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

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Team Members:

Project Summary

Motivation

- Transformers have been a mainstay of power grids for over a century. However, they are passive, offering no controllability
- Large Power Transformers further have several logistical issues – large, heavy and bespoke – requiring large turn around time. Not easily transportable or replaceable

Objectives

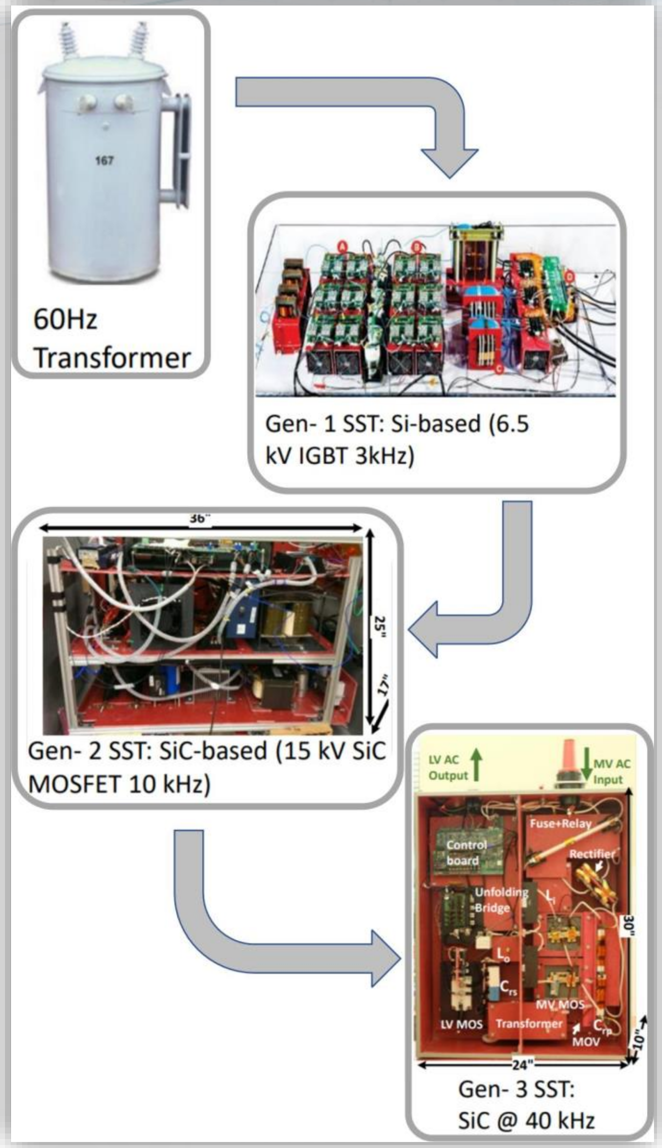
- Develop and demonstrate a modular Hybrid Solid State Transformer (HSST) for next generation Flexible and Adaptable large power transformer (LPT)
- Demonstrate advanced control functions of the H-SST that is currently not available in traditional transformers

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:
  Completed
- AWARD AMOUNT (DOE CONTRIBUTION):
  $1,730,000
- AWARDEE CONTRIBUTION (COST SHARE):
  $433,000

Technical Approach

- 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.



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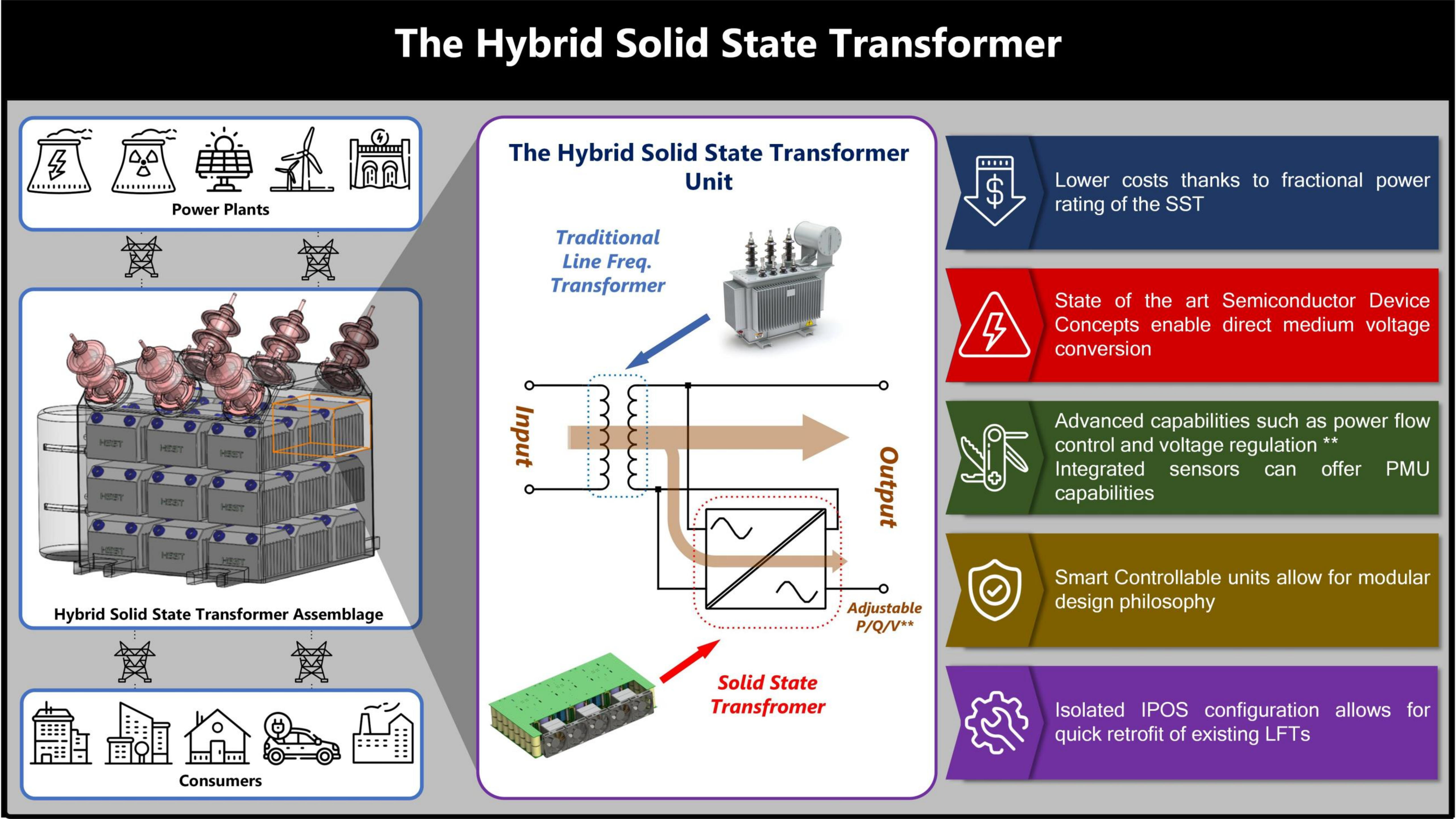
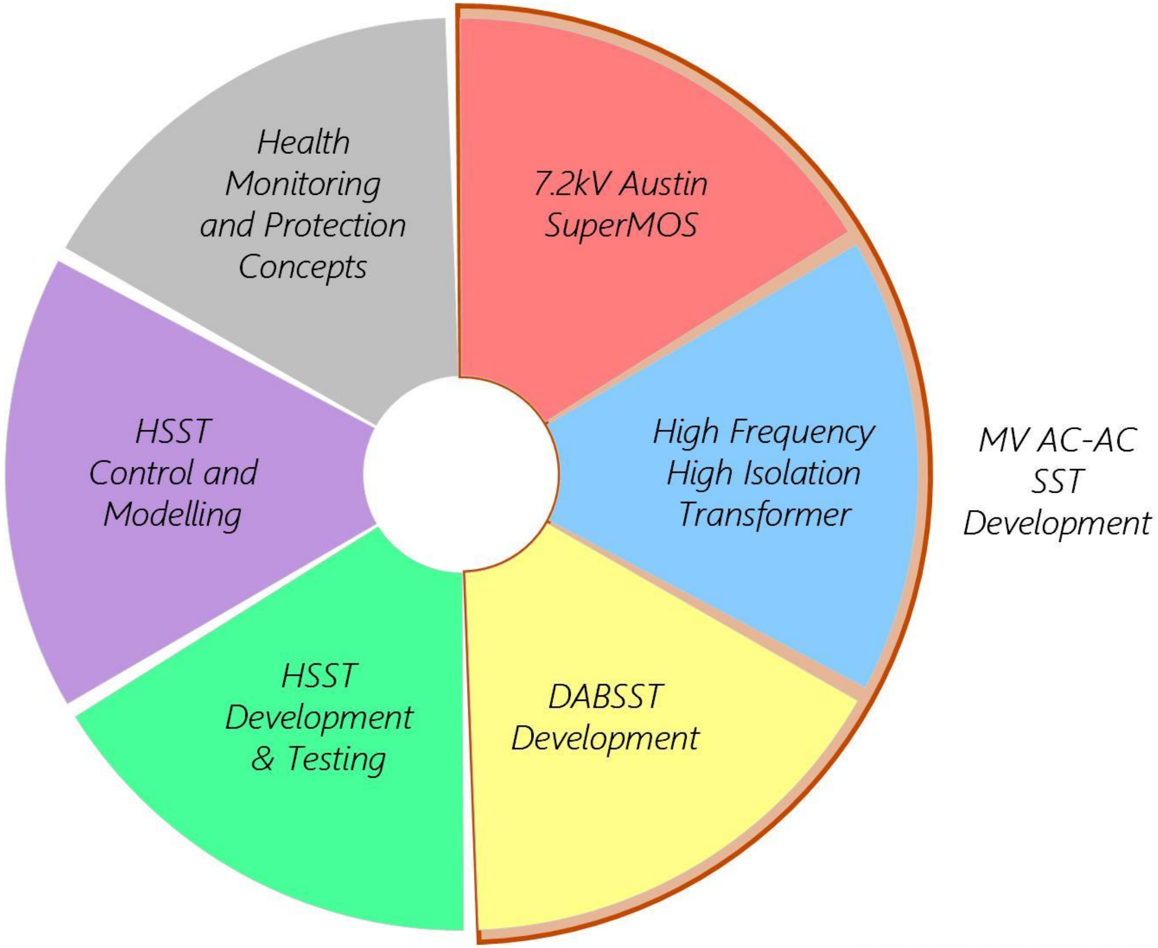


The Hybrid Solid State Transformer
Power Plants
Hybrid Solid State Transformer Assemblage
Consumers
The Hybrid Solid State Transformer Unit
Traditional Line Freq. Transformer
Input
Output
Adjustable P/Q/V**
Solid State Transfromer
Lower costs thanks to fractional power rating of the SST
State of the art Semiconductor Device Concepts enable direct medium voltage conversion
Advanced capabilities such as power flow control and voltage regulation **
Integrated sensors can offer PMU capabilities
Smart Controllable units allow for modular design philosophy
Isolated IPOS configuration allows for quick retrofit of existing LFTs

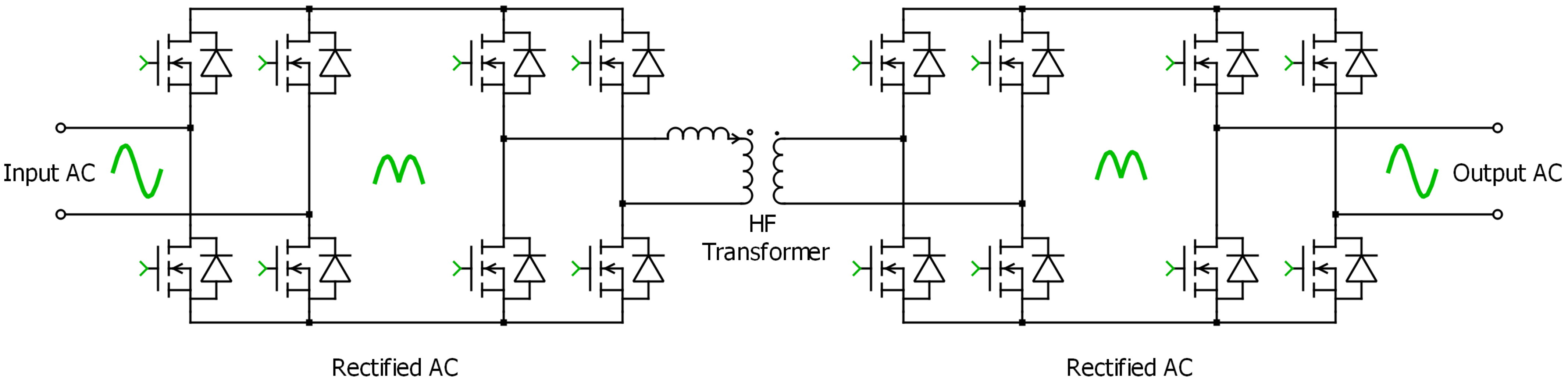
Accomplishments

Accomplishments Subtasks



Accomplishments

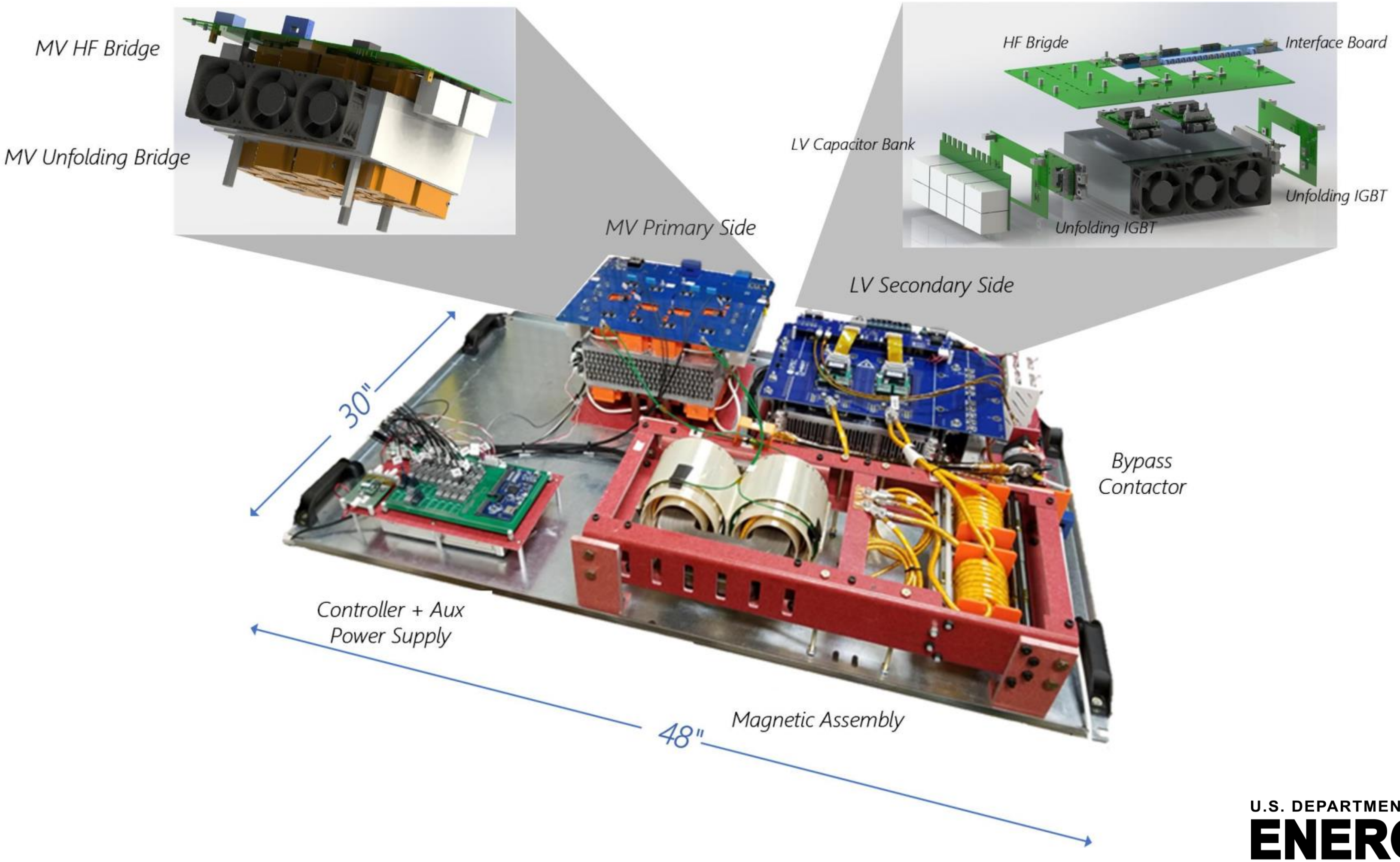
The Medium Voltage AC-AC SST



DAB based AC/AC converter – 3500V/500V/100kVA

Accomplishments

The Medium Voltage AC-AC SST



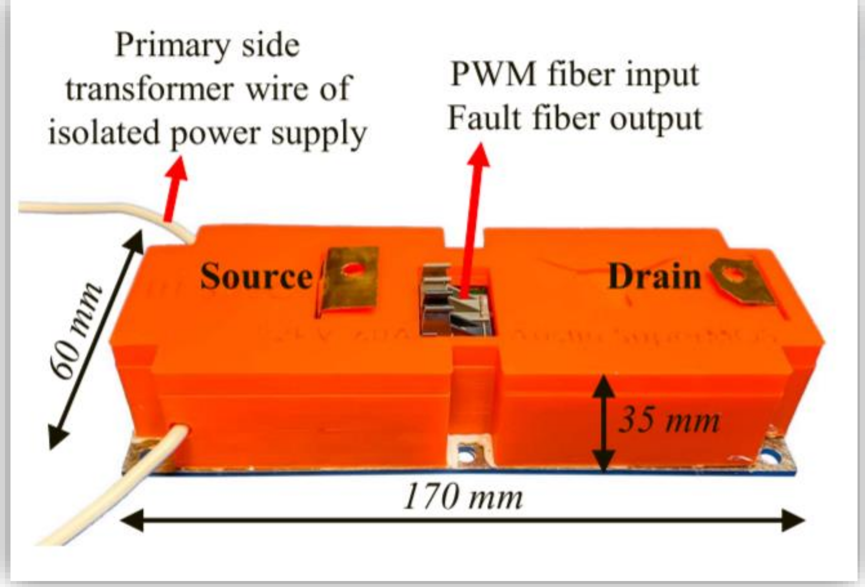
Accomplishments

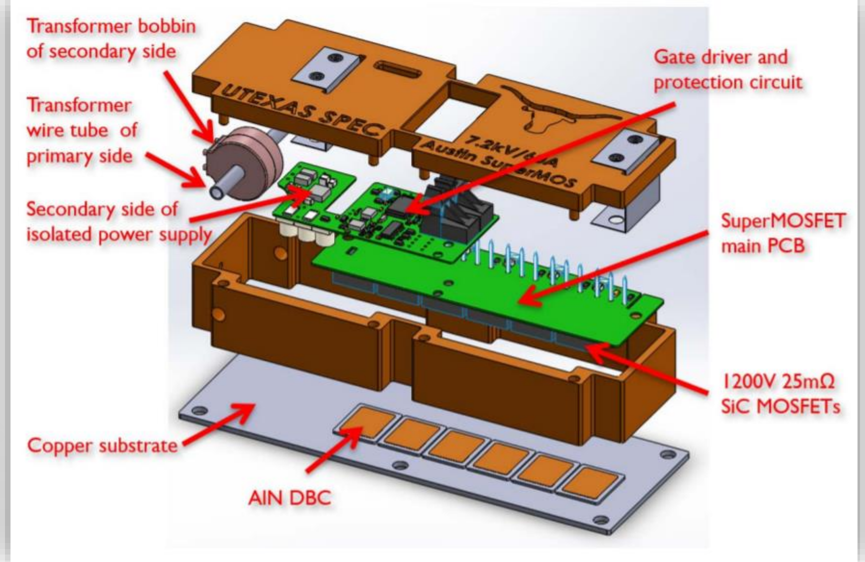
The Medium Voltage AC-AC SST –
The 7.2kV Austin SUPERMOS

- 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 / 0.18Ω)





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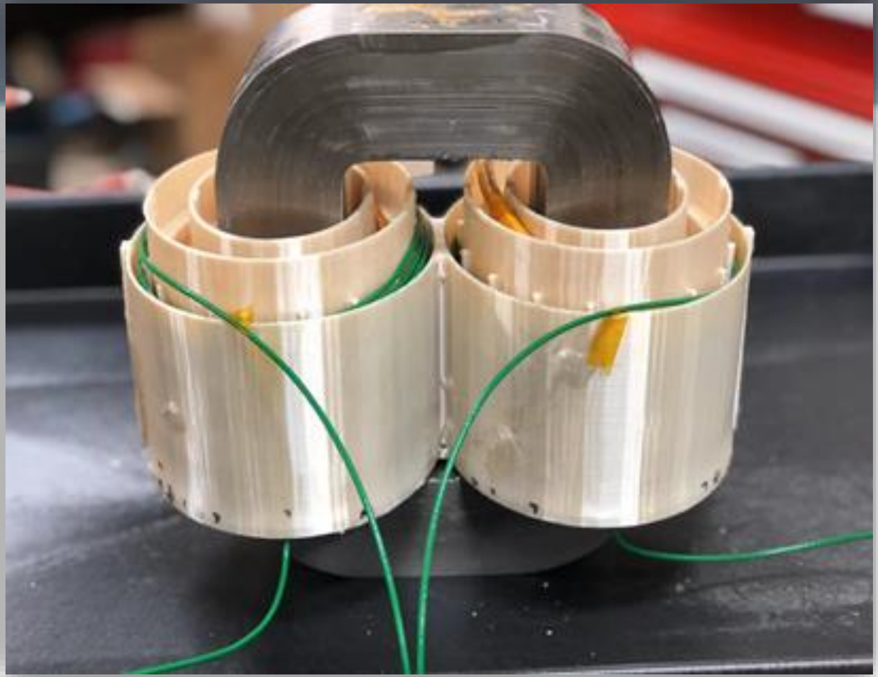
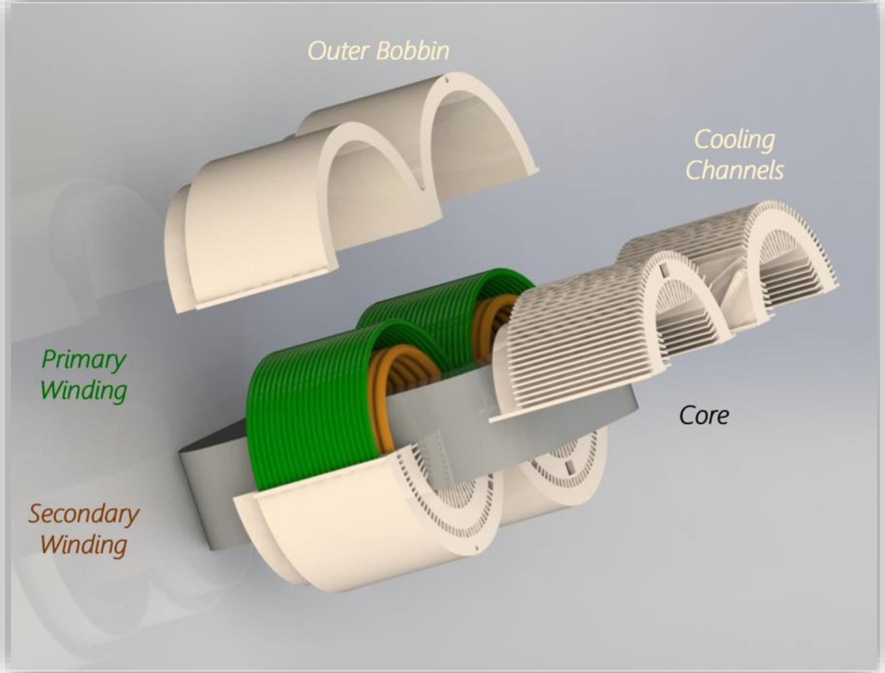
Accomplishments

The Medium Voltage AC-AC SST –
The High Frequency and High Isolation Transformer

- 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
- Turns ratio of 7:1





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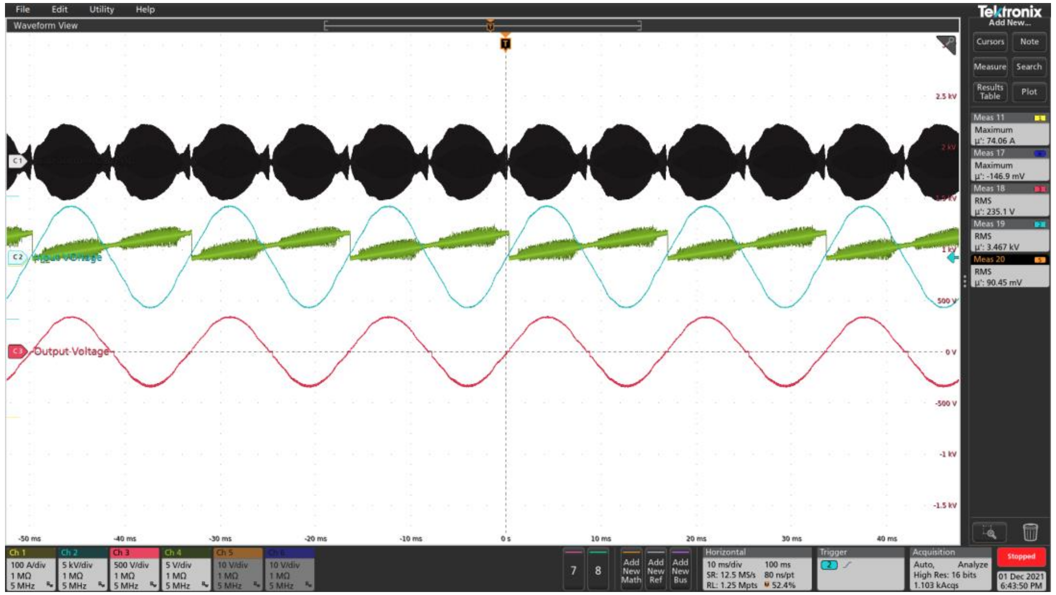
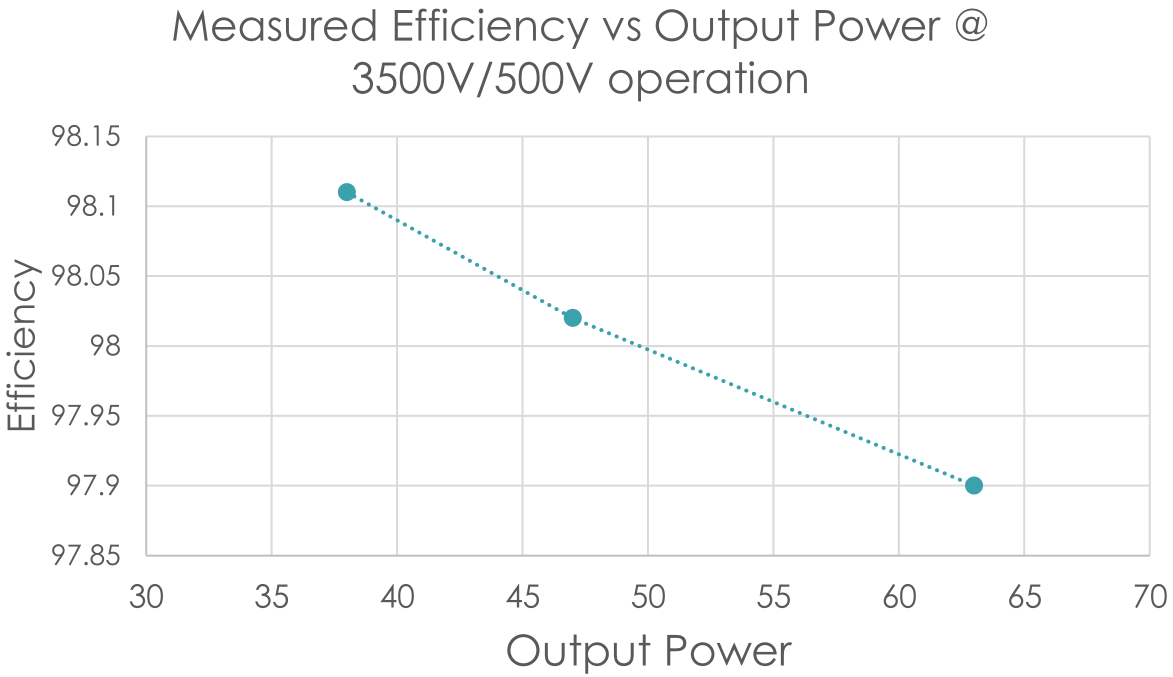
Accomplishments



3500V Standalone SST Operation

HF Transformer Current
Input AC Voltage
System PLL
Output AC Voltage



DABSST Efficiency vs Output Power
** Calculated using back-to-back circulation test bed operating in DC-DC mode*

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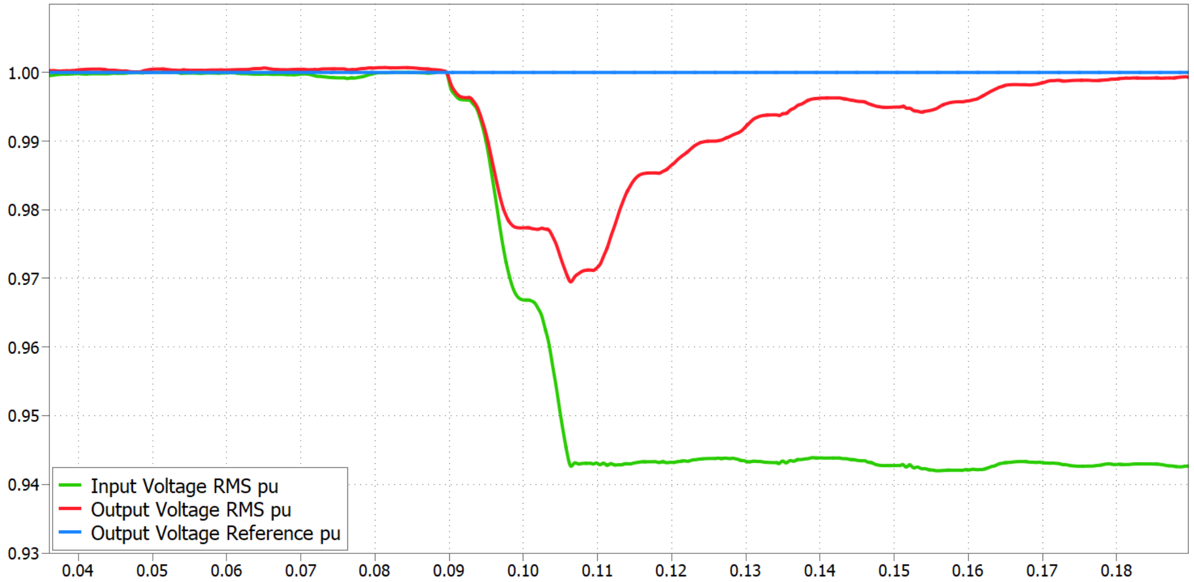
Accomplishments

The 500kVA HSST

- DABSST coupled with a standard dry type 20kV/4kV single phase transformer
- Total system dimensions : 60” x 62” x 94”

Accomplishments

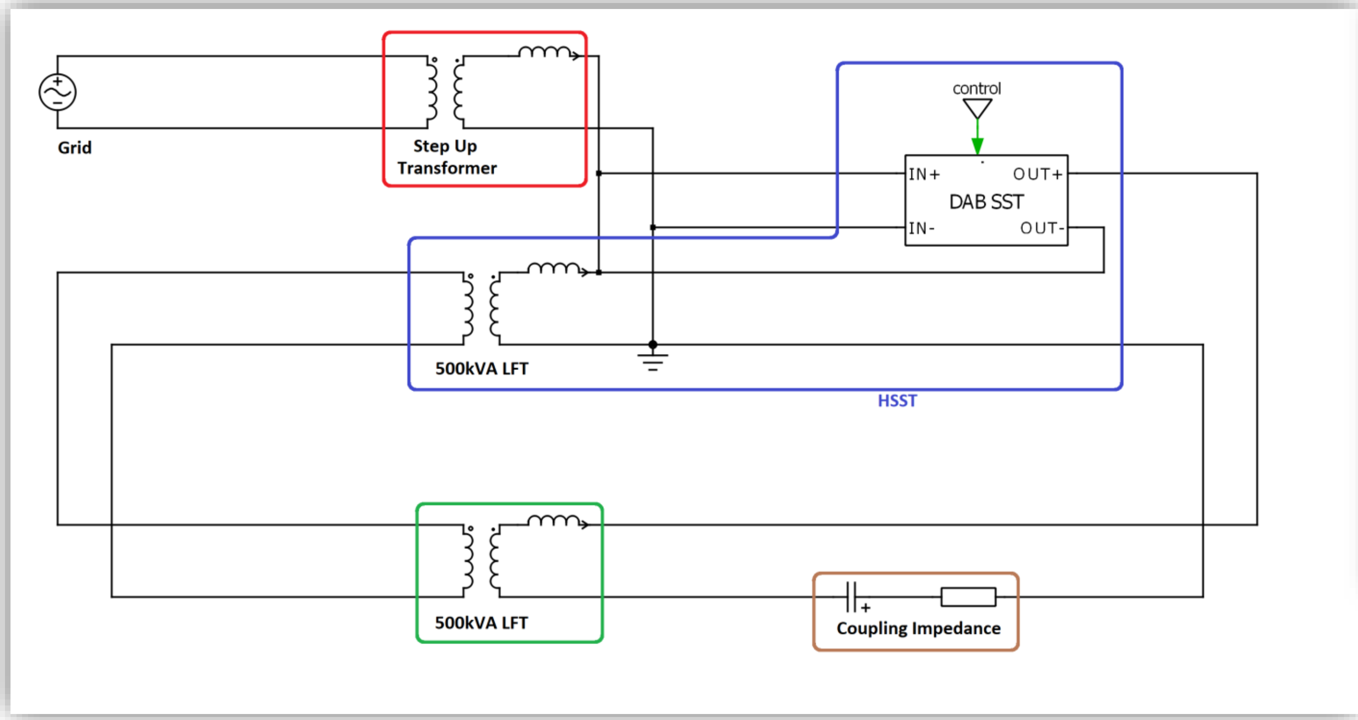
The 500kVA HSST – Control Capabilities



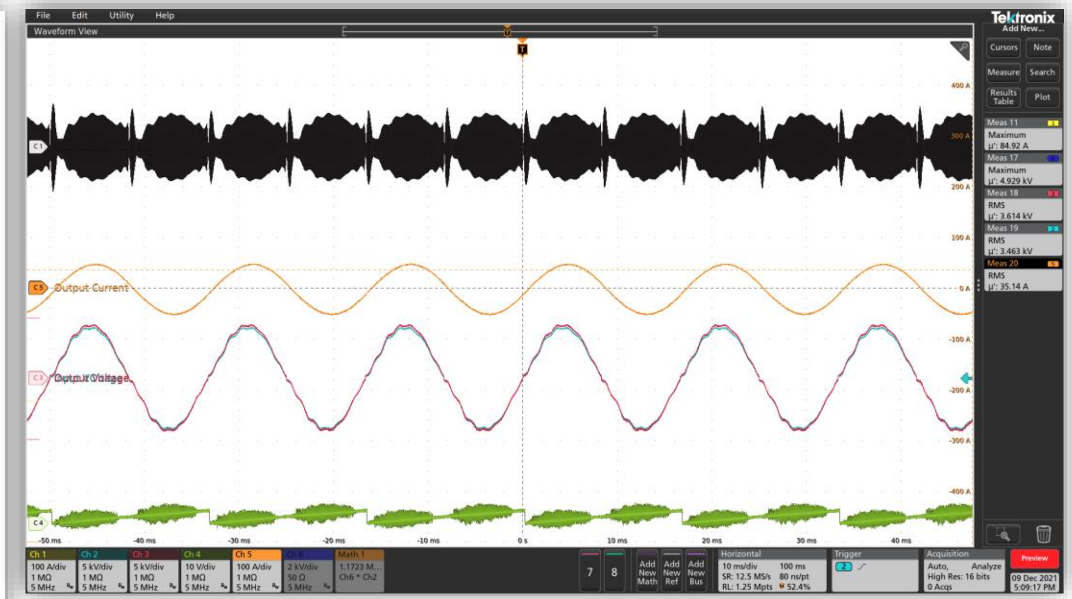
- HSST Unit demonstrating voltage regulation capability (voltage sag of ~6%)
- Lower power operation shown to facilitate closed loop testing (14kVA @ 0.93pf leading)

Accomplishments

The 500kVA HSST – High Power Test



HSST Circulation Test Circuit

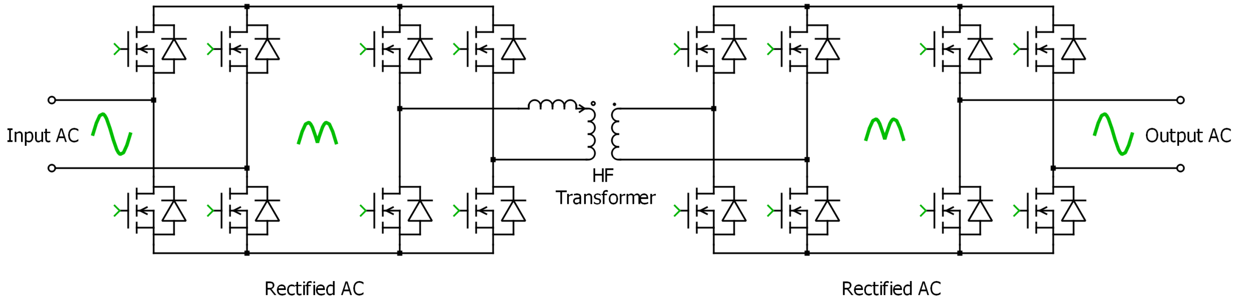


Test Waveforms @ 136kVA 0.98 lagging

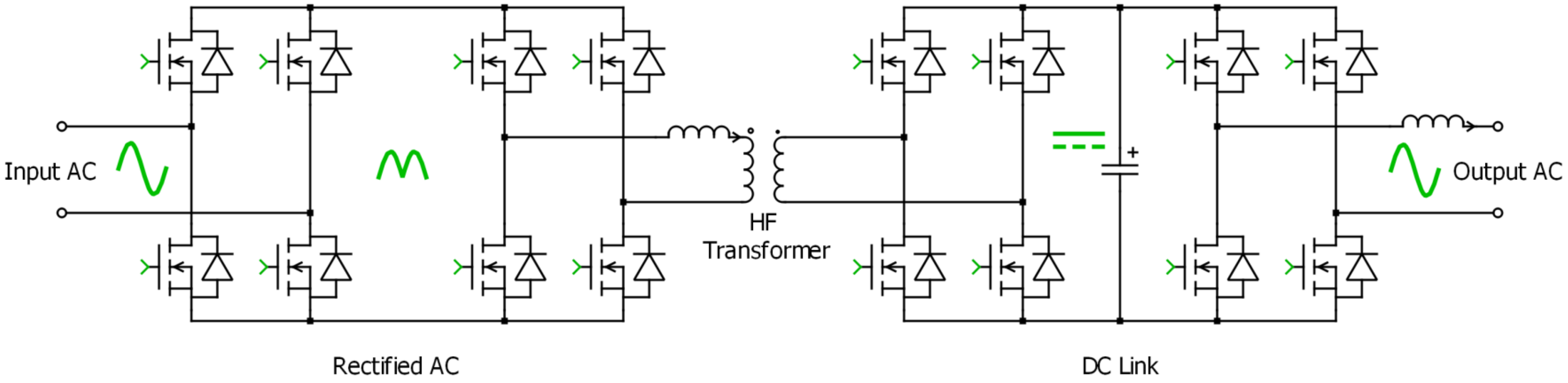
HF Transformer Current
Output Current
Input Voltage
Output Voltage
System PLL

Accomplishments

The 500kVA HSST – Two Stage SST based HSST

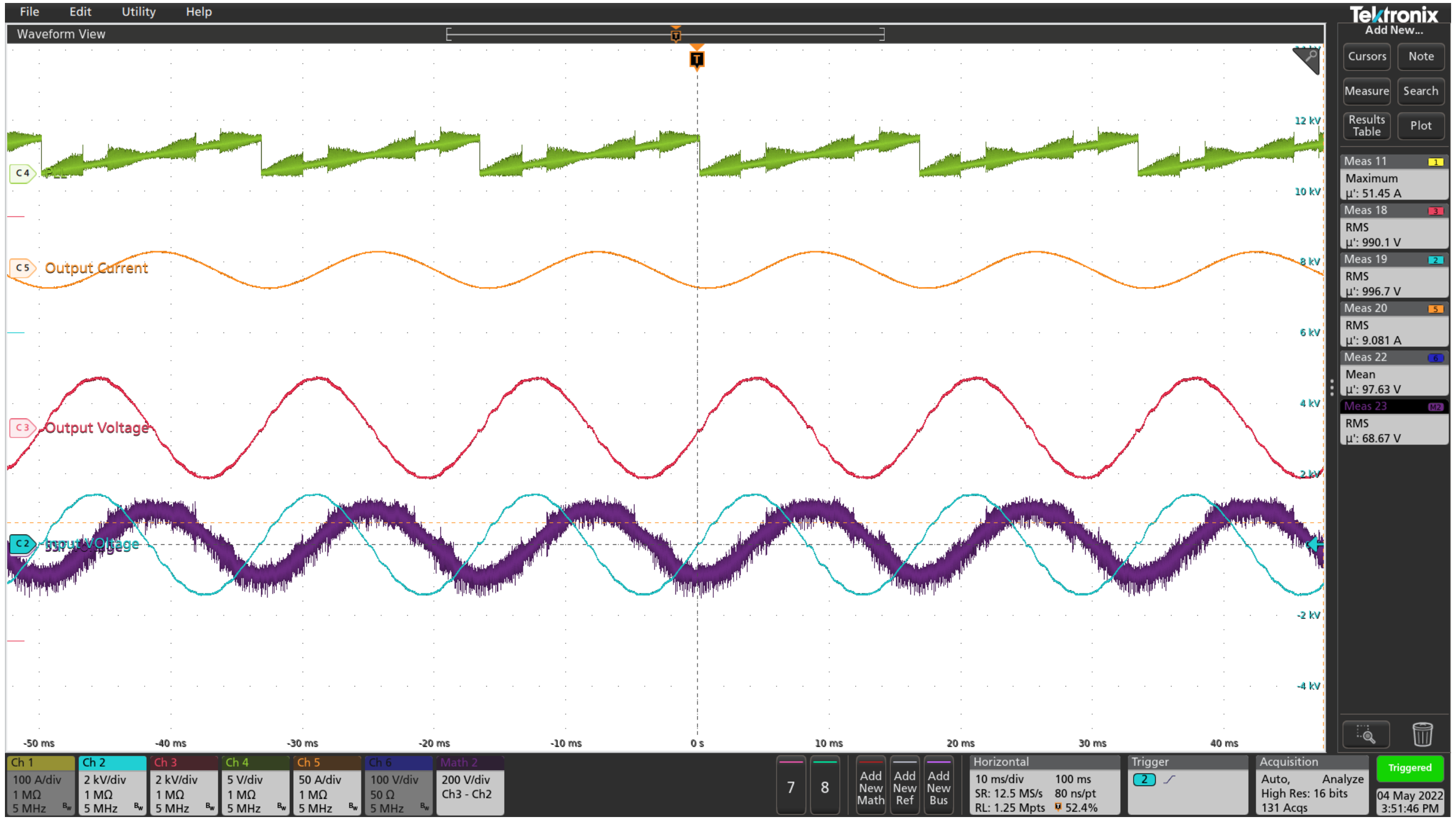


Single Stage vs 2-stage



Accomplishments

The 500kVA HSST – Two Stage SST based HSST



Test Waveforms @ 33.8kVA @ 0.1pf laggin
7.5kV/1.5kV

Output Current
Input Voltage
Output Voltage
SST Voltage
System PLL

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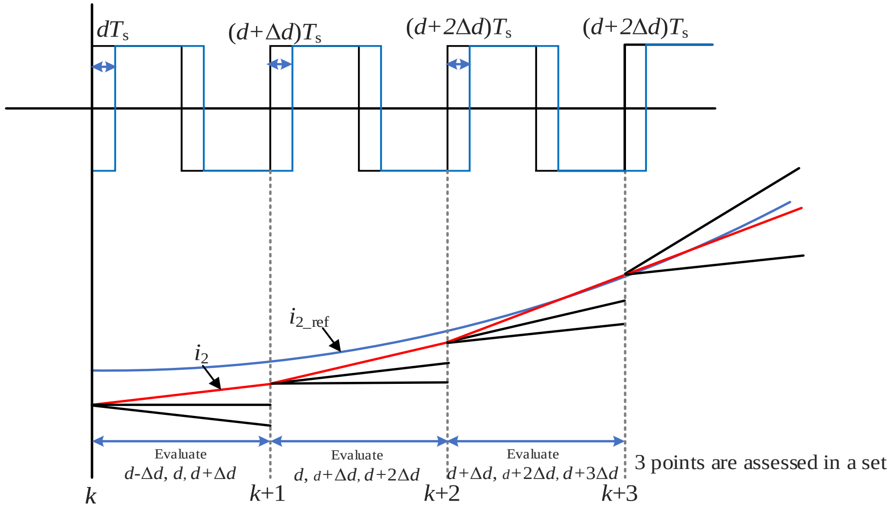
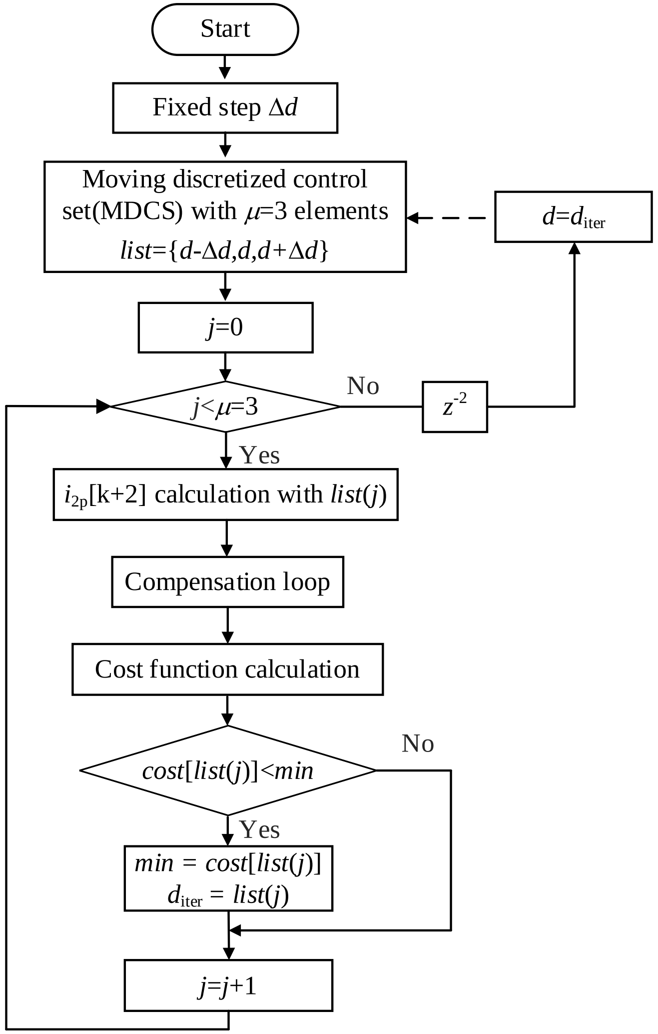
Accomplishments

HSST Dynamic Modeling w/ Model Predictive Control (MPC)

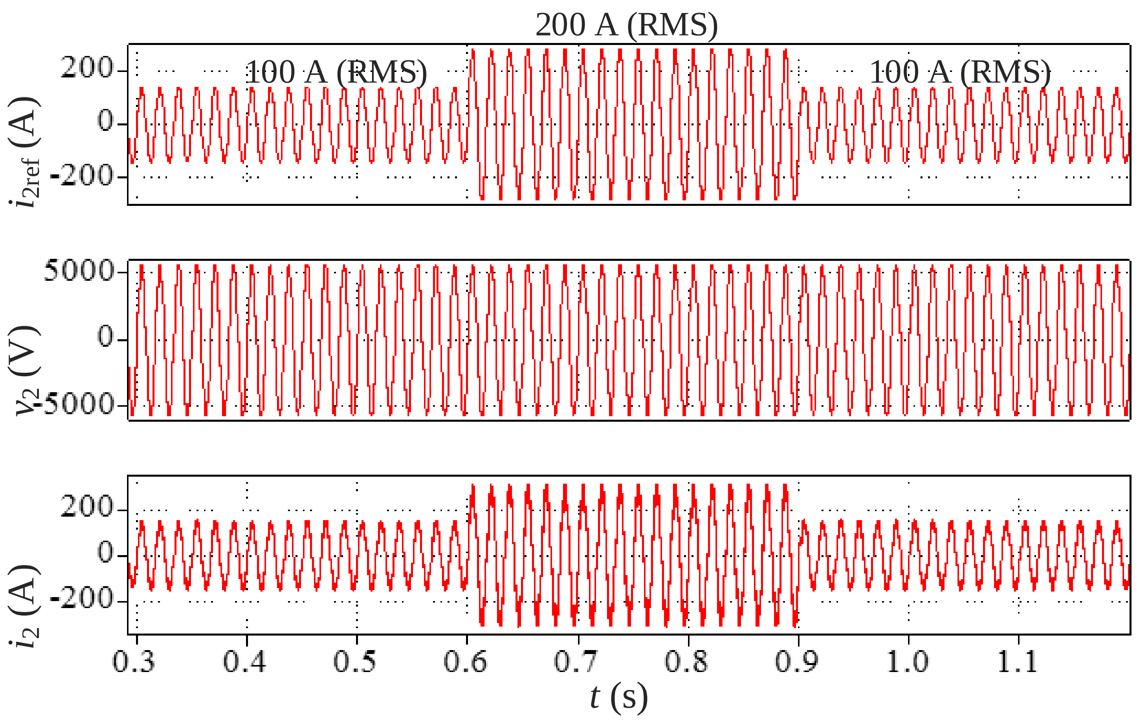




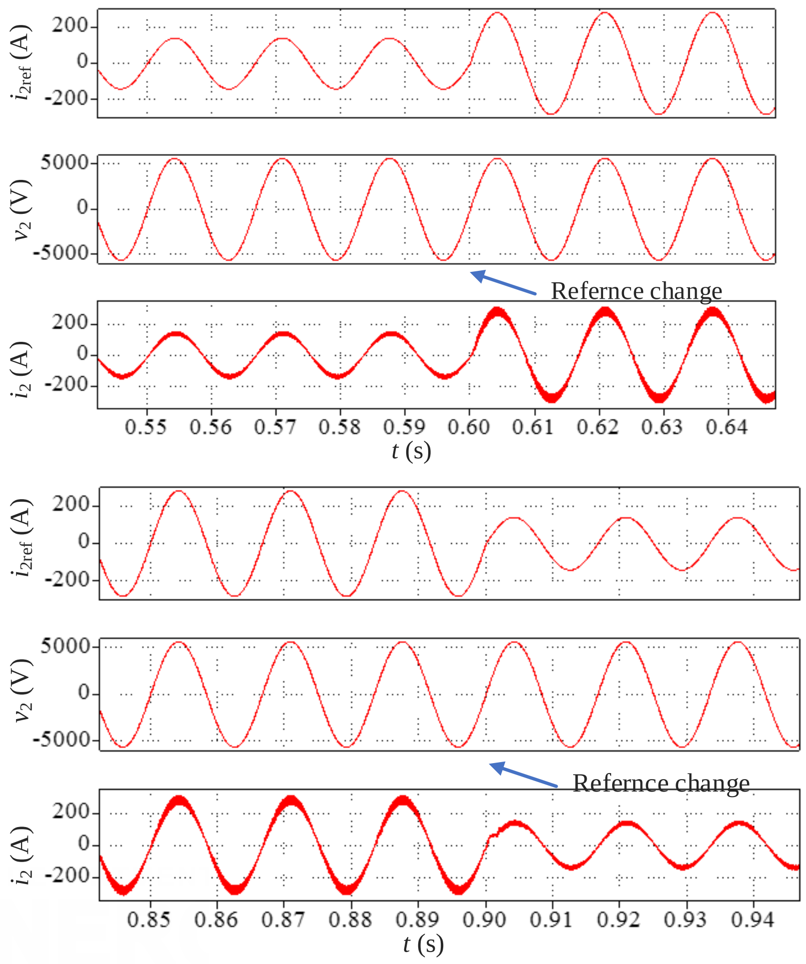
- A model predictive control developed for the HSST, building on the phasor model for the HSST
- MPC model tasked for two modes of control - Voltage Regulation Mode and Power Control Mode

Accomplishments

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



Current reference step-up and step-down changes



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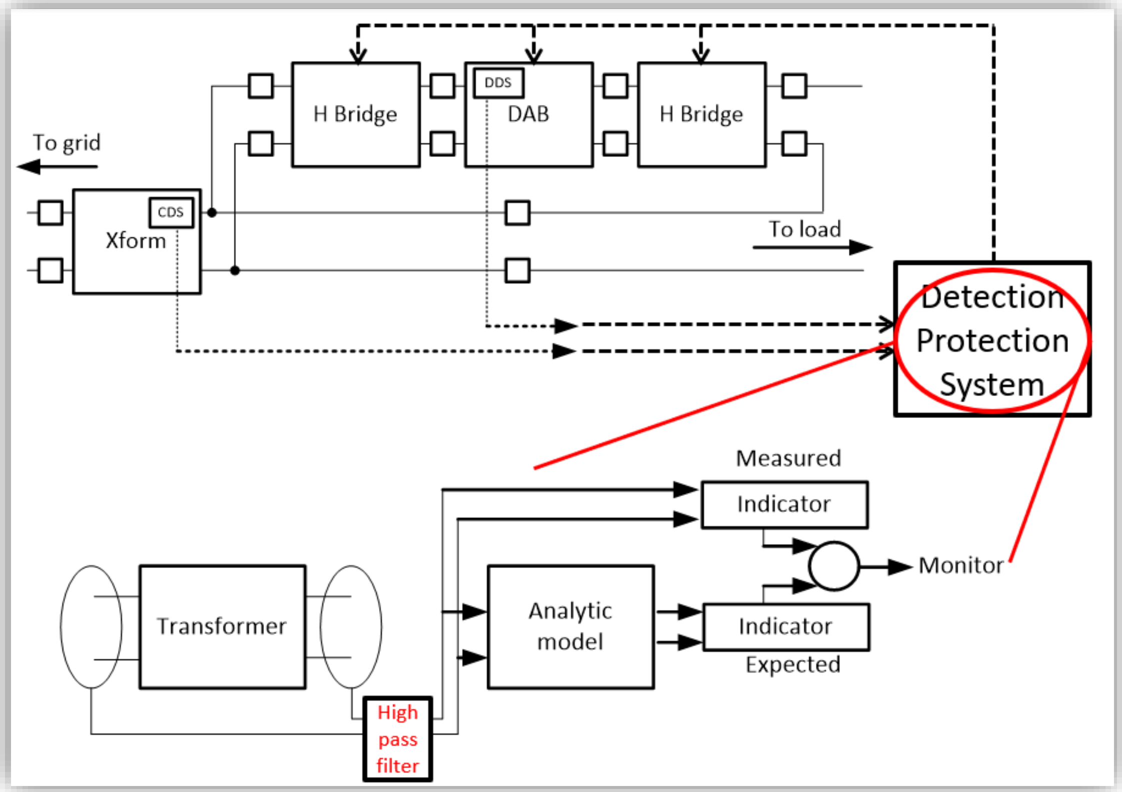
Accomplishments

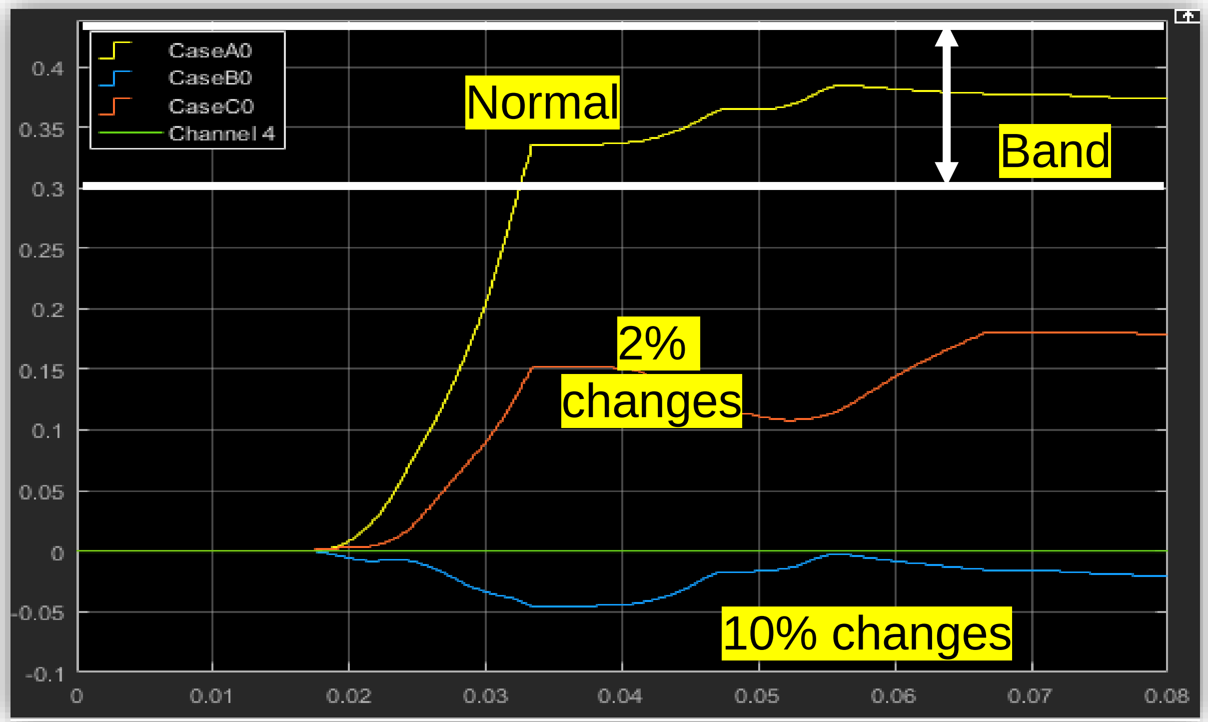
HSST – Online/Offline Monitoring and Fault Detection

- 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.



Accomplishments

HSST – Online/Offline Monitoring and Fault Detection

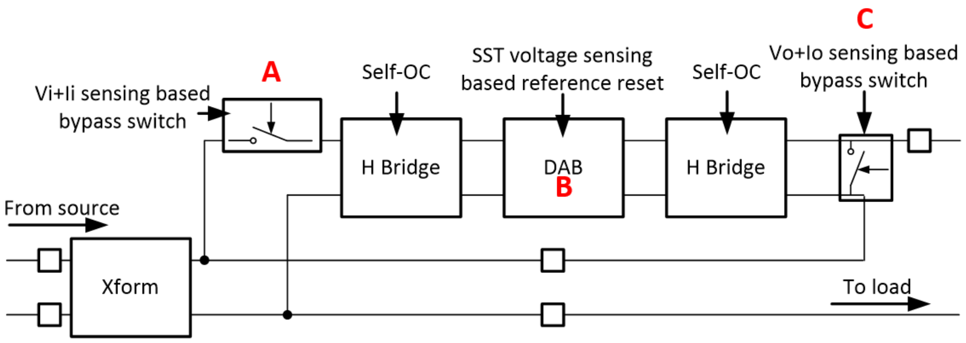


- Algorithm has been tested with actual test conditions (having altered the HFT impedances in the actual hardware)
- Proposed method has been proven to identify the system deformation and internal faults considering the measurement bias and noise.

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

Accomplishments

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.

Future Work

- Long-term reliability assessment of *AustinSUPERMOS*
- SST Cost Improvements
- Greater improvements in insulation design to enable series stacking of HSST
- System level mechanical packaging and protection (include faults such as lightning strikes and such)
- On field demonstration and studies of the HSST

Impact

Publications

- Alvaro Carreno, Marcelo Perez, Carlos Baier, Alex Huang, Sanjay Rajendran, Mariusz Malinowski “Configurations, Power Topologies and Applications of Hybrid Distribution Transformers”, in Energies 14 (5), 1215
- Z. Guo, R. Yu, W. Xu, X. Feng and A. Q. Huang, "Design and Optimization of a 200-kW Medium-Frequency Transformer for Medium-Voltage SiC PV Inverters," in IEEE Transactions on Power Electronics, vol. 36, no. 9, pp. 10548-10560, Sept. 2021. doi: 10.1109/TPEL.2021.3059879
- Z. Guo, S. Sen, S. Rajendran, Q. Huang, X. Feng and A. Q. Huang, “Design of a 200 kW Medium-Frequency Transformer (MFT) With High Insulation Capability,” 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020.
- Q. Huang, S. Sen, S. Rajendran, Z. Guo, L. Zhang and A. Q. Huang, “500kVA Hybrid Solid State Transformer (HSST): Architecture, Functionality and Control,” 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020.
- S. Rajendran, S. Sen , L. Zhang, Z. Guo, Q. Huang and A. Q. Huang, “500kVA Hybrid Solid State Transformer (HSST): Design and Implementation of the SST” 2020 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2020.
  - This paper was awarded the best paper at the IEEE-IAS-RES Committee Conference Paper Awards.
- B. Xie, D. Zhao, T. Hong, A. Q. Huang, Z. Guo and Y. Lin, "Dynamic State Estimation Based Monitoring of High Frequency Transformer," 2020 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), Tempe, AZ, USA, 2020
- S. Sen, L. Zhang, X. Feng and A. Q. Huang, "High Isolation Auxiliary Power Supply for Medium-Voltage Power Electronics Building Block," 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 2020, pp. 2249-2253.
- S.Rajendran, S. Sen, Z. Guo and A. Q. Huang, "500kVA Hybrid Solid State Transformer (HSST): Modelling and Control," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021, pp. 1135-1141, doi: 10.1109/ECCE47101.2021.9595105.
- L. Ding, X. Lu and A. Q. Huang, "Versatile Control Functions of Hybrid Solid-State Transformers in Distribution Systems," 2021 6th IEEE Workshop on the Electronic Grid (eGRID), 2021, pp. 01-05, doi: 10.1109/eGRID52793.2021.9662162.
- L. Ding, Y. Du, X. Lu, and A. Q. Huang, “Dynamic Modeling and Model Predictive Control of Hybrid Solid-State Transformers,” IEEE ISGT NA 2022, accepted and in press

THANK YOU

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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

Additional Slides