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

Principal Investigator: Dr. Deepak Divan, Professor

Affiliation: Georgia Institute of Technology

Team Members: Georgia Tech, Clemson University, Southern Company

PACE
ACCELERATING ELECTRIFICATION

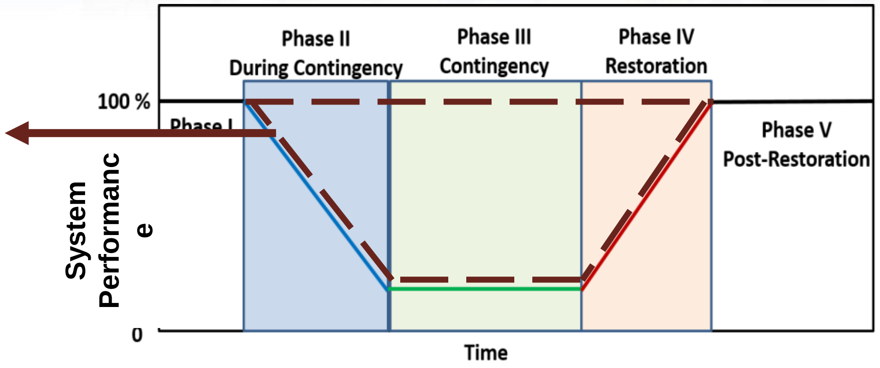
U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

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



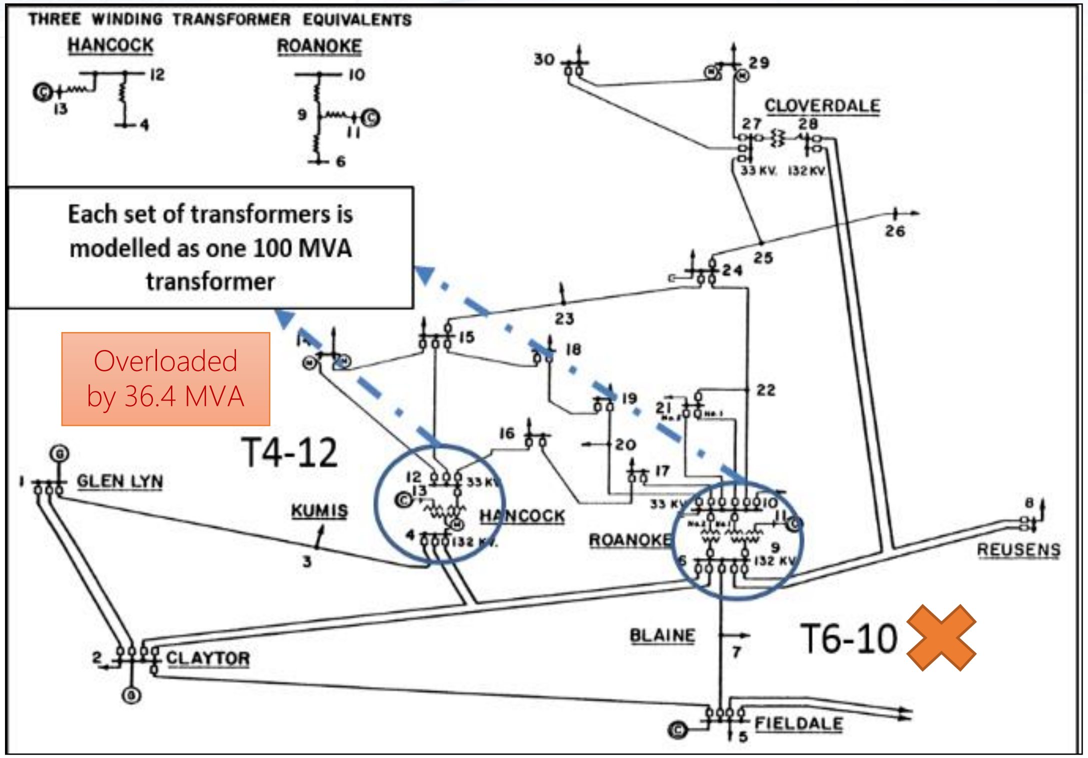
MVA-months lost could serve as a measure for resiliency

PACE ACCELERATING ELECTRIFICATION

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

Introduction: 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**

Project Objectives

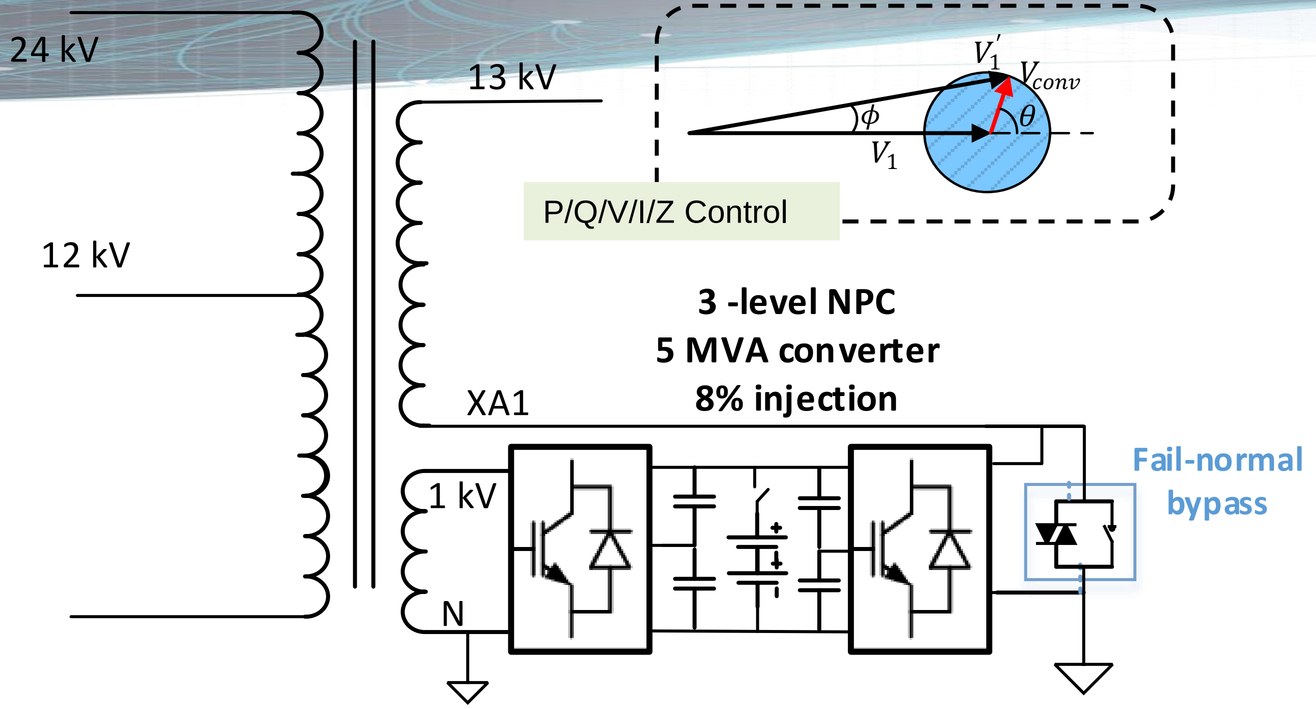
- Design, build and test a 5 MVA 24 kV/12 kV MCT and demonstrate the functionality, which includes modularity, power flow control, interoperability through variable impedance and connection of multiple voltage levels, storage integration, and fail-normal design

- Assess the impact and penetration level of the proposed MCT and evaluate cost-effectiveness compared to traditional LPTs

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 01/31/2024 (NCE pending)
- PROJECT STATUS:
  Ongoing
- AWARD AMOUNT (DOE CONTRIBUTION):
  $1,798,315
- AWARDEE CONTRIBUTION (COST SHARE):
  $495,032
- PARTNERS:
  Clemson University, Southern Company

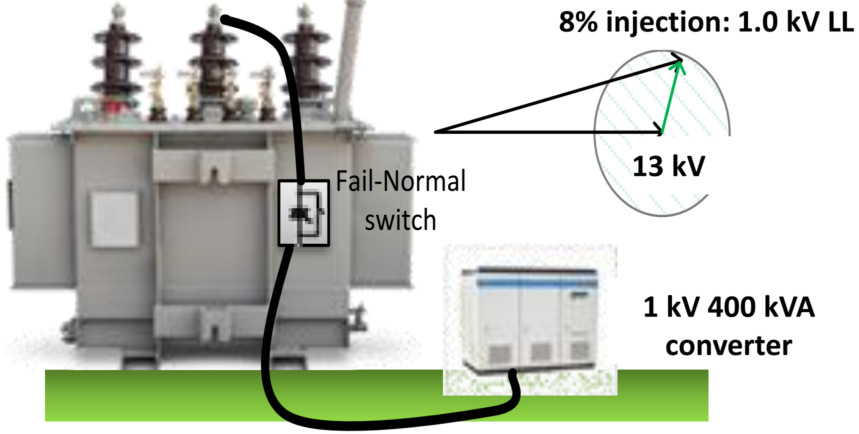
5 MVA Modular Controllable Transformer



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

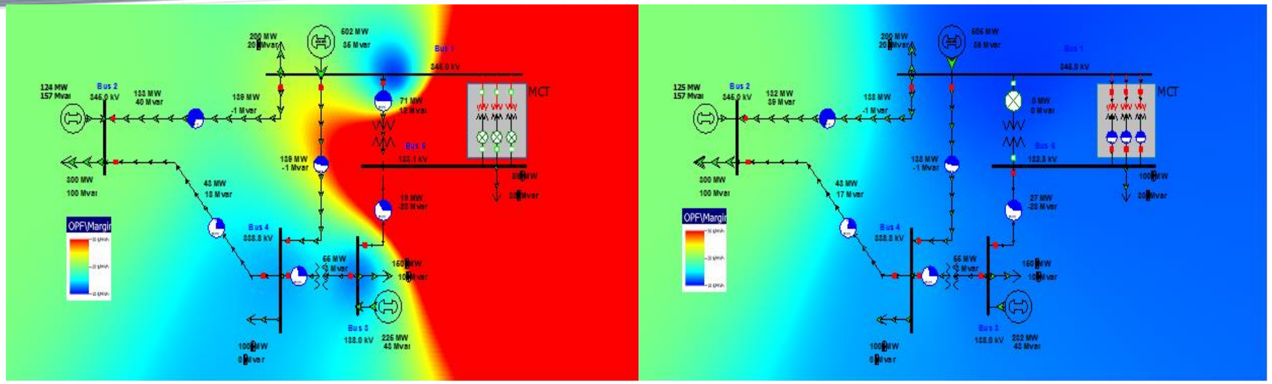
Metric	Units	Goal
Fail Normal Switch – Fault current carrying capability	A	20000 per 20 cycles
Multiple voltages	Number	Dual primary voltages - 24 kV and 12 kV
System efficiency	%	>98.8%
Power flow control	MVA	+/- 0.9 pu
Voltage regulation	%	+/- 8%
Impedance control	%	+/- 3%

PACE ACCELERATING ELECTRIFICATION

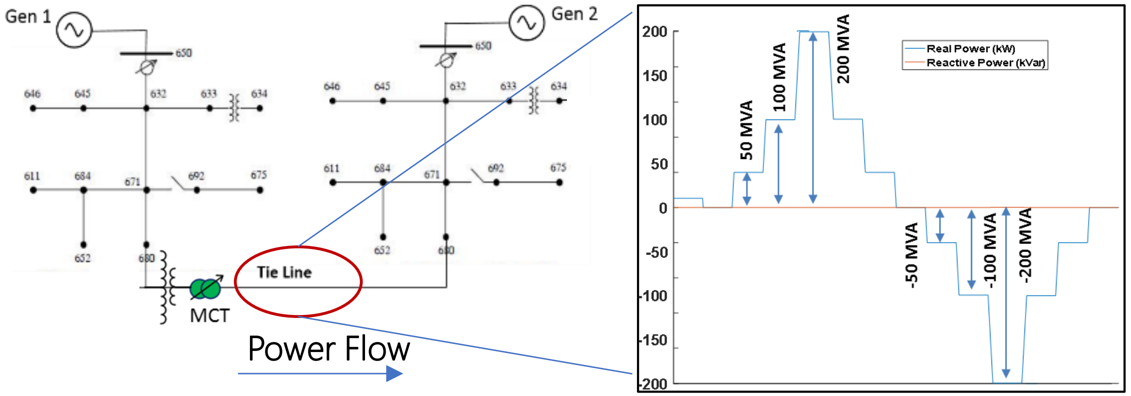
U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

5 MVA Modular Controllable Transformer

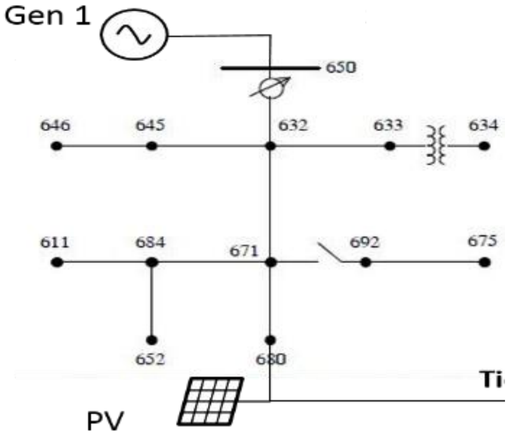
Congestion Management

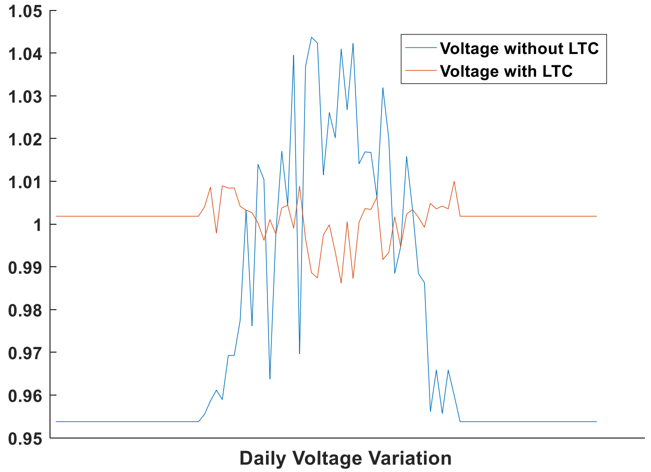


Power Flow Control with MCT

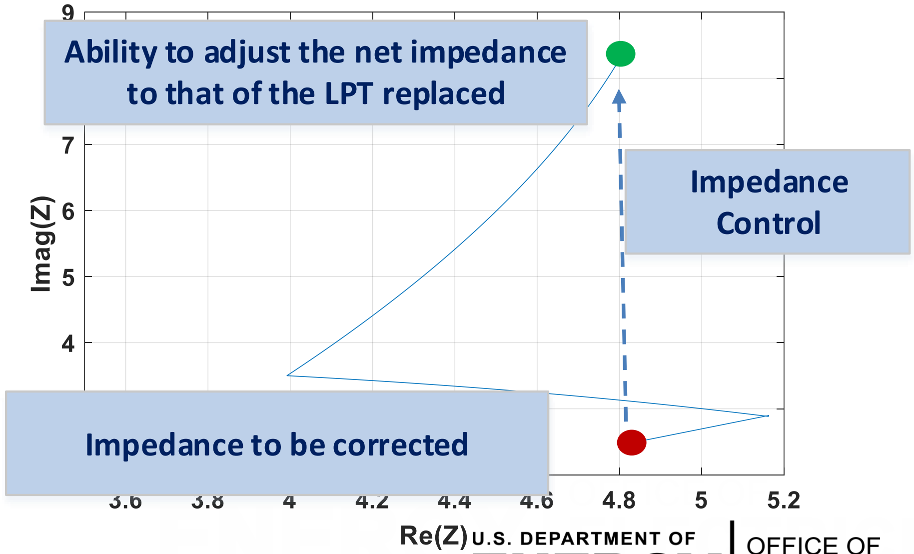


Voltage Control





Variable Impedance



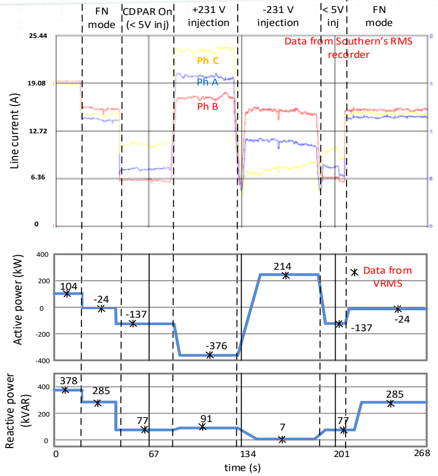
PACE ACCELERATING ELECTRIFICATION

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

Technology Status

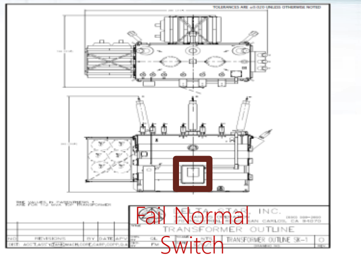
2013-2016/ ARPA-E/G-CDPAR

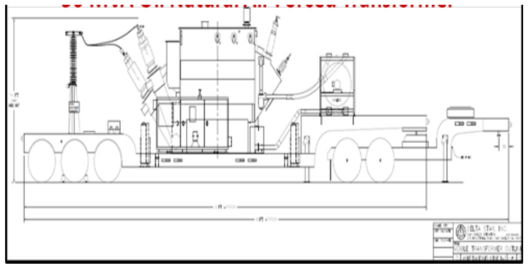
- 1 MVA Xmr w/ 3% voltage injection capability
- 13 kV/1 MW Field Demonstration on a two feeder system



2017 – 2018 / DOE/ MCT Phase -1

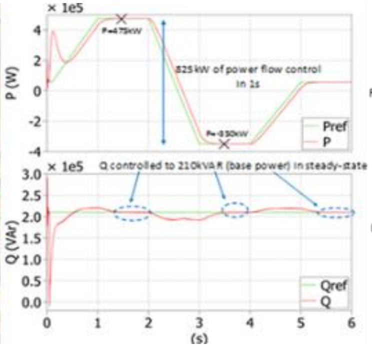
- Replace 200 MVA LPT with multiple small rated Modular Controllable Transformers (MCT) to improve grid resiliency and operational control (P/Q/V/I/Z).
- 139 kV/ 39 kV 56 MVA transformer w/ 8 % voltage control.
- Delta Star designed 56 MVA LPT to
  - integrate fail-normal switch
  - minimize transportation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

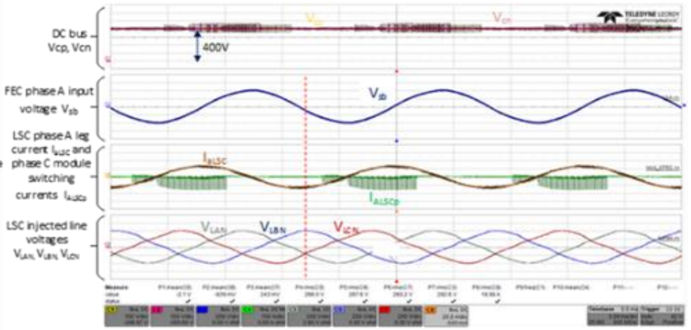




2017/ARPA-E/G-CNT

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

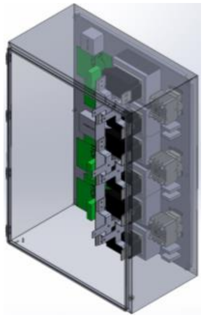


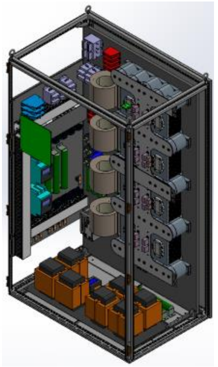


12.47 kV/ 1 MW Back-to-back converter

2019 – 2024 / 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

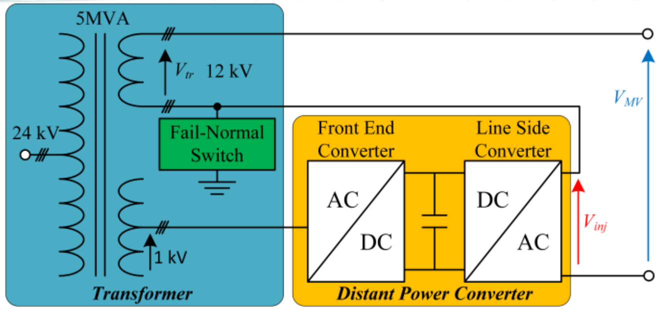


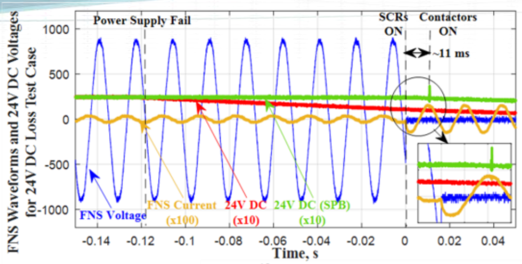


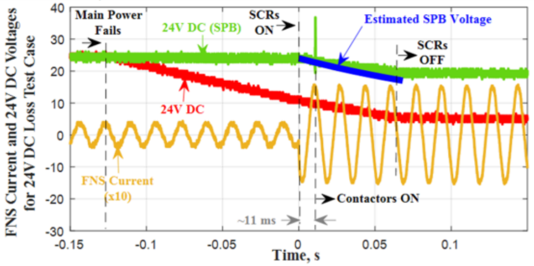
PACE
ACCELERATING ELECTRIFICATION

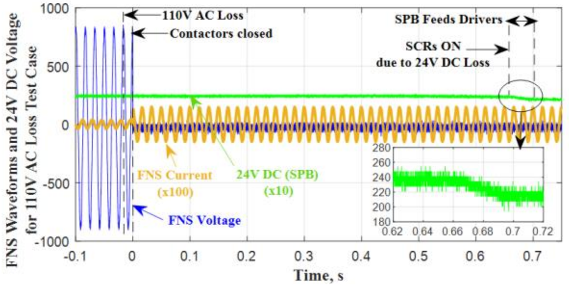
U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

Build and Testing — Fail-Normal-Switch









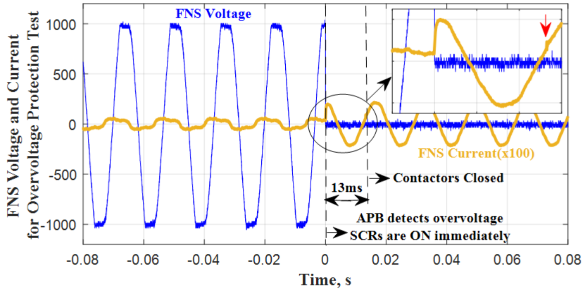
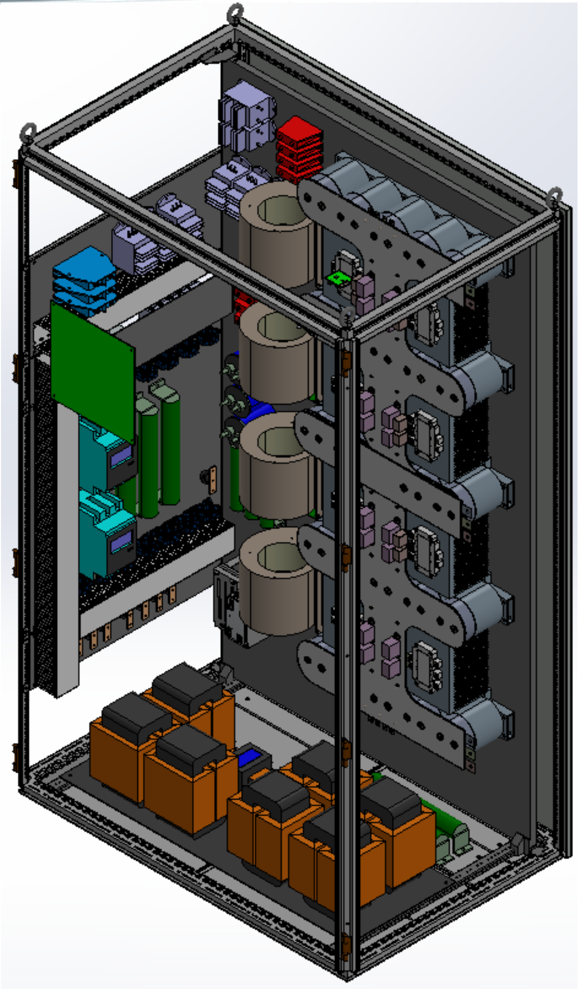


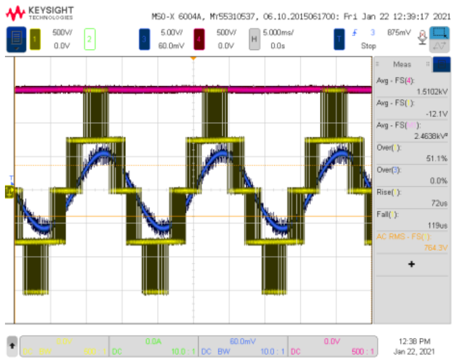
TABLE 1 Summary of the protection mechanisms of proposed FNS under any possible abnormal conditions		
Failure Type	**FNS Element**	**Protection Mechanism**
1) Power System Level Faults		
External Spike or Surge	MOV	Suitable MOVs are selected for spikes and surges
External Short Circuits	SCRs	SCRs are 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.

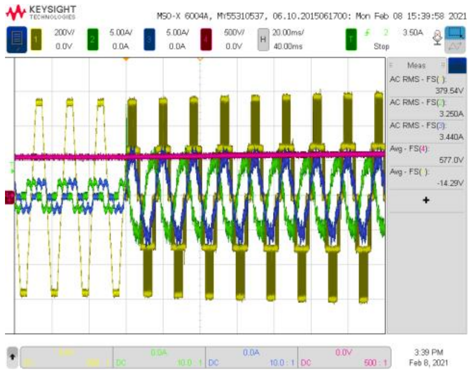
PACE ACCELERATING ELECTRIFICATION

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

Build and Testing — 400kVA Converter





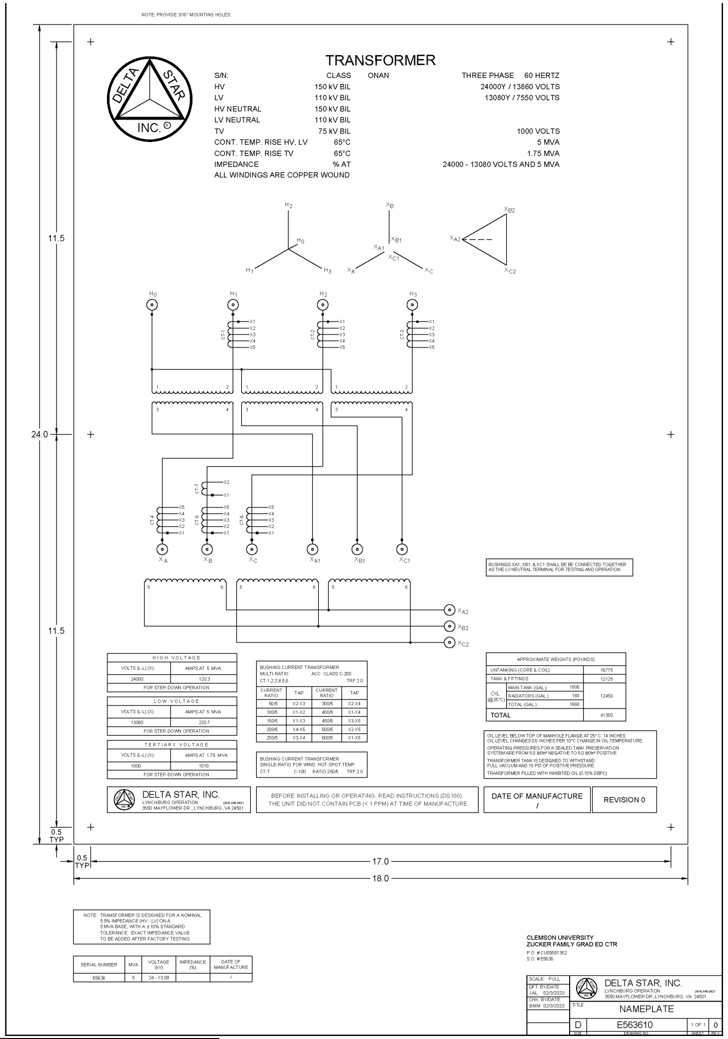


Open & Closed-Loop Low power testing

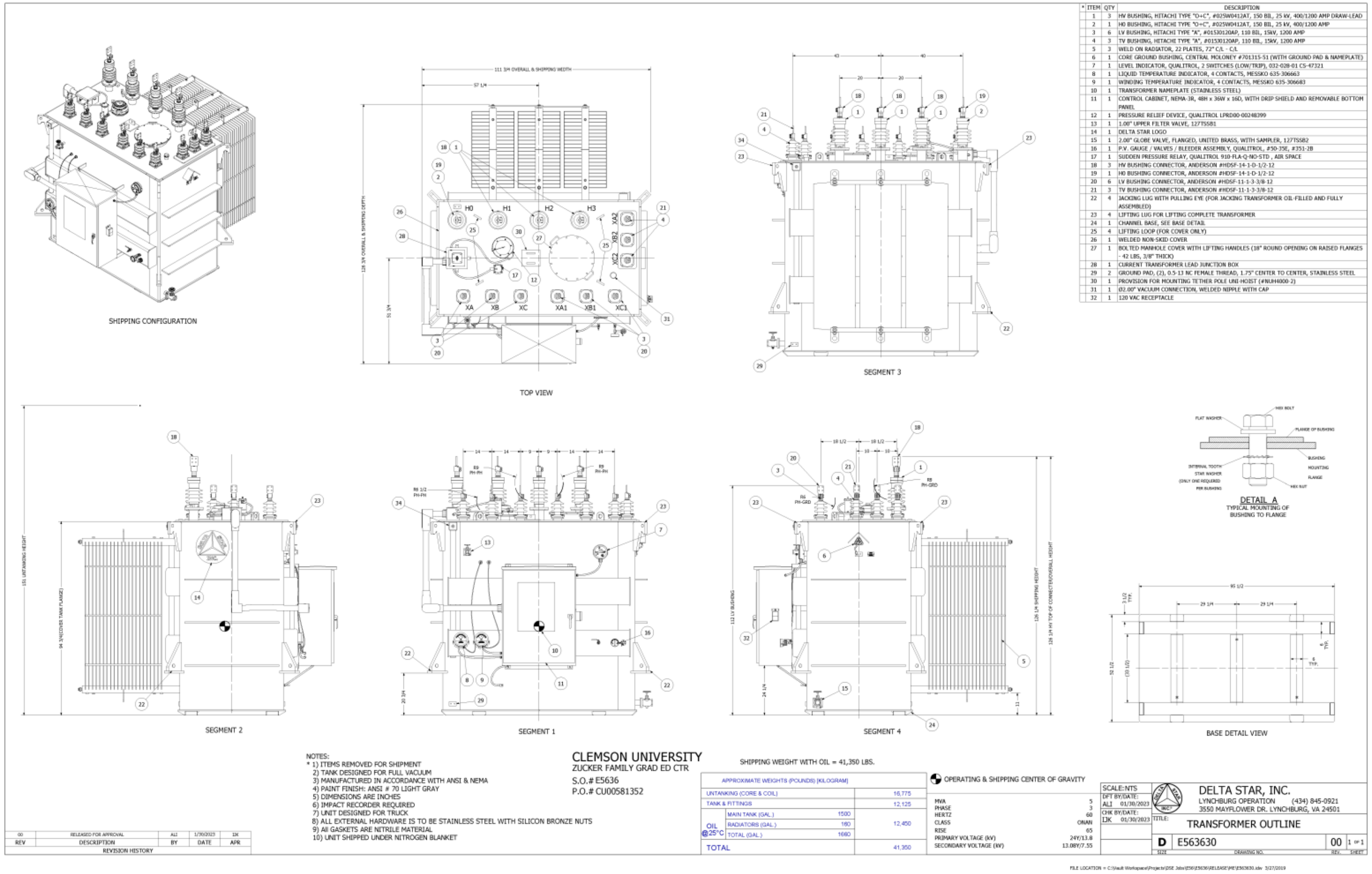
PACE
ACCELERATING ELECTRIFICATION

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

5-MVA LPT Design & Build



The team engaged with the Delta Star team on the final specifications and design for the 5 MVA, 24 kV to 13.08 kV MCT transformer

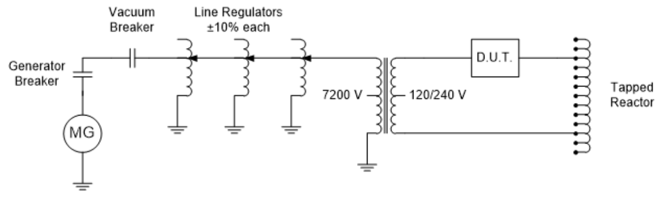


PACE
ACCELERATING ELECTRIFICATION

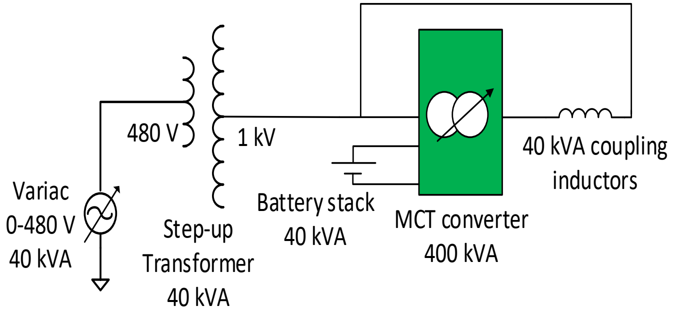
U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

eGrid Testing

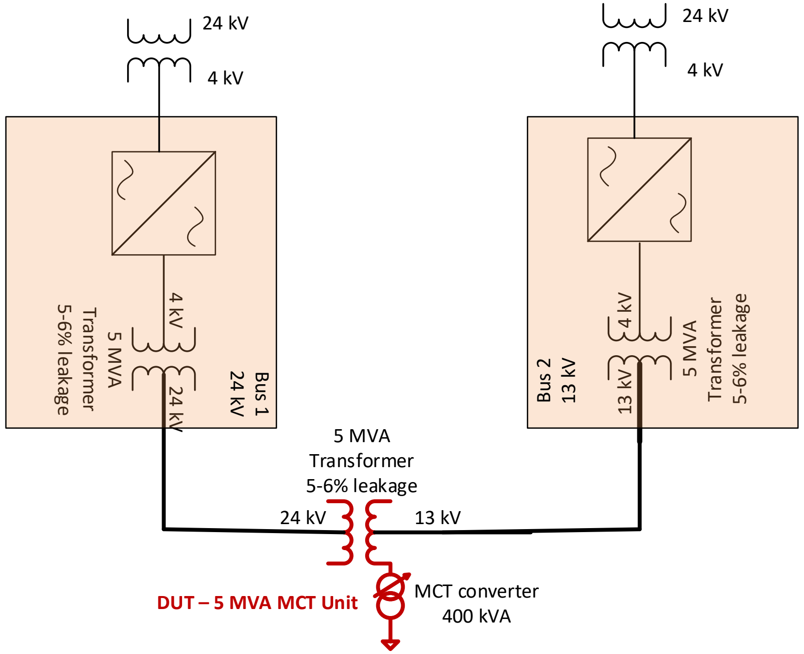
Test fail-normal switch at 20 kA for 20 cycles at NEETRAC, GT facility

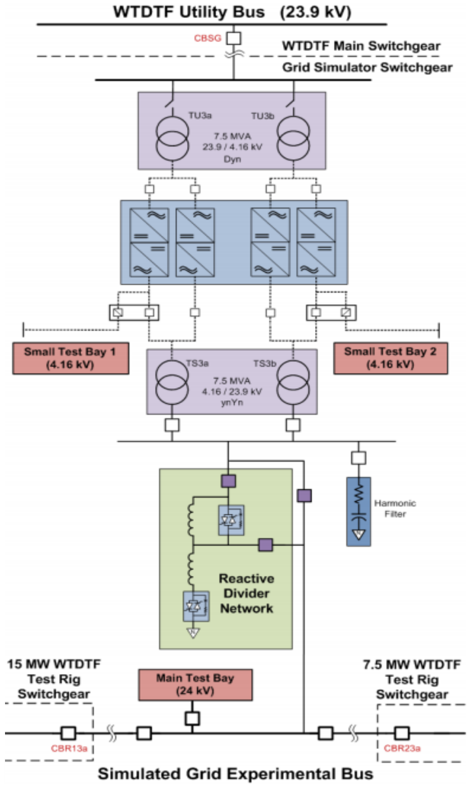


Test 1.0 kV 400 kVA converter at CDE, GT lab



Test at 24 kV Grid Simulator facility, Clemson University





Timeline

SCHEDULE (Proposed Revised Timeline based on LPT delivery)		
SOPO Task/ Subtask Number	SOPO Task/ Subtask Title	Revised timeline
6.0	***Test site preparation***	
6.1	*Develop test protocol and data collection mechanism*	*08/31/23*
6.2	*Testbed prep*	*08/31/23*
6.3	*Component level testing - Converter, F/N functionality*	*09/30/23*
7.0	***Integration and testing***	
7.1	*Integration of Xr and converter*	*10/31/23*
7.2	*MCT testing - F/N function*	*01/31/24*
7.3	*MCT testing - Power flow control: +/-5 MVA*	*01/31/24*
7.4	*MCT testing - Voltage control +/-8%*	*01/31/24*
7.5	*MCT testing - Impedance control*	*01/31/24*
8.0	***System Analysis***	
8.1	*Identification of switchgear, protection, communications, and others*	*07/31/23*
8.2	*Resiliency Analysis*	*01/31/24*
8.3	*Cost-benefit analysis for MCT at distribution and transmission level*	*01/31/24*
8.4	*Identification of near-term applications/ use cases*	*01/31/24*

Task 1-5 Completed or Underway

- Project Management and Planning
- Product Requirement Document
- Fail-normal switch build/test
- Transformer design, and build
- HIL testing
- 400-kVA MCT converter build and testing underway

Impact/Commercialization

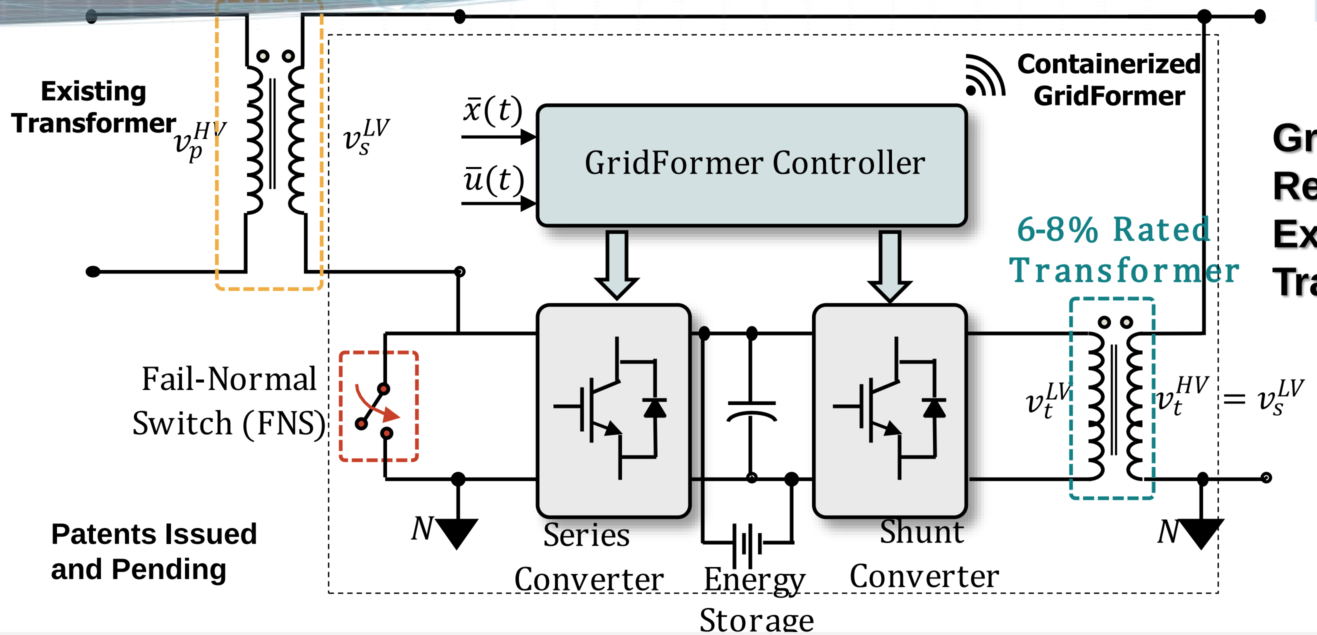
- The MCT creates a building block for the future grid by integrating a modest level of dynamic control with a smaller rated modular transformer
- It provides flexibility in locating devices, increases system capacity through power routing, increases renewable energy integration through volt-VAR control, 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

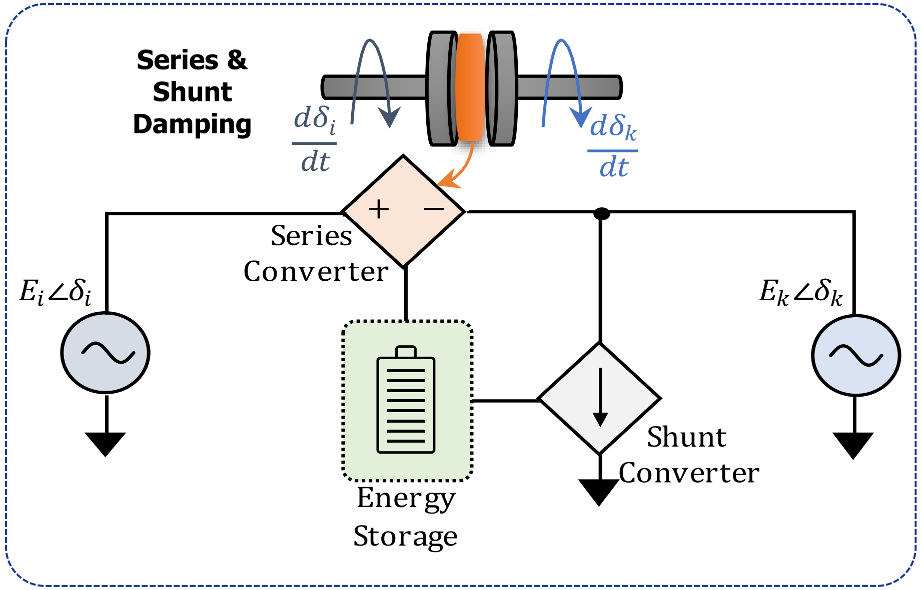
GridFormer — New Approach to Stabilize & Manage High IBR Penetration Grids

GridFormer builds on a decade of R&D on hybrid transformers



Patents Issued and Pending

GridFormer: Retrofit on Existing Transformer



Partners:
GT-CDE, EPRI, GE, Southern

20% GFM penetration helps stabilize the grid

GridFormer Capabilities

The 'GridFormer' integrates standard containerized fractionally-rated off-the-shelf GFM inverters and storage with already deployed transformers to realize:

- ❑ Steady-state control of power flows, voltage, impedance and VARs
- ❑ Grid forming capability, including inertial support, improving grid stability
- ❑ Series/parallel damping of oscillations, incl. interactions between regions
- ❑ Non-compliant multi-vendor inverters can interoperate w/o grid interactions
- ❑ Black-start capability

GridFormer Benefits:

- Allows deployment of IBRs to continue even while GFM inverters are developed into grid codes and standards
- Rapid low-risk deployment - improves steady state & transient response, can prolong current grid paradigm

PACE ACCELERATING ELECTRIFICATION

Low-risk & cost-effective solution - scales to distribution & transmission systems

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

Unique Attributes of GridFormer

- Electricity industry is moving fast to decarbonization (1050 GW of PV solar by 2035), grid is not keeping up with pace of change
- Lagging standards & still emerging consensus on IBR grid stabilization, suggests ~750 GW of non-compliant GFL inverters over 10+ years
- GridFormer is a utility asset that expands capacity of existing grid while improving grid control & stabilization to manage high DER penetration
- <u>Fractionally rated (8-10%) standard back-to-back converter and storage (10 minutes) can be retrofitted to an existing (or new) transformer</u> to provide both steady-state and transient grid support, including:
  - Power flow control, impedance control, voltage support
  - Grid-forming, inertia support, series/shunt damping, black-start
- GridFormer can be deployed at PV or wind farm level, on transmission or distribution substation, giving grid operators increased control

Commercial partners are ready – need to demonstrate and deploy

Substation Transformer

2 MWH storage

MV AC Drive

GridFormer Example:
- 100 MW transmission transformer
- 345 kV/132 kV connection
- 11 kV/8 MW GridFormer converter
- 2 MWH energy storage
- Retrofit within existing substation
- Series and shunt dynamic injection
- **1/6th cost of HVDC Light system**

THANK YOU

This project is supported by the U.S. Department of Energy (DOE) Office of Electricity's Transformer Resilience and Advanced Components (TRAC) program. It is led by Andre Pereira, TRAC program manager.

Georgia Tech Center for Distributed Energy

PACE ACCELERATING ELECTRIFICATION

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY