



# DOE Office of Electricity TRAC

Peer Review

U.S. DEPARTMENT OF  
**ENERGY** | OFFICE OF  
**ELECTRICITY**

## PROJECT SUMMARY

---

# *Modular Hybrid Solid State Transformer for Next Generation Flexible and Adaptable Large Power Transformer*

- Develop and demonstrate a modular Hybrid Solid State Transformer (HSST) for next generation Flexible and Adaptable large power transformer (LPT)
- Demonstrate advanced control functions of the H-SST that is currently not available in traditional transformers

## PRINCIPAL INVESTIGATORS

Alex Qin Huang, Professor,  
Semiconductor Power Electronics Center  
The University of Texas at Austin

## WEBSITE

<https://spec.ece.utexas.edu>

### Project Participants



### Project Advisors



# The Numbers

DOE PROGRAM OFFICE:

**OE – Transformer Resilience and  
Advanced Components (TRAC)**

FUNDING OPPORTUNITY:

**DE-FOA0001876**

LOCATION:

**Austin, Texas**

PROJECT TERM:

**03/18/2019 to 5/31/2022 (With  
NCE)**

PROJECT STATUS:

**Incomplete, No Cost Extension**

AWARD AMOUNT (DOE CONTRIBUTION):

**\$1,730,000**

AWARDEE CONTRIBUTION (COST SHARE):

**\$433,000**

# Motivation

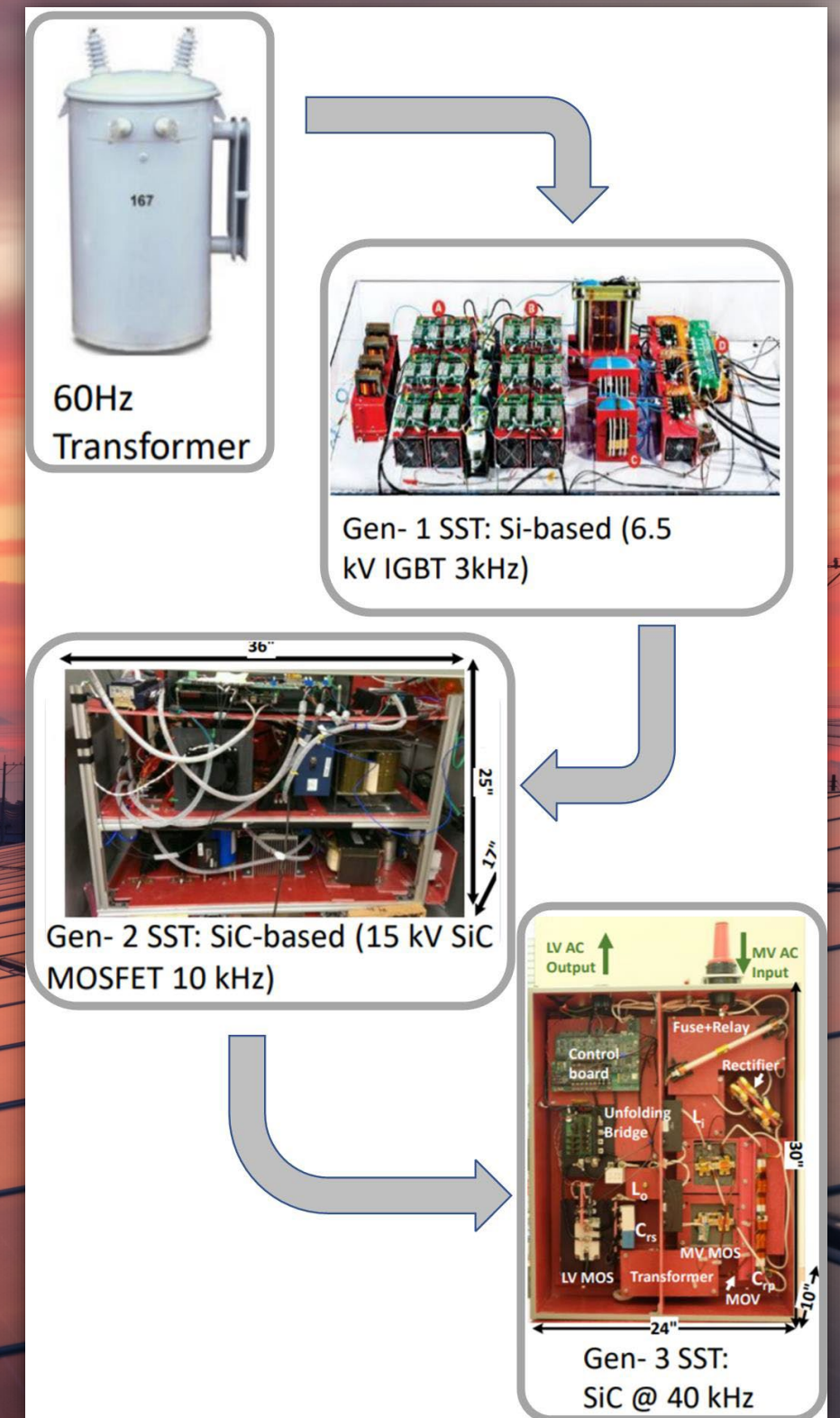
- Transformers have been a mainstay of power grids for over a century, utilizing large amount of materials (iron/copper etc). Very reliable, efficient and cost effective.
- However, they are passive, offering no controllability such as voltage regulation or power flow control, or protection against harmonics and other grid disturbances
- Integration of renewables is also a challenge
- Large Power Transformers further have several logistical issues – large, heavy and bespoke – requiring large turn around time. Not easily transportable or replaceable



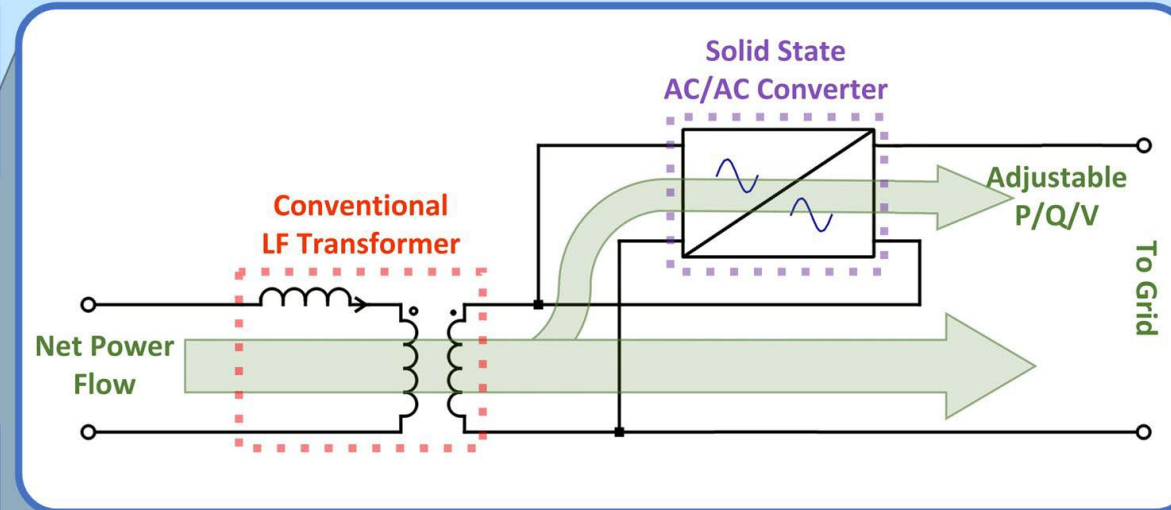
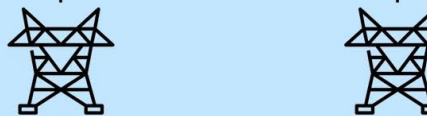
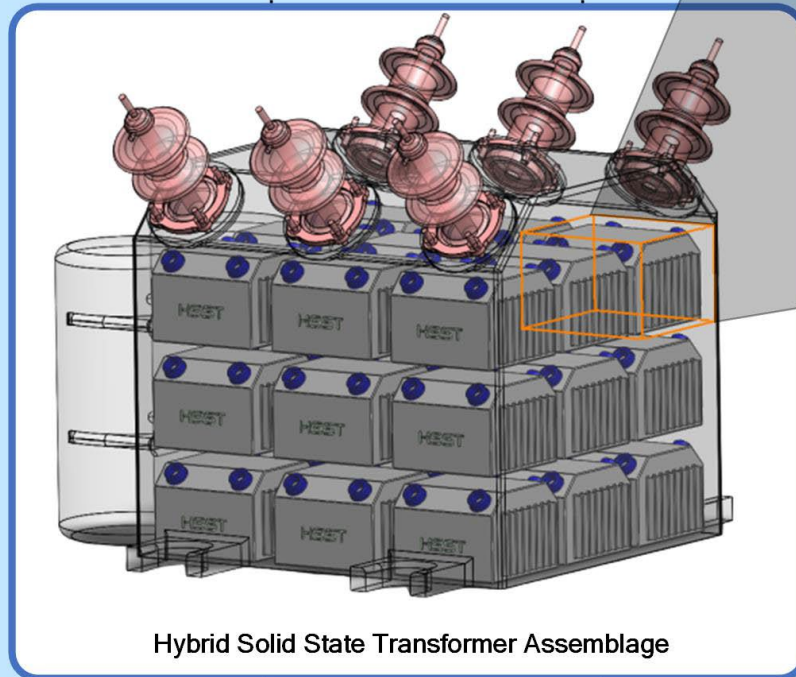
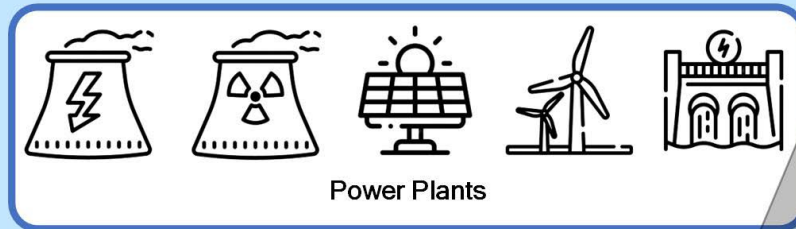
# Motivation


- Solid State Transformers (SSTs) have been touted as a respite, offering not only a whole array of controllability, but also smaller in size and weight
- With advent of wide band gap devices, SSTs are approaching LFT efficiencies while offering broad range of control and flexibility
- However, large costs and issues at scaling to higher voltages and powers have resulted in slow adoption of the SST in T&D applications. Adoption in distribution system is expected first


*Thus presenting .....*





# The Hybrid Solid State Transformer




 Modular, standardized designs pave way for faster deployment time

 Lower costs thanks to possibility of mass production and hybrid design philosophy

 Swappable and fast deployable units improve system reliability and resiliency

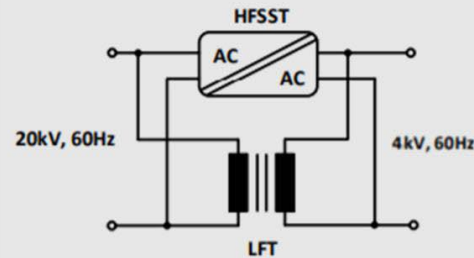
 Advanced control provide additional protection and power flow functionalities

 Compact and lightweight units aid in transportation and logistics

# Primary Innovation

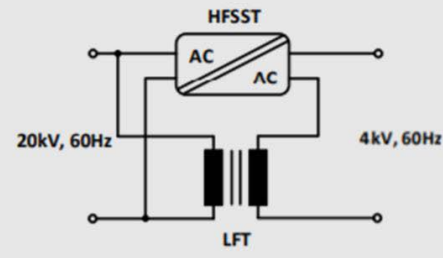
## The suitable HSST configuration

**C1: Input parallel and output parallel**



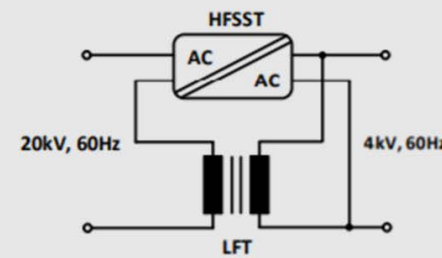
- ✓ Flexible partial power control
- ❖  $V1/V2=n1/n2$
- ❖ No voltage regulation
- ❖ 20kV devices
- ❖ 100kV insulation

**C2: Input parallel and output series**



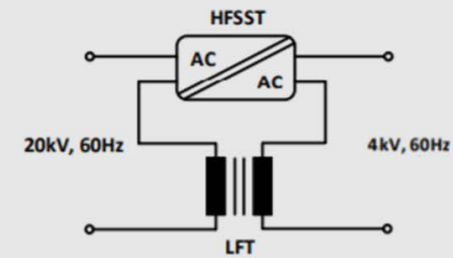
- ✓ Partial power
- ✓ Voltage regulation
- ❖ 20kV devices
- ❖ 100kV insulation

**C3: Input series and output parallel**



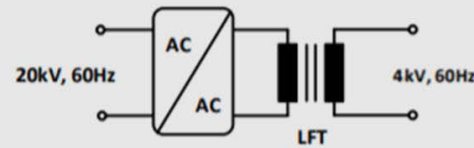
- ✓ Partial power
- ✓ Voltage regulation
- ✓ No 20kV devices
- ❖ 100kV insulation

**C4: Input series and output series**



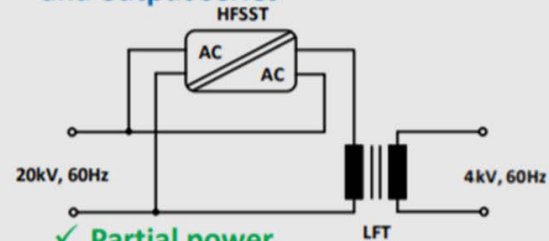
- ✓ Partial power
- ✓ No 20kV devices
- ❖  $V1/V2=n1/n2$
- ❖ No voltage regulation
- ❖ 100kV insulation

**C5: Primary side cascaded**



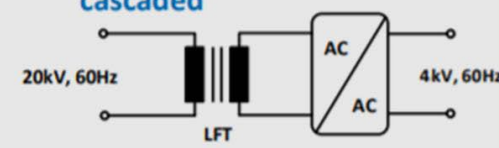
- ✓ Voltage regulation
- ✓ No transformer
- ❖ 20kV devices
- ❖ No partial power

**C6: Primary side input parallel and output series**



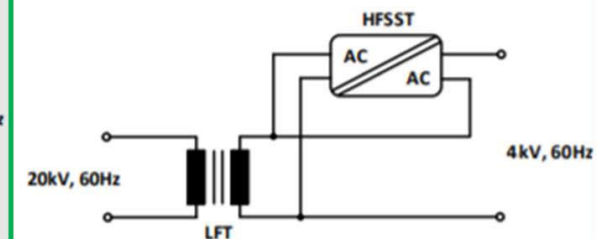
- ✓ Partial power
- ✓ Voltage regulation
- ❖ 20kV devices
- ❖ 100kV insulation

**C7: Secondary side cascaded**



- ✓ Voltage regulation
- ✓ No 20kV devices
- ✓ No transformer
- ❖ No partial power

**C8: Secondary side input parallel and output series**



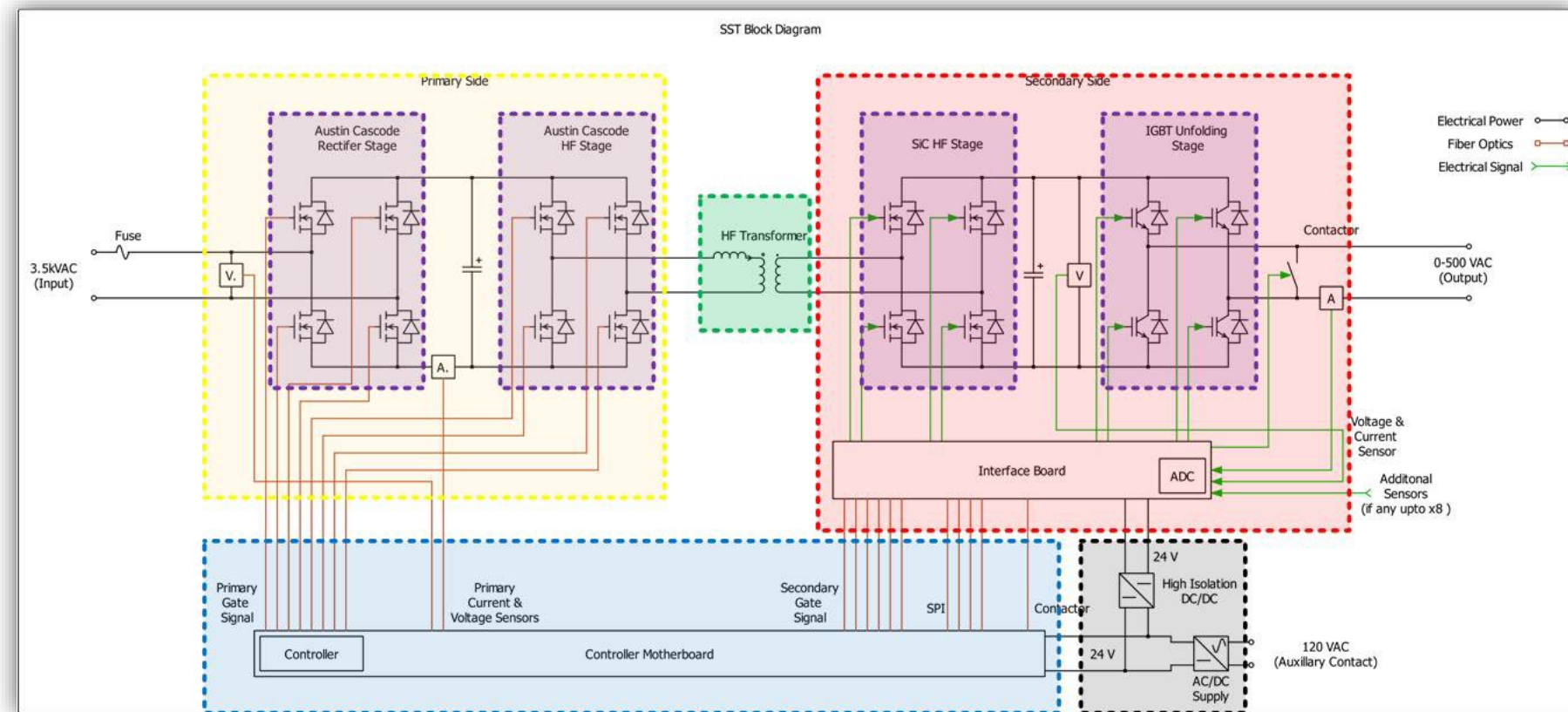
- ✓ Partial power
- ✓ Low voltage insulation
- ✓ Voltage regulation
- ✓ No 20kV devices



# Innovation Update

## *The MV AC-AC SST*

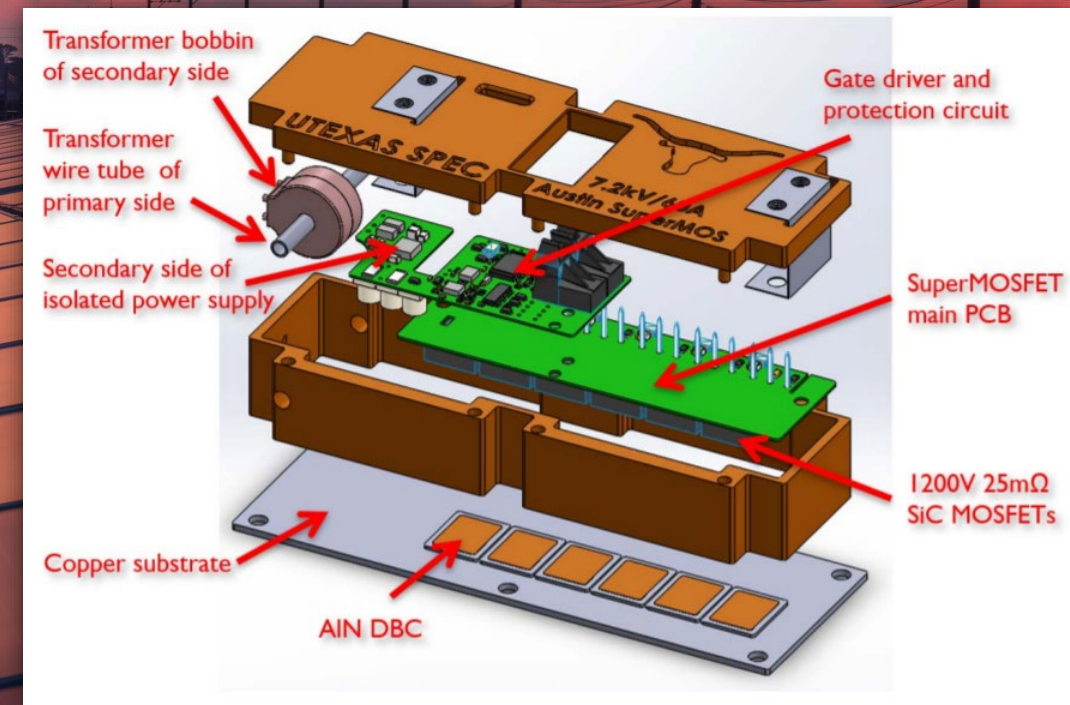
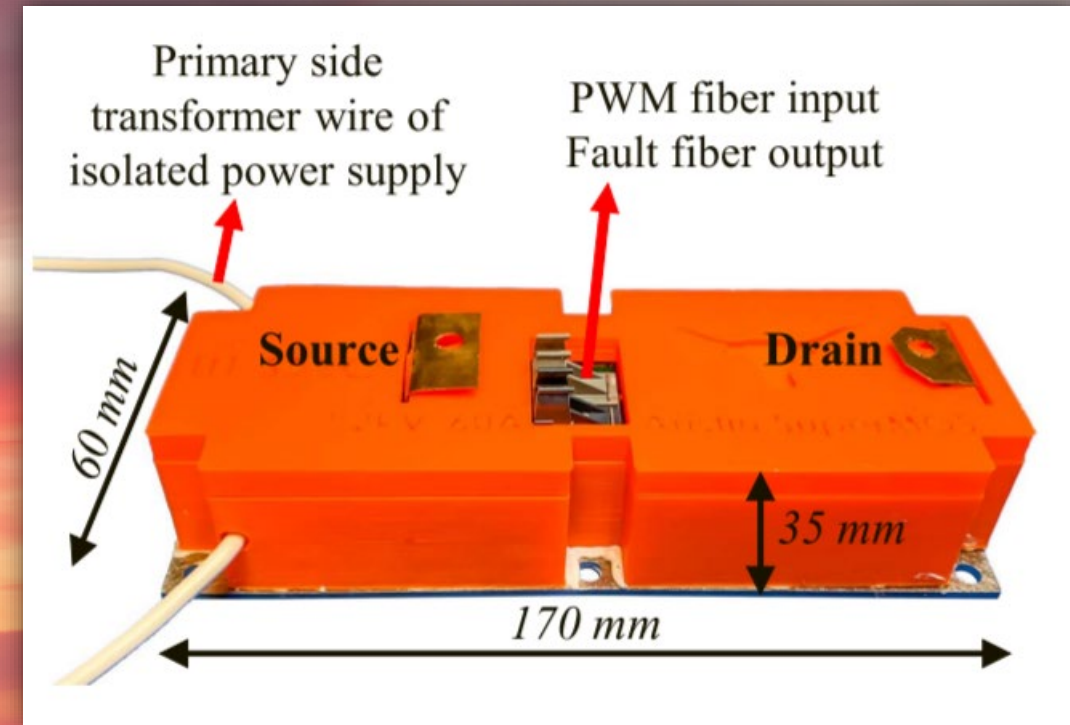
- A single stage Dual Active Bridge based AC-AC SST
- Inherent ZVS operation to keep efficiency high
- High power density due to lack of bulky DC Link capacitors
- Direct MV to LV AC conversion avoids the need for 60Hz transformers or auxiliary windings



# Innovation Update

## *The 7.2kV SiC Austin SuperMOS*

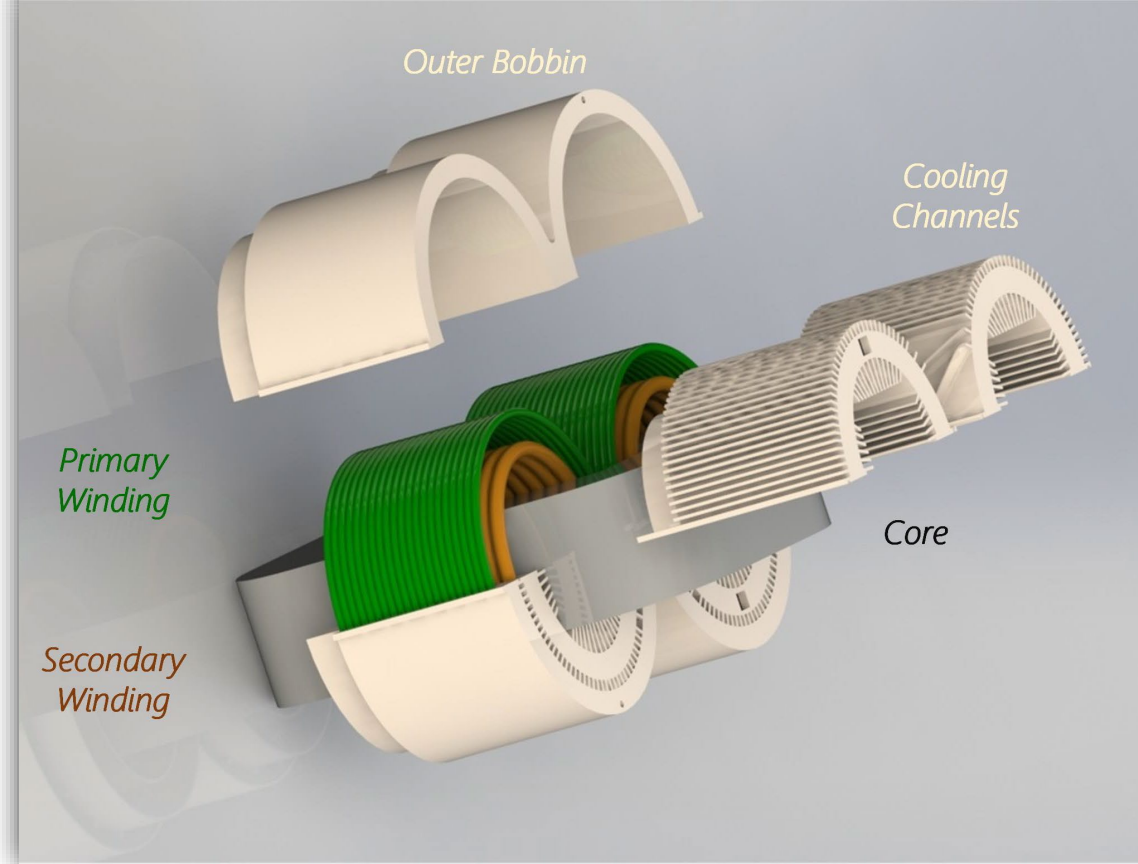
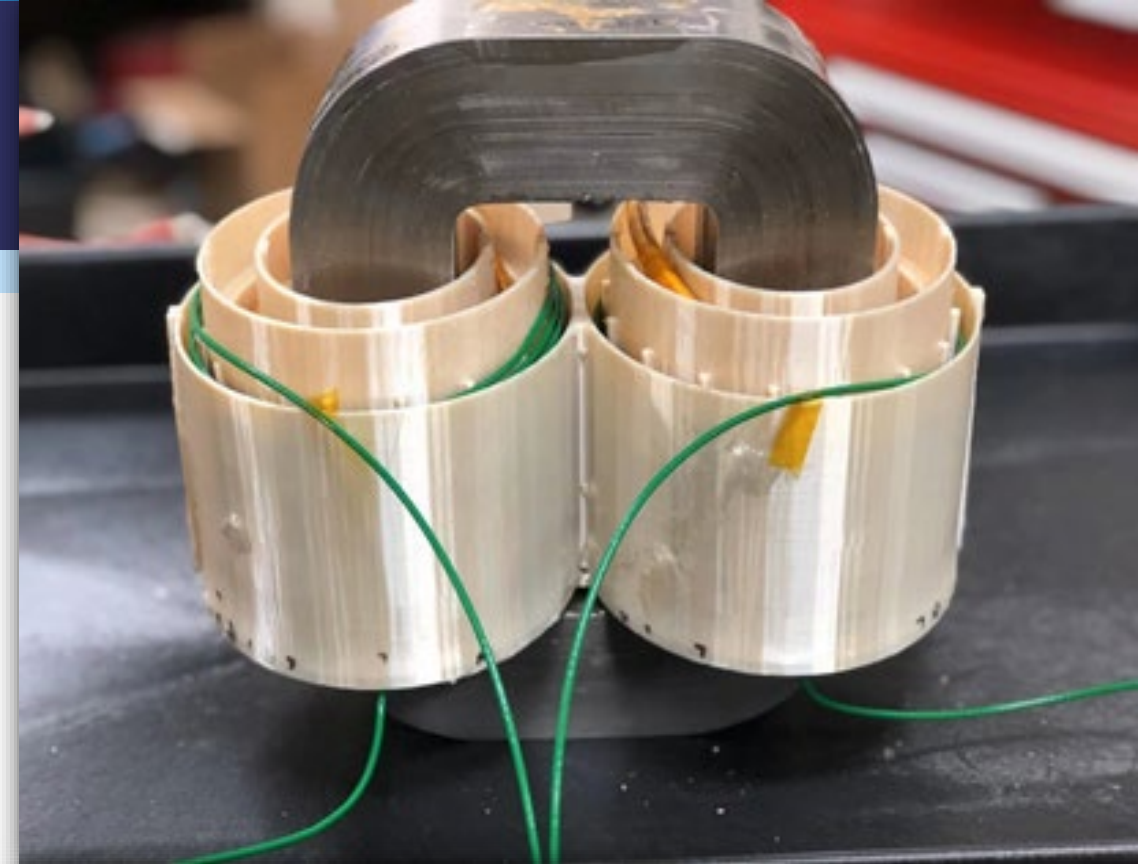
- UT Austin developed low cost and high performance medium voltage switch serves as a key enabler for medium voltage SST applications
- Integrated gate driver with overcurrent protection and highly isolated power supply
- High blocking voltage with low on-resistance (7.2kV / 60A / 0.18 $\Omega$ )
  - Future developments (leveraging other funding) underway for even higher voltage and current devices



# Innovation Update

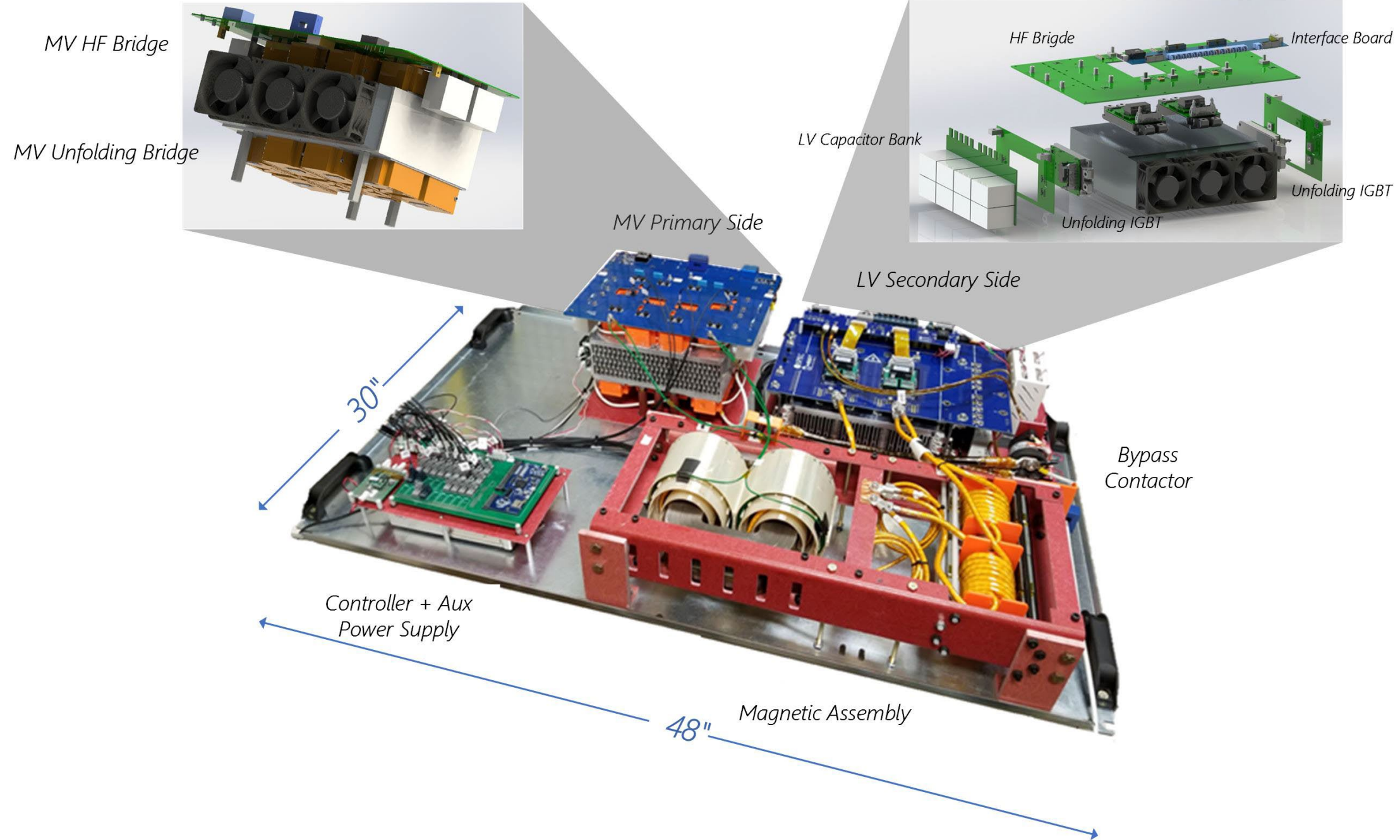
## *The High Frequency and High Isolation Transformer*

- Designed for 100 kVA/20 KHz operation with a turns ratio of 7:1
- A novel 3D printed bobbin design that offers an impressive 14kV isolation (tested for partial discharge)
- Intricate cooling channels in bobbin help keep thermals at bay



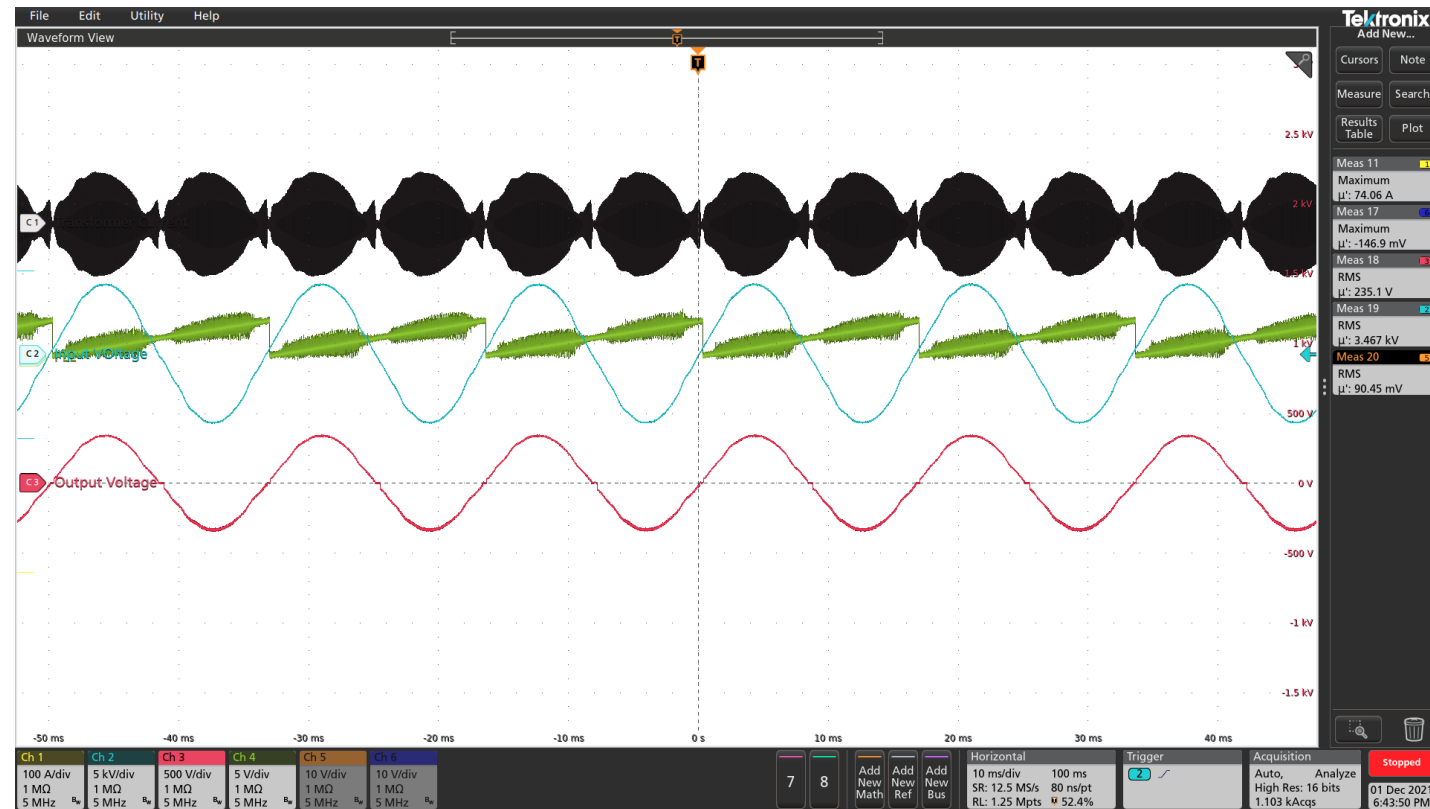
# Innovation Update

## The MV AC-AC SST



# Innovation Update

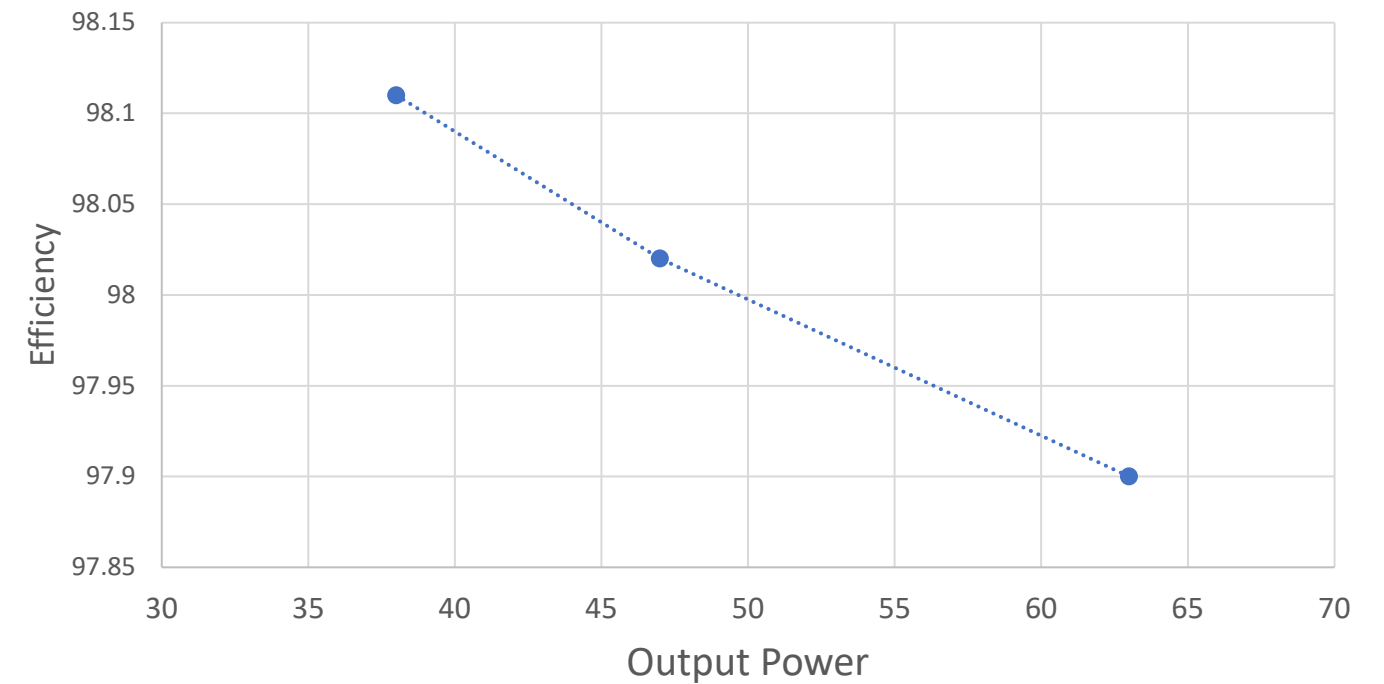
## The MV AC-AC SST Tested



3500V Standalone SST Operation

- HF Transformer Current
- Input AC Voltage
- System PLL
- Output AC Voltage

Measured Efficiency vs Output Power @ 3500V/500V operation



DABSST Efficiency vs Output Power

\* Calculated using back-to-back circulation test bed operating in DC-DC mode

HSST efficiency is "LFT efficiency – 0.3%"

# Innovation Update

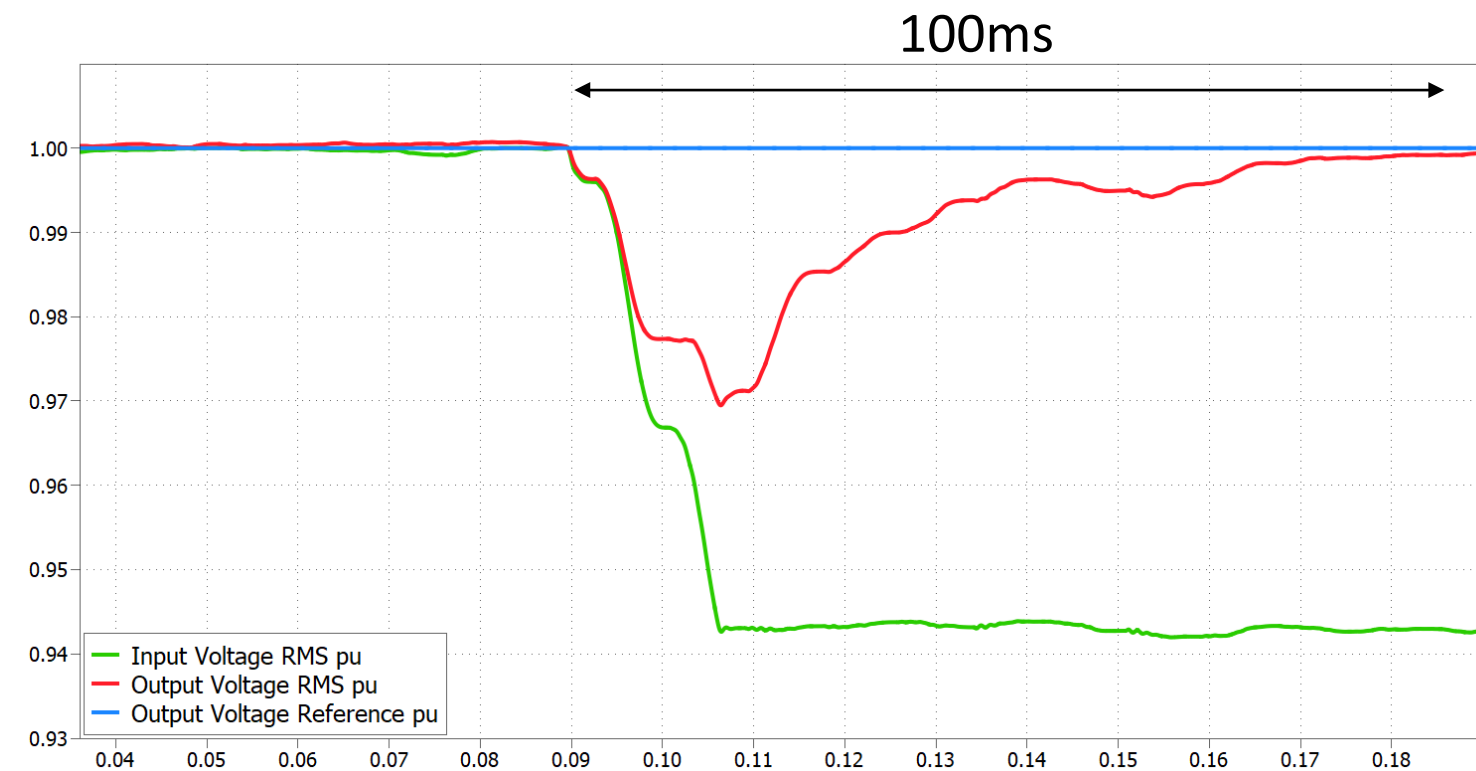
*The 500kVA HSST developed and assembled*

- DABSST coupled with a standard dry type 500kVA 20kV/4kV single phase transformer
- Total system dimensions : 60" x 62" x 94"
- *DABSST is very small compared to the LFT*



# Innovation Update

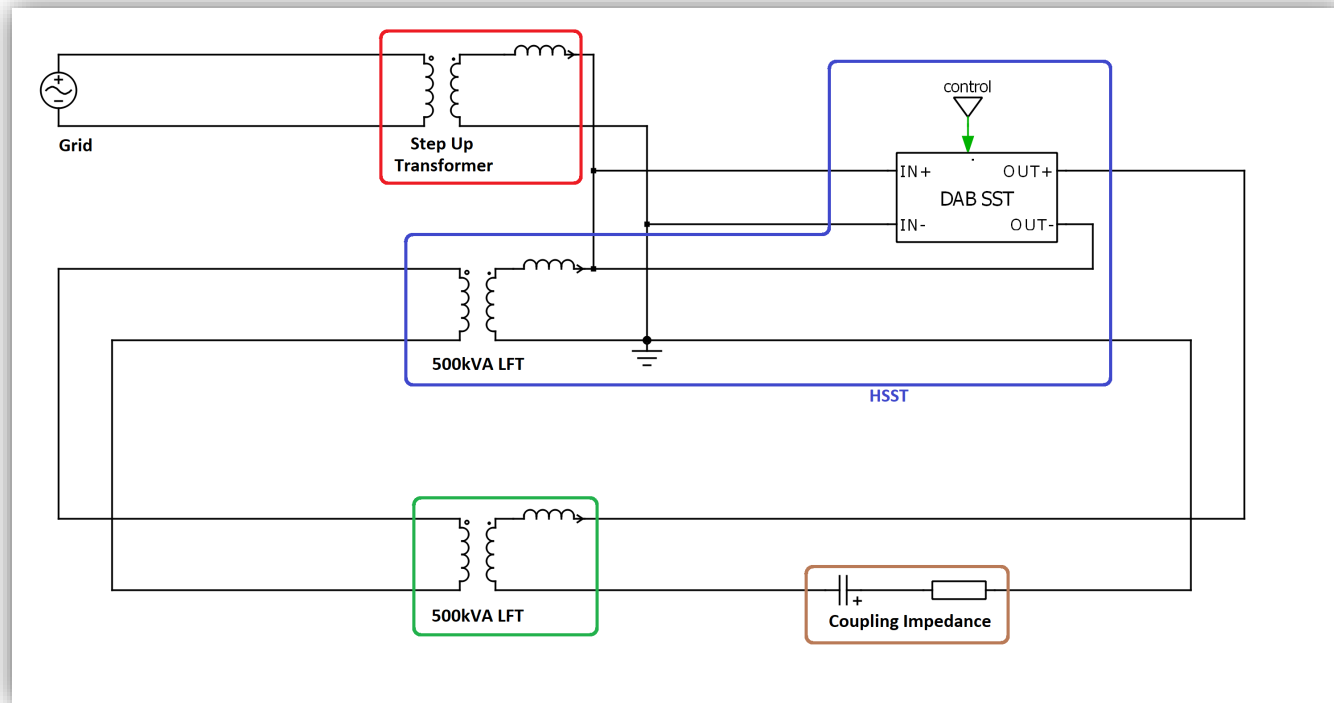
## The 500kVA HSST - Voltage Regulation Capability



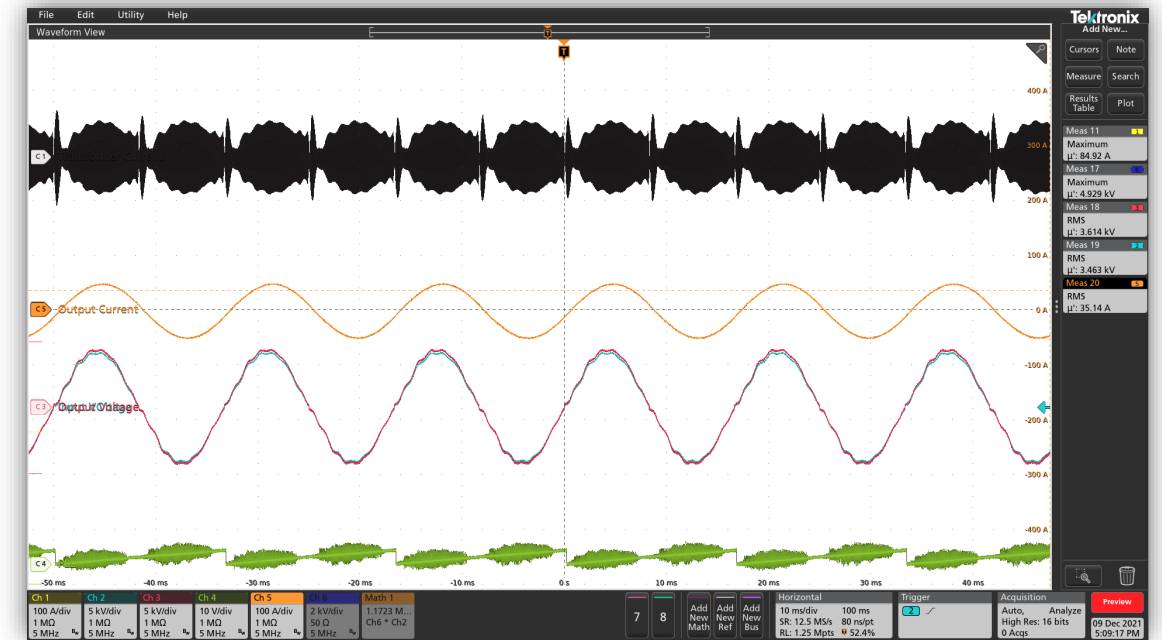
- HSST demonstrating voltage regulation capability (voltage sag of ~6%)
- this is a lower power operation at 14kVA @ 0.93pf leading power factor

# Innovation Update

## The 500kVA HSST - High Power Circulation Test



HSST Circulation Test Circuit



Test Waveforms @ 136kVA 0.98 lagging

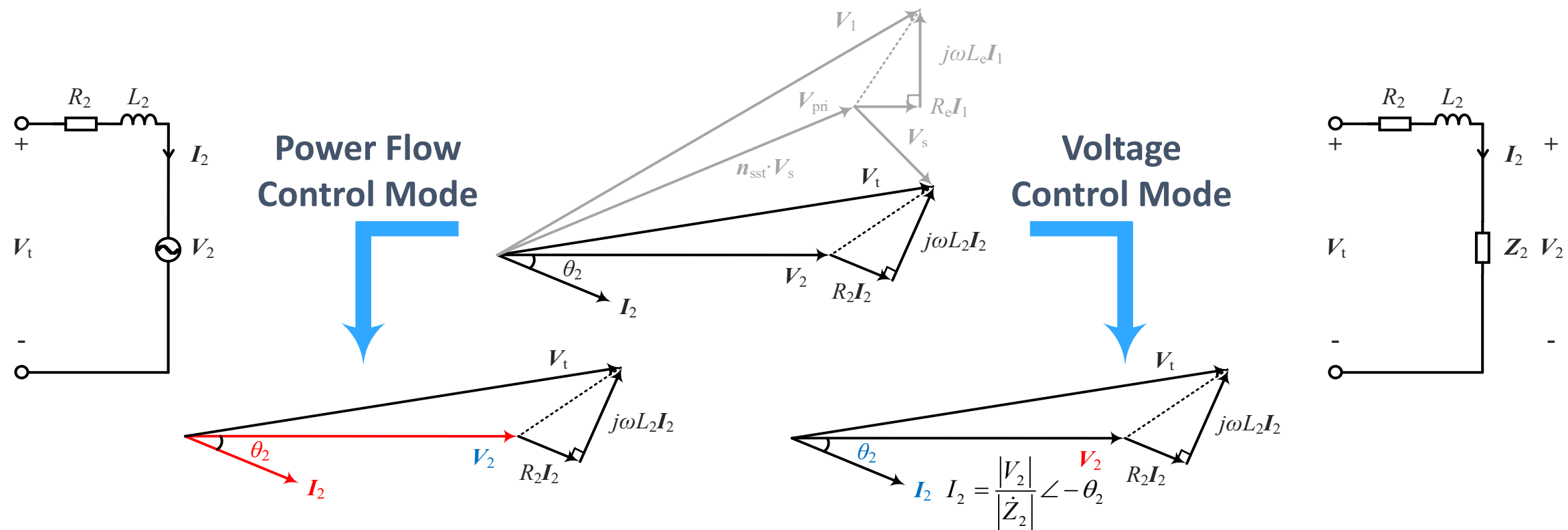
HF Transformer Current  
Output Current  
Input Voltage  
Output Voltage  
System PLL

- HSST tested at rated voltage and high power through a novel circulation test setup
- Power flow controlled remotely through optical communication interface (video demonstration at end)



# Innovation Update

## HSST Phasor-Domain Modeling



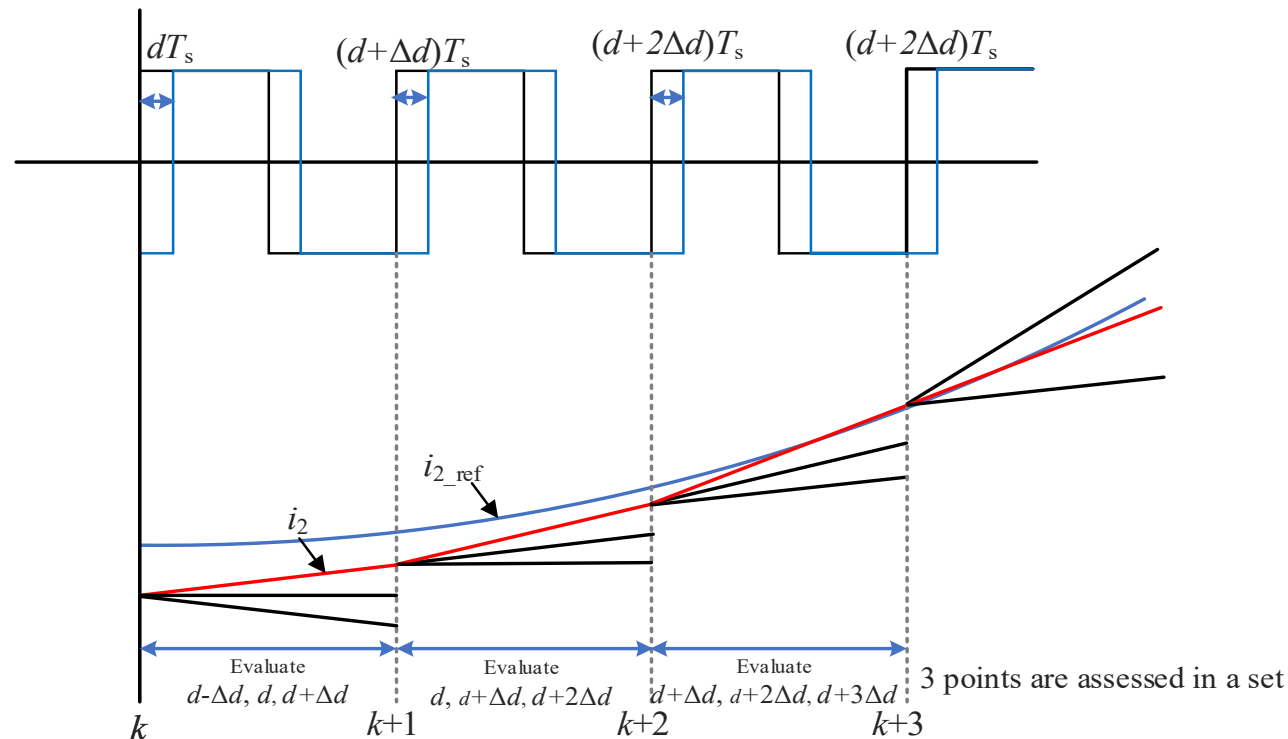
- Secondary side grid voltage is present
- Secondary side current phasor is set in the control diagram

- Secondary side load is present (w/ load amplitude and phase angle)
- Secondary side voltage phasor is set in the control diagram

A generic representation with  $V_2$ ,  $I_2$ , and  $\theta_2$  is used for both operation modes

# Innovation Update

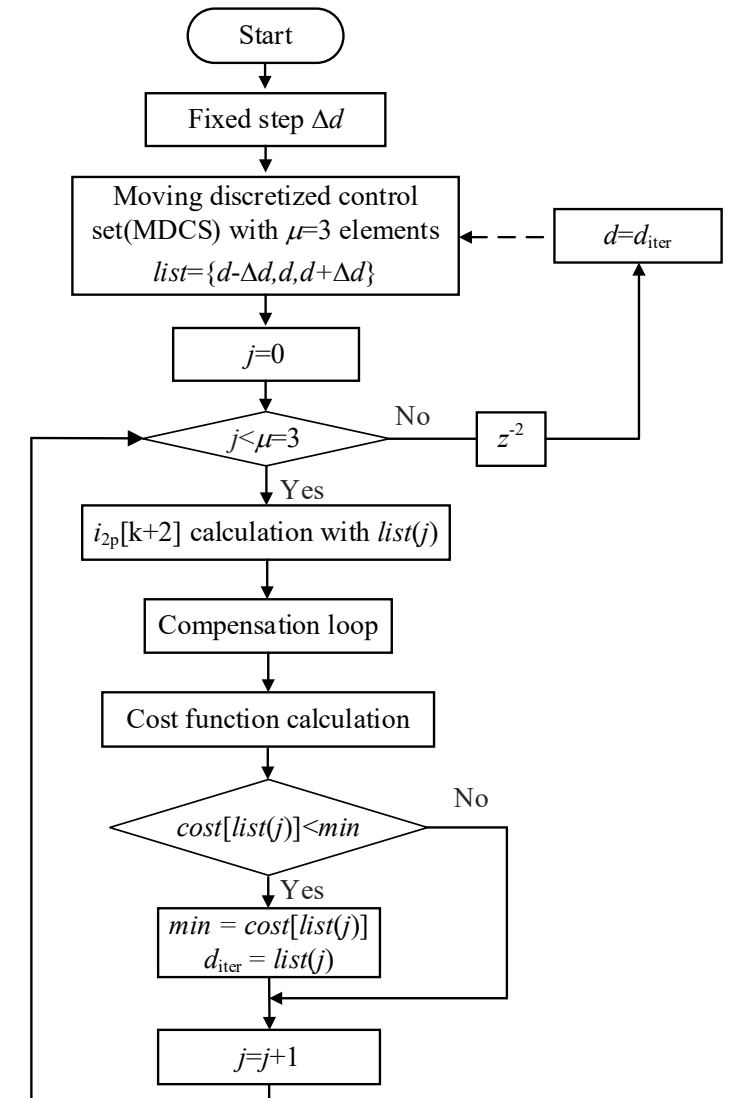
## HSST Dynamic Modeling w/ Model Predictive Control (MPC)



$$f_{\text{cost}} = \alpha_1 G_1 + \alpha_2 G_2$$

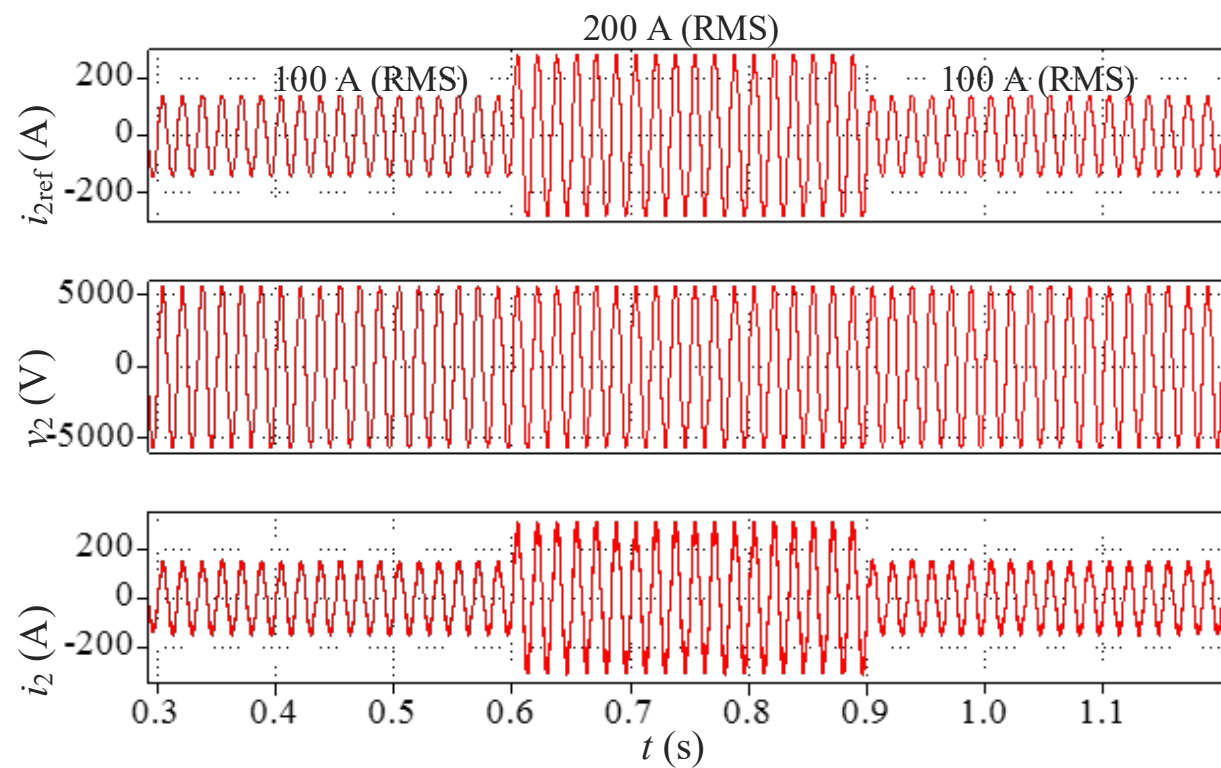
$$G_1 = (i_{2\_ref} - i_2)^2, \quad G_2 = (i_{2p}[k+3] - i_2[k])^2$$

- A model predictive control developed for the HSST is also developed
- MPC model tasked for two modes of control - Voltage mode control for output voltage regulation i.e., distribution applications, and Current mode control for Output power control i.e., transmission applications

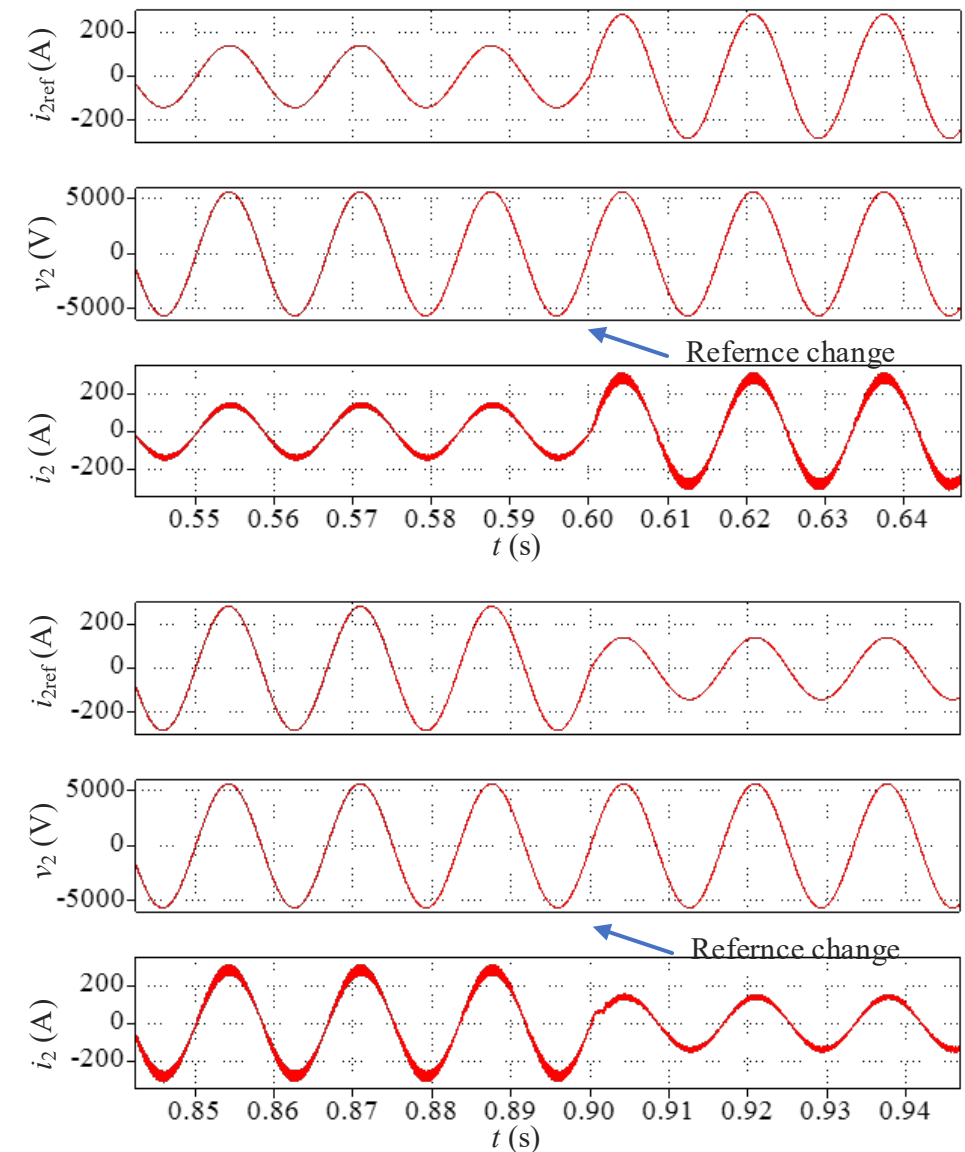


# Innovation Update

## HSST Dynamic Modeling w/ Model Predictive Control (MPC) – Simulation Results



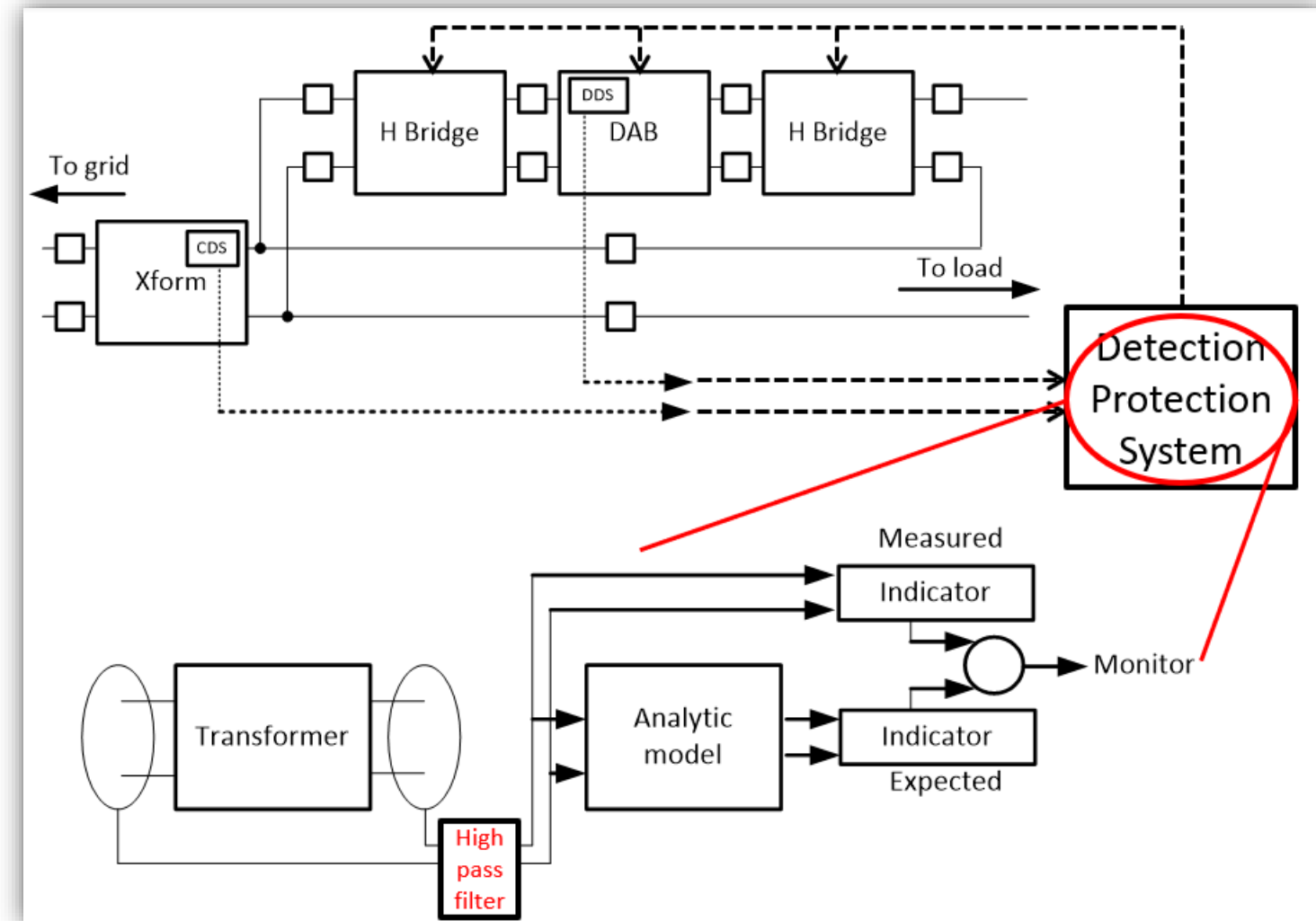
Current reference step-up  
and step-down changes



# Innovation Update

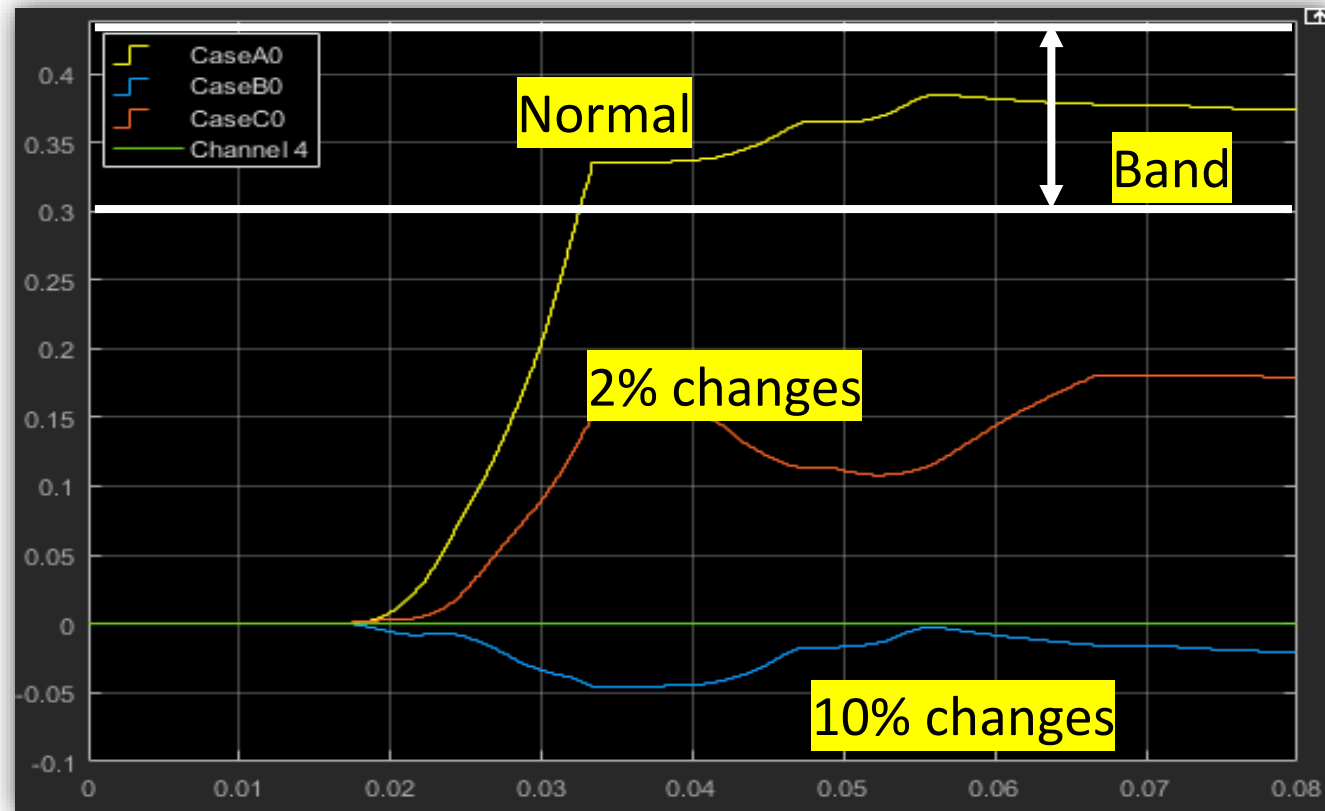
## *HSST – Online/Offline Monitoring and Fault Detection*

- A comprehensive fault monitoring system has been envisioned to monitor the health of the high frequency transformer.
- Algorithm computes real time impedance of the transformer to detect any anomalies.



# Innovation Update

## HSST – Online/Offline Monitoring and Fault Detection

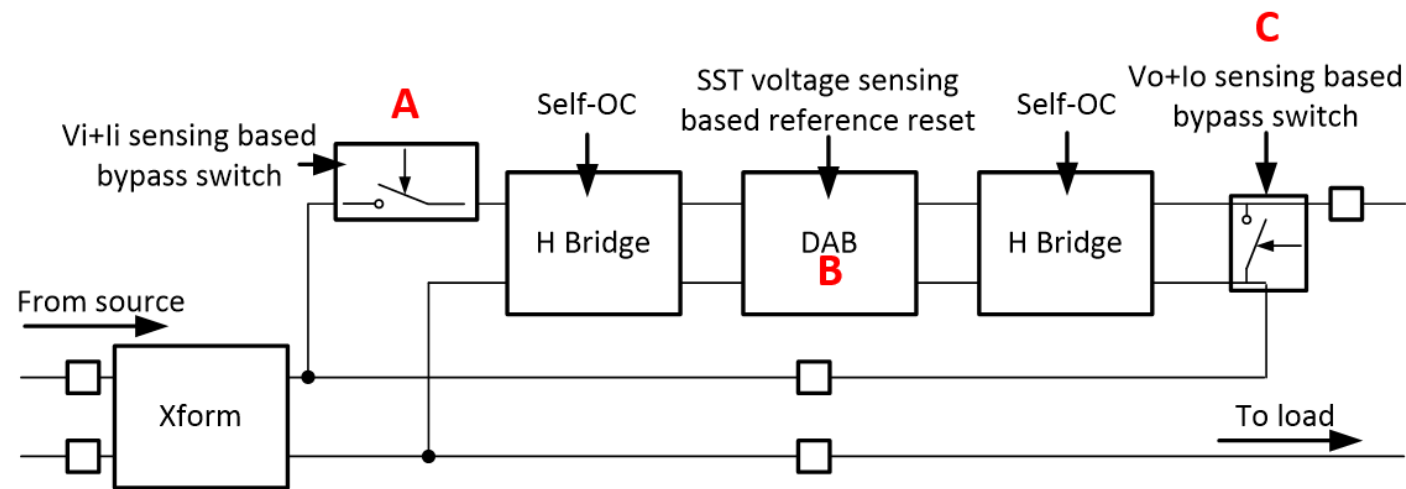


- Algorithm has been tested with actual test conditions (having altered the HFT impedances in the actual hardware)
- Proposed method has been proven to identify the system deformation and internal faults considering the measurement bias and noise.

	$L_{LX}$ (uH)	$ Z_{sc} $ [%]
Healthy unit (case A0)	960	0
Case B0	960+20	2.1
Case C0	960+95	9.9

# Innovation Update

## HSST – Proactive Protection Tool



- A. Input voltage and current sensing based fast protection switch (optional)
- B. SST input/output voltage sensing based reference reset (very fast)
- C. Output voltage and current sensing-based bypass switch (the faster as better)

- A proactive protection tool has been envisioned to form a comprehensive protection concept for the HSST unit against grid faults and disturbances
- Several fault scenarios have been studied i.e.,
  - single module faults
  - multiple module faults
  - inter phase faults under both wye and delta configuration
- Simulation results have demonstrated ability the protection system to safely contain the issues and prevent SST damage.

# Acronyms

*HSST – Hybrid Solid State Transformer*

*SST – Solid State Transformer*

*DAB – Dual Active Bridge*

*HF - High Frequency*

*LPT – Large Power Transformer*

*MPC- Model Predictive Control*

*ZVS – Zero Voltage Switching*

*MV – Medium Voltage*

*LV – Low Voltage*

***THANK YOU***