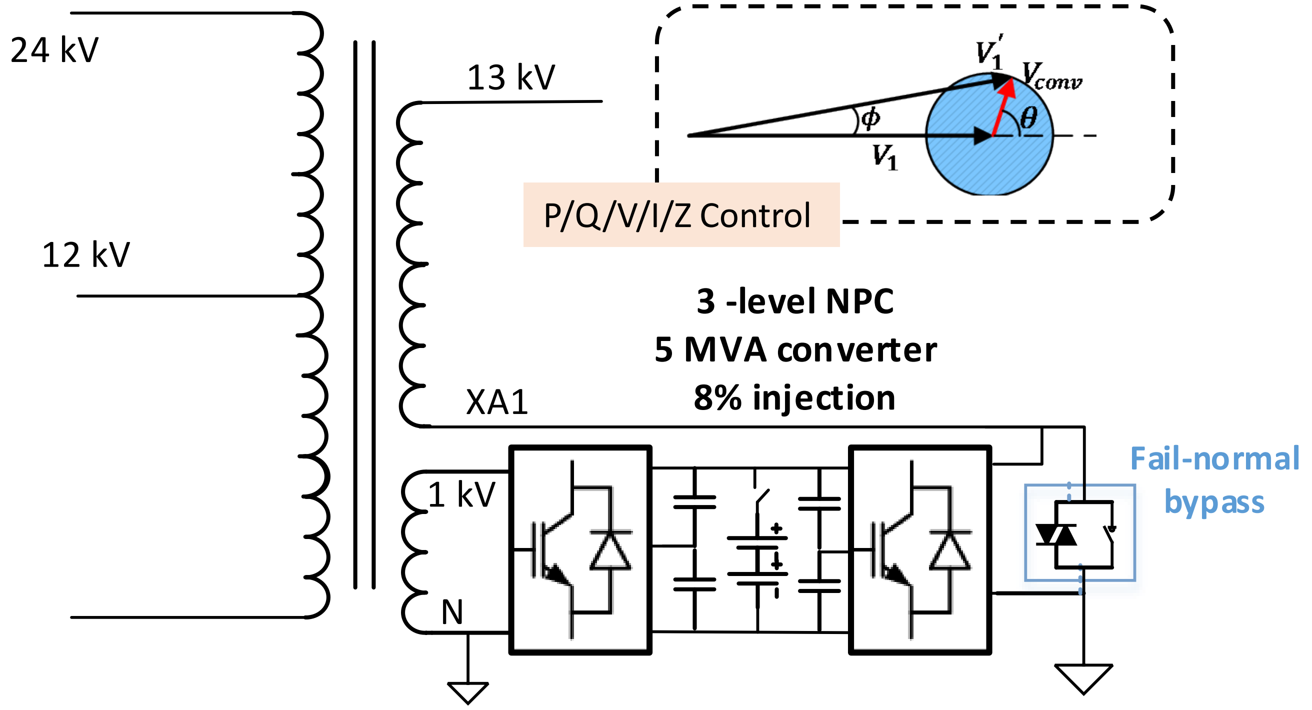
Large Power Transformers — Problems

- Large Power Transformers (LPTs) are critical pieces of today's electricity infrastructure.
- Failure of a single LPT can disrupt electrical services to 30-100,000 customers.
- Following problems make LPTs extremely vulnerable and very difficult to replace upon failure
  - Unique designs
  - Aging assets,
  - limited flexibility embedded in the grid,
  - long turn-around times,
  - transportation delays and
  - foreign manufacturing infrastructure make.
- Case simulated on IEEE 30 bus system.
  - T6-10 fails and overloads T4-12.
- What is the most resilient approach to handling loss of LPT contingency?



Scenario	LPT T4-12 (MVA)	LPT T6-10 (MVA)	Overload (MVA)
Base	95.2	68.8	0
LPT Outage	**136.4**	Outage	36.4

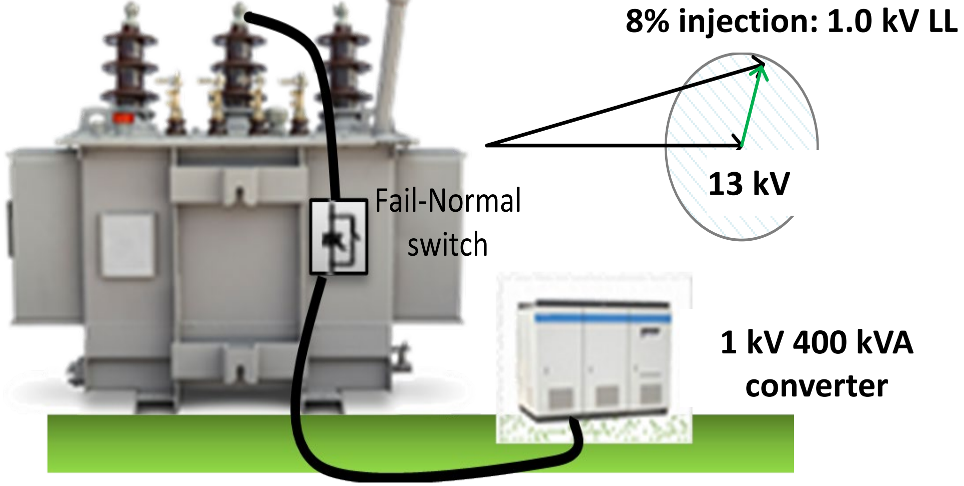
5 MVA Modular Controllable Transformer



Standard Transformer **24 kV/ 13 kV 5 MVA**
Transformer

MCT Implementation

Power electronics provide dynamic load balancing caused by mismatched impedances



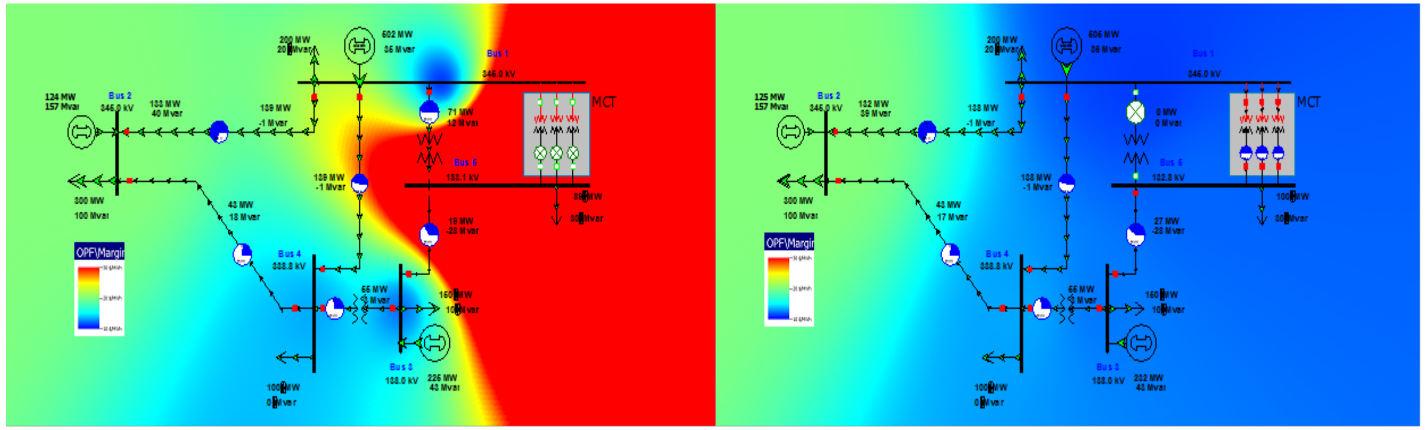
Proposed System Features

- ✓ Modularity
- ✓ Scalability
- ✓ Backwards compatibility
- ✓ Interoperability
- ✓ Voltage regulation
- ✓ Power flow control
- ✓ Storage integration
- ✓ Fail normal design
- ✓ Manufacturability
- ✓ Transportability
- ✓ OEM requirements
- ✓ Overload capability
- ✓ Protection

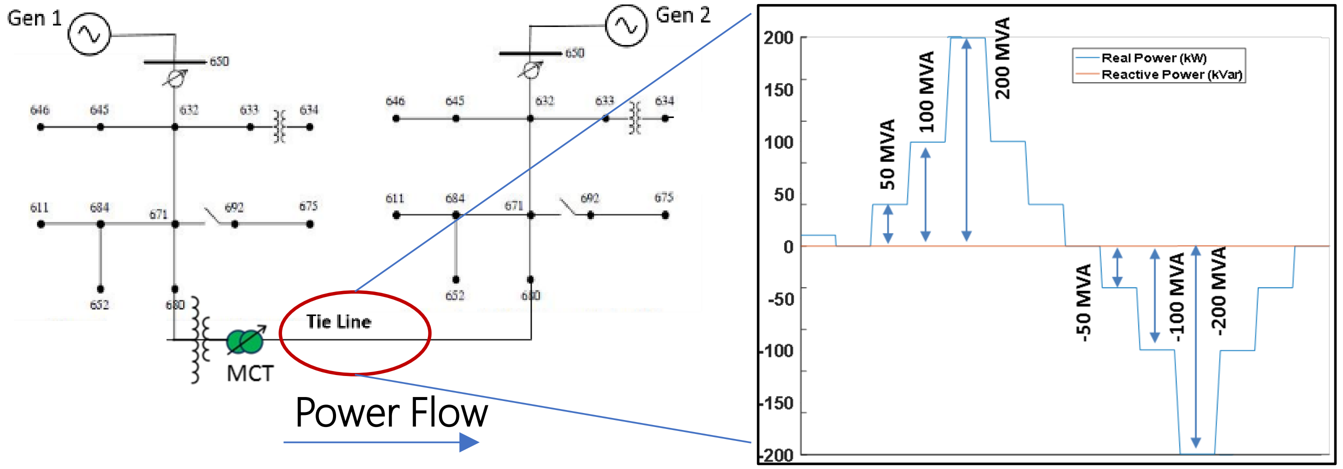
Metric	Units	Goal
Fail Normal Switch – Fault current carrying capability	A	20000 per 20 cycles
Multiple voltages	Number	Dual primary voltages - 24 kV and 12 kV
System efficiency	%	>98.8%
Power flow control	MVA	+/- 0.9 pu
Voltage regulation	%	+/- 8%
Impedance control	%	+/- 3%

5 MVA Modular Controllable Transformer

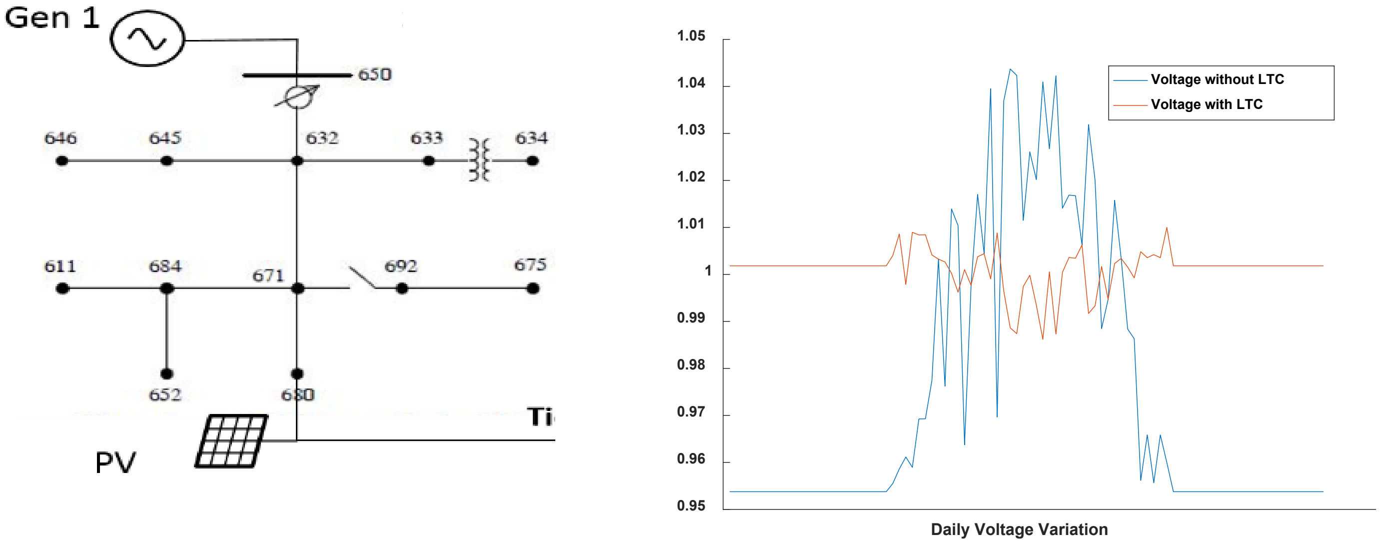
Congestion Management



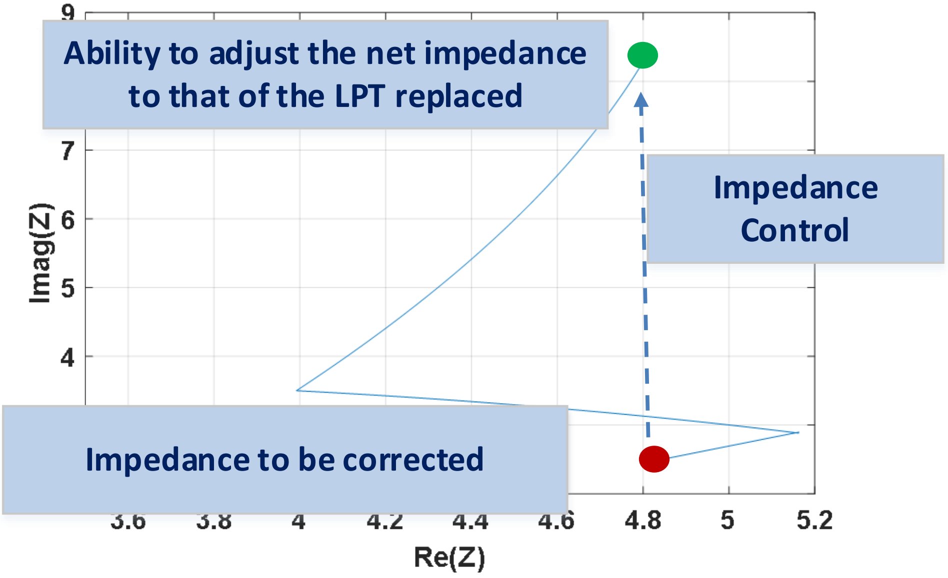
Power Flow Control with MCT



Voltage Control



Variable Impedance



Primary Innovation

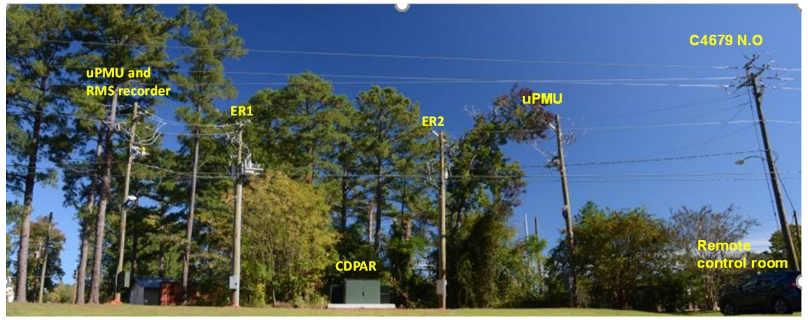
- Modular controllable transformers (MCTs) consist of fractionally rated power converters integrated with standard HV transformers rated at 10-200 MVA
- MCTs provide unprecedented resiliency for high-impact low-frequency events through flexibility in configuration, easier transportability, and faster restoration time
- The MCT provides dynamic control to mitigate congestion issues and to integrate higher levels of variable renewable energy on the grid
- MCTs can enable multi-terminal AC systems (MTACs) at a fraction of the cost of multi-port DC systems (MTDCs)

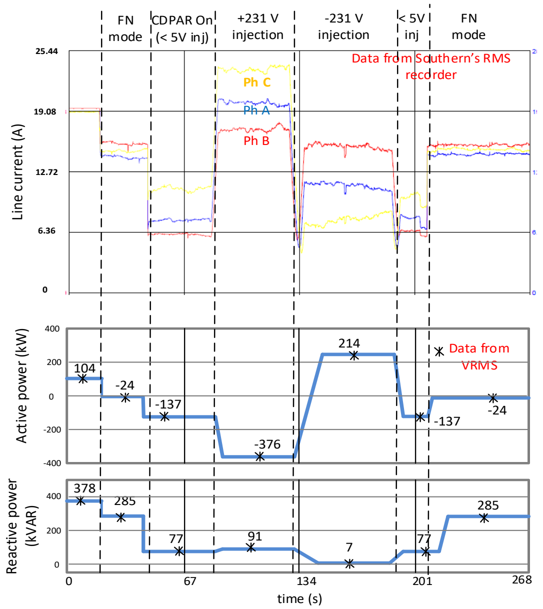
Technology Status

2013-2016/ ARPA-E/G-CDPAR

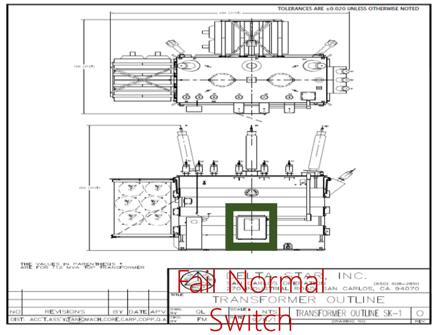
- 1 MVA Xmr w/ 3% voltage injection capability
- 13 kV/1 MW Field Demonstration on a two feeder system

13 kV 1 MW Power Router Field Demo

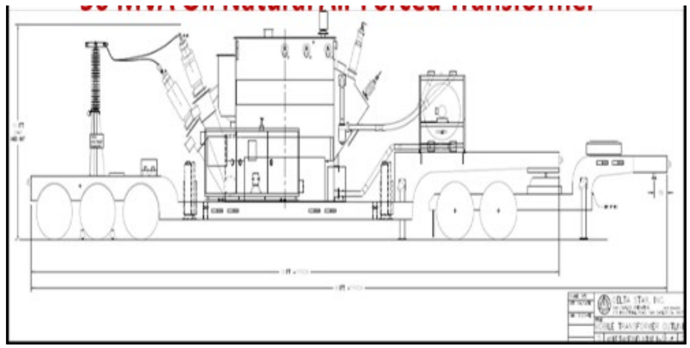




2017 – 2018 / DOE/ MCT Phase -1

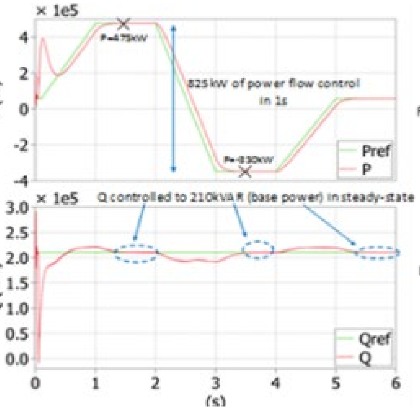


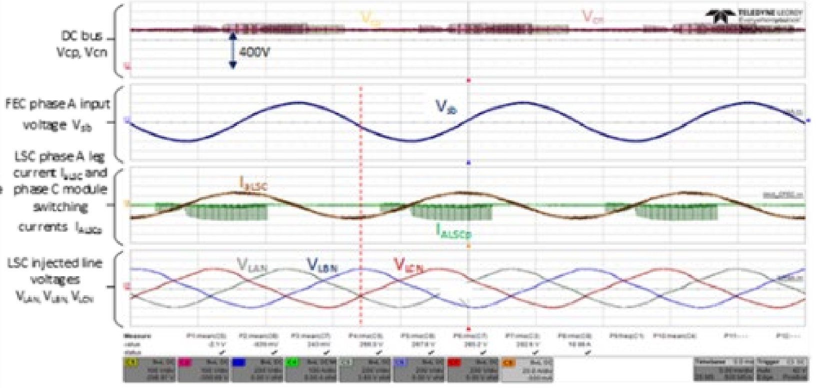
- Replace 200 MVA LPT with multiple small rated Modular Controllable Transformers (MCT) to improve grid resiliency and operational control (P/Q/V/I/Z).
- 139 kV/ 39 kV 56 MVA transformer w/ 8 % voltage control.
- Delta Star designed 56 MVA LPT to
  - integrate fail-normal switch
  - minimize transportation and commissioning time
  - Shipped with bushings and oil filled



2017/ARPA-E/G-CNT

- 13 kV 1 MVA Xmr + 5% control 3-level BTB converter
- Demonstrated in lab environment

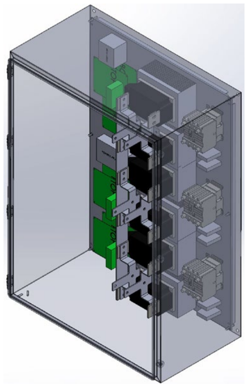


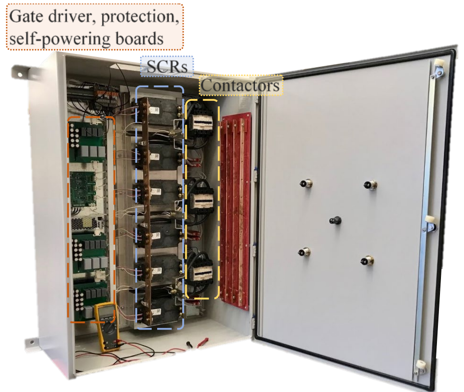


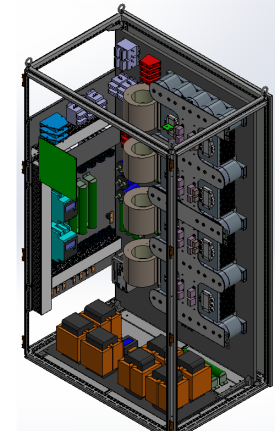
12.47 kV/ 1 MW Back-to-back converter

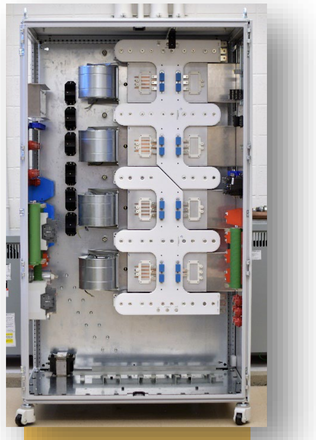
2019 – 2022 / DOE/ MCT Phase -2

- Design, build and test a 5 MVA 24 kV/12 kV MCT and demonstrate the functionality, which includes modularity, power flow control, interoperability through variable impedance and connection of multiple voltage levels, storage integration, and fail-normal design





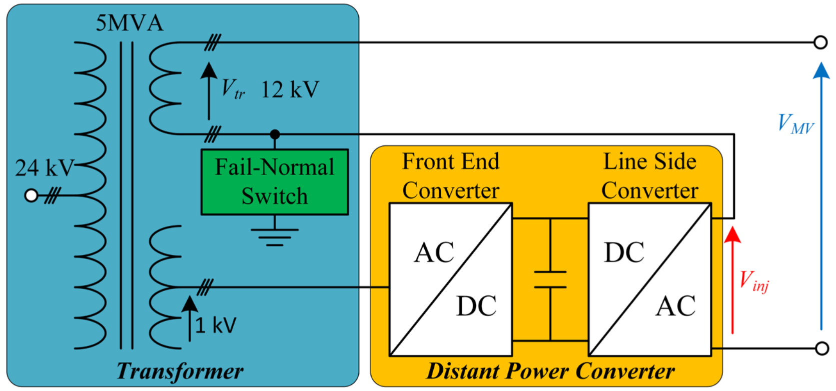


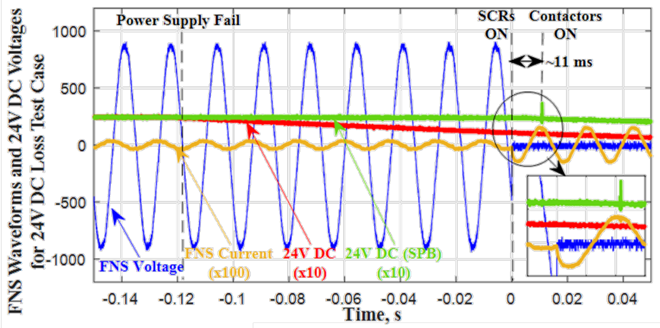


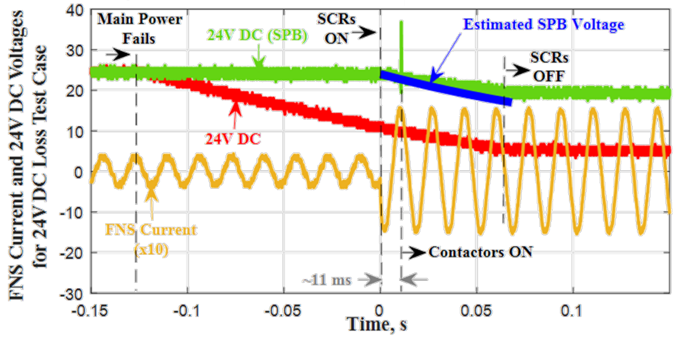
Project Objectives

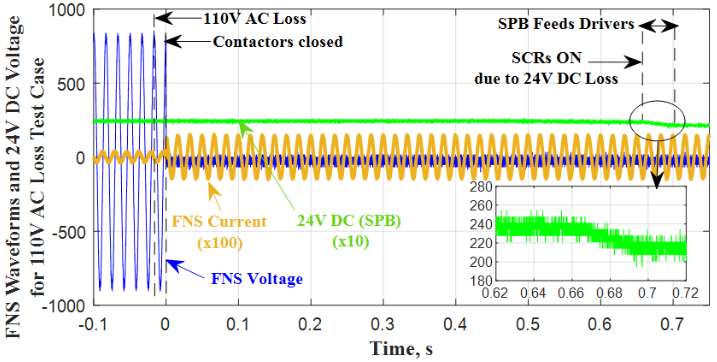
- Design, build and test a 5 MVA 24 kV/12 kV MCT and demonstrate the functionality, which includes modularity, power flow control, interoperability through variable impedance and connection of multiple voltage levels, storage integration, and fail-normal design
- Assess the impact and penetration level of the proposed MCT and evaluate cost-effectiveness compared to traditional LPTs

Build and Testing — Fail-Normal-Switch









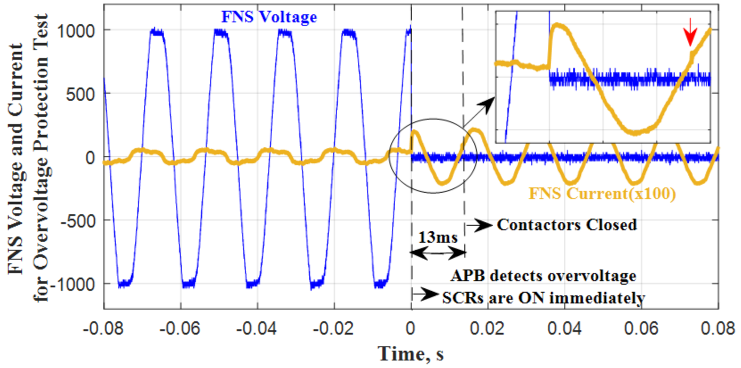
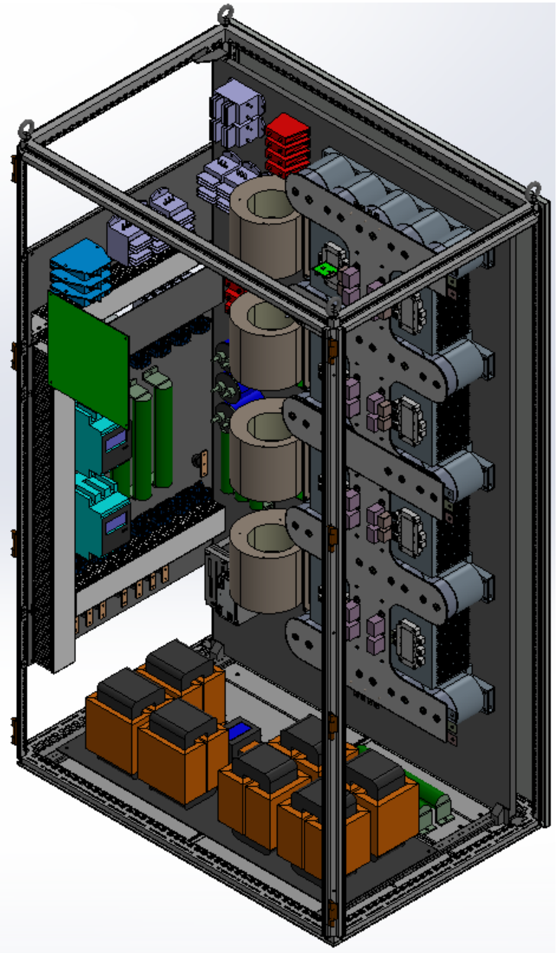
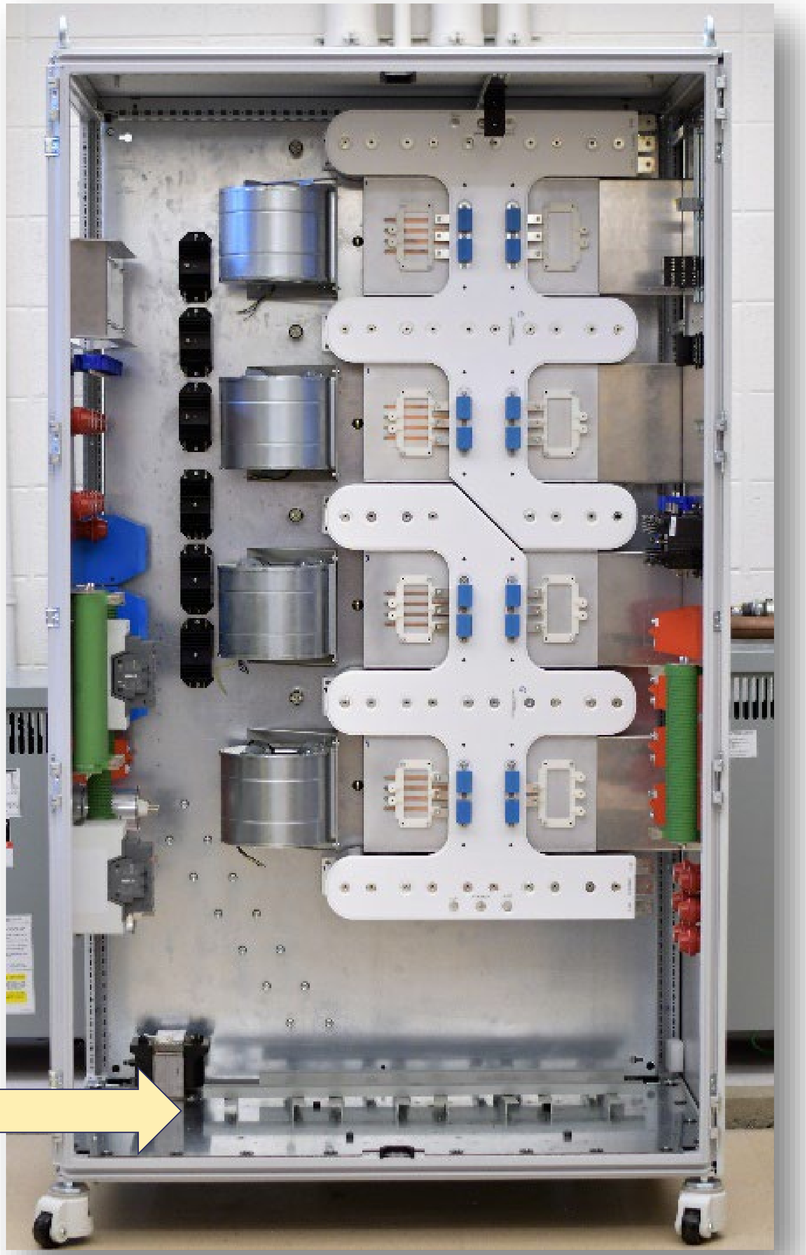


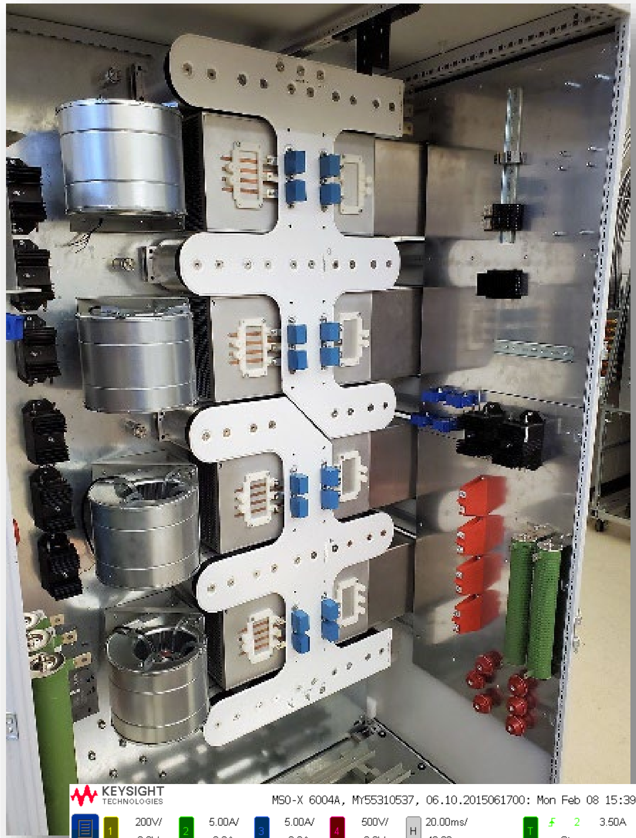
TABLE 1 Summary of the protection mechanisms of proposed FNS under any possible abnormal conditions

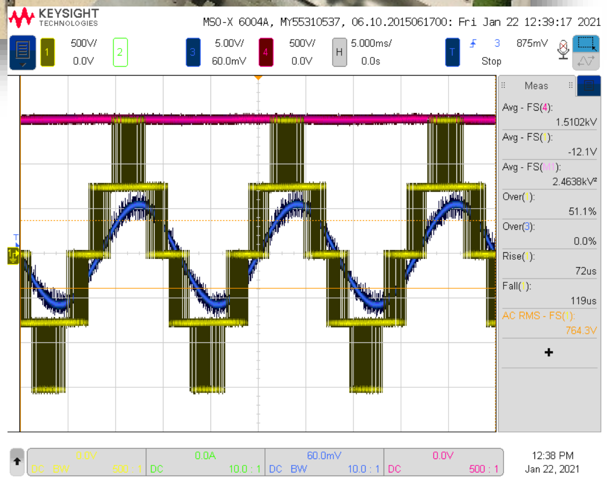
Failure Type	FNS Element	Protection Mechanism
1) Power System Level Faults		
External Spike or Surge	MOV	Suitable MOVs are selected for spikes and surges
External Short Circuits	SCRs	SCRs are designed to sustain 10-cycle 20kA short circuit current
2) Converter Internal Faults	SCRs Contactors	FNS is informed by an active low fault signal from the converter, then SCRs and contactors are immediately closed
3) Auxiliary Power Losses		
24V DC Power Loss	SCRs SPBs	SCR gate drivers operate immediately by the active low trigger pulse. As their power is supplied by SPB, drivers continue operating without interruption until NC contactors close.
110V AC Power Loss	Contactors	Contactor coils are fed by 110V AC. Contactors immediately close in case of 110V AC power loss since they are normally closed.
4) Last-Gasp Protection		
Undetected Open Circuits for any reason	APB	APB is designed to monitor induced overvoltage across FNS and operates both SCRs and contactors in case of an overvoltage.
Cable Cut	Control Logic	FNS is proposed to immediately act in case of any cable cuts via active low/high control logic.
Multiple Faults at the same time and/or SCR gate driver faults	Self-Triggering Circuit	Any undetectable open circuits together with an APB malfunction and/or gate driver faults can be cleared by the proposed overvoltage self-triggering circuit for SCRs.

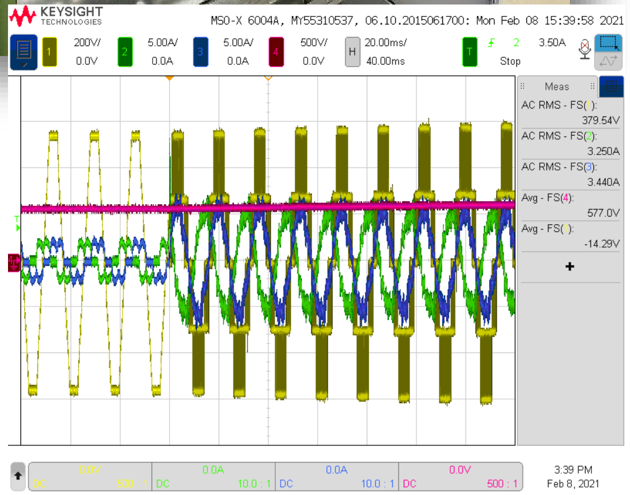
Build and Testing — 400kVA Converter







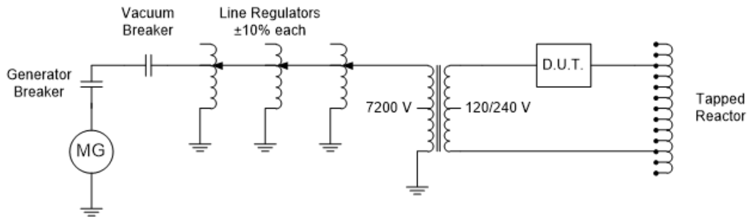




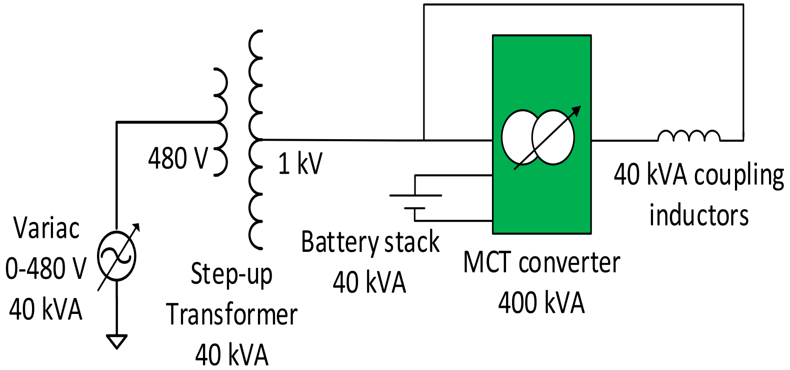
Open & Closed-Loop Low power testing

Build and Testing — Testing Plan

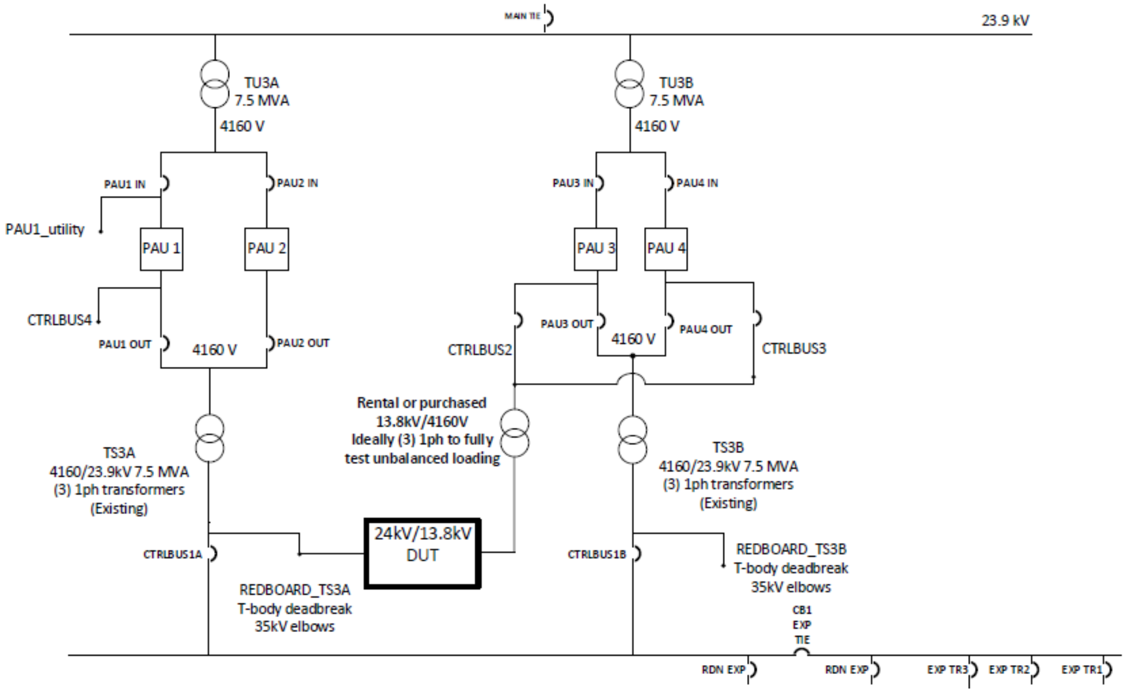
Test fail-normal switch at 20 kA for 20 cycles at NEETRAC, GT facility

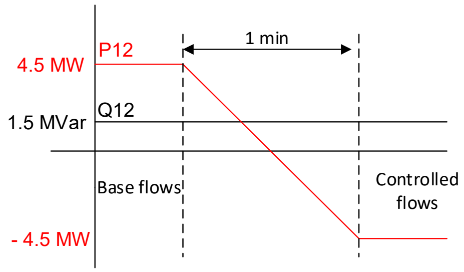


Test 1.0 kV 400 kVA converter at CDE, GT lab



Test at 24 kV Grid Simulator facility, Clemson University





Impact/Commercialization

- The MCT creates a building block for the future grid by integrating a modest level of dynamic control with a smaller rated modular transformer
- It provides flexibility in locating devices, increases system capacity through power routing, increases renewable energy integration through volt-VAR control, and improves overall grid resiliency and reliability
- It also addresses the logistical and economic barriers, by allowing the build of smaller rated standardized transformers that can be built and inventoried.

IP STATUS

Basic IP is issued. Additional IP, if any, will be filed during the project duration.

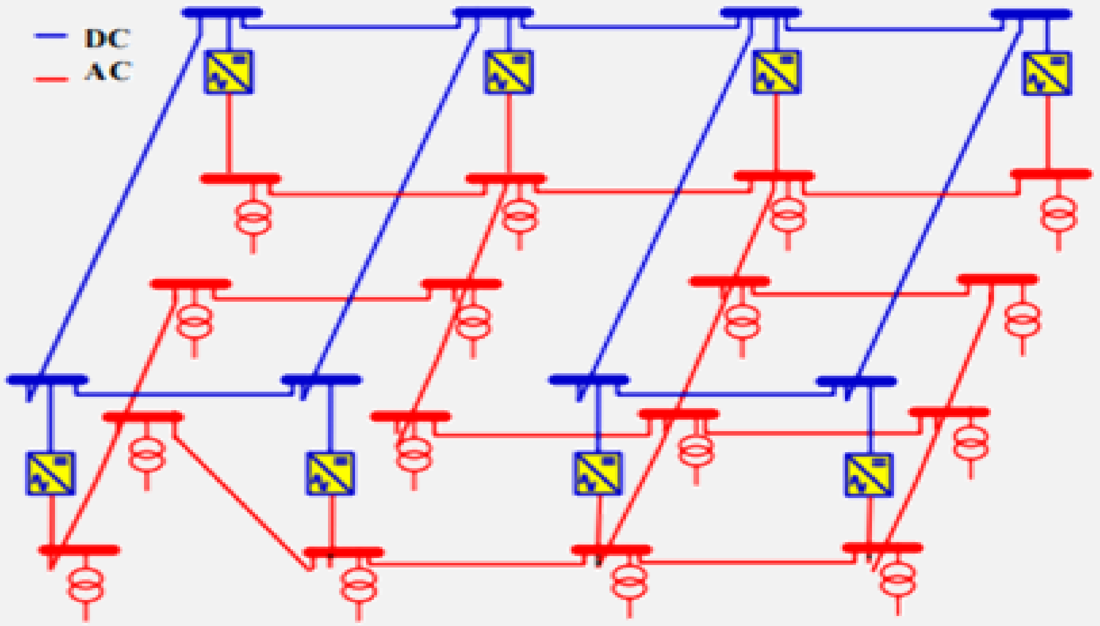
Innovation Update — Enabling Multi-Terminal AC Systems with MCT

Multi-Terminal Systems (MTS) Advantages:

- MTS can provide additional **controlled** paths to transport or integrate large amount of power
- *What more can MTS do?*
  - ✓ Re-enforce transmission/distribution system
  - ✓ Improve system stability
  - ✓ Damp power oscillation between areas
  - ✓ Frequency control

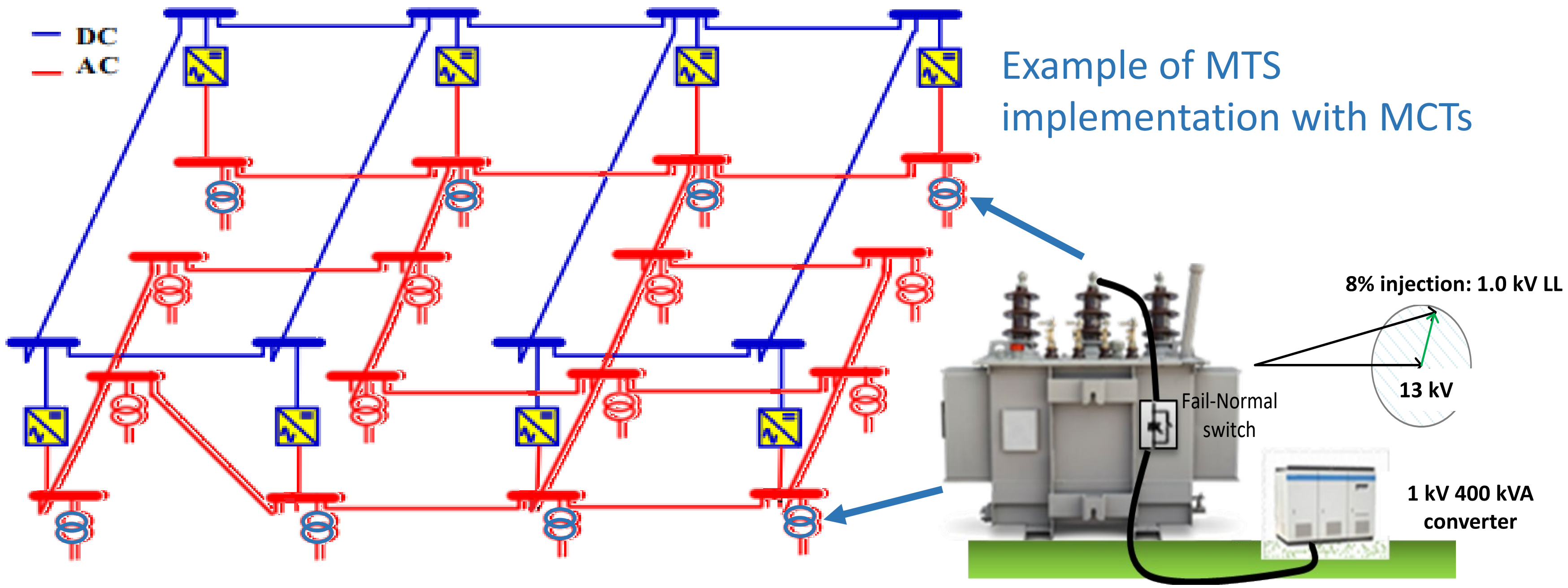
DC solutions are costly and complex fault protection needed

Example of MTS implementation with HVDC-light



Advantages of MCT

- ✓ Uses standard large power transformer and widely available BTB converters
- ✓ **Allows scaling** to 100's of kV and 100's of MW with low-cost & small footprint
- ✓ Fail-normal approach retains basic functionality in case of converter failure.
- ✓ High impact at 10,000 bus system and Texas system (simulations)
- ✓ Multiple units can be deployed in one centralized location or in a dispersed fashion
- ✓ **Reduces cost and size for P/Q/V/I/Z control by 6X as compared with HVDC Light**



MCT can provide the advantages of MTDC at a fraction of the cost and become the key enabler for future multi-terminal AC (MTAC) systems

Project schedule, deliverables, and current status

Budget: $2,293,347 ($1,798,315 + $495,032)

<table>
<tr><th>Milestone</th><th>Completion Date</th><th>Status</th></tr>
<tr><td>Project Management and Planning</td><td>6/31/2019</td><td>Completed</td></tr>
<tr><td>Product Requirement Document</td><td>7/28/2019</td><td>Completed</td></tr>
<tr><td>Fail-Normal Switch</td><td>11/30/2019</td><td>Completed</td></tr>
<tr><td>5 MVA Transformer Design and Build</td><td>12/30/2021</td><td>Delayed (Lockdown & NCE execution)</td></tr>
<tr><td>400 KVA Converter tested</td><td>12/30/2021</td><td>In-Progress (Delayed)</td></tr>
<tr><td>Test Site Preparation</td><td>1/30/2022</td><td rowspan="3">Delayed (Lockdown & NCE execution)</td></tr>
<tr><td>Integration and Testing</td><td>5/30/2022</td></tr>
<tr><td>System Analysis</td><td>5/30/2022</td></tr>
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THANK YOU

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