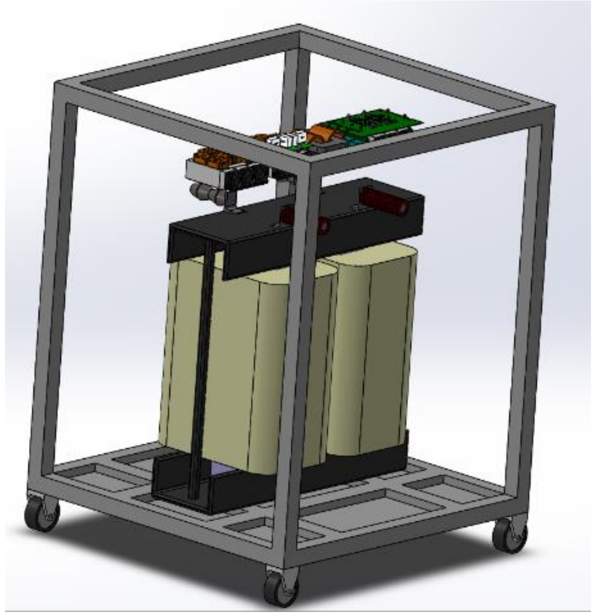
U.S. DEPARTMENT OF ENERGY
Office of Electricity

Modular Hybrid Solid State Transformer (H-SST) for Next Generation Flexible and Adaptable Large Power Transformer (LPT)



TRAC Program Review

US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory

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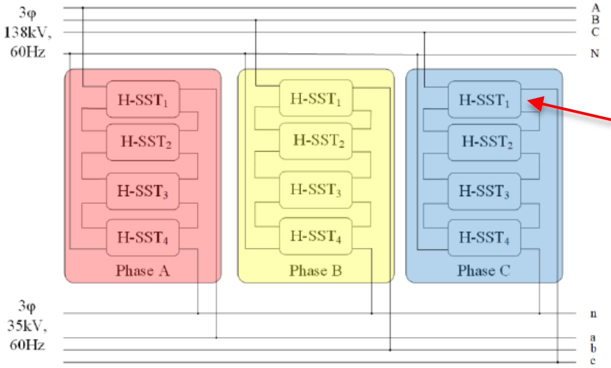
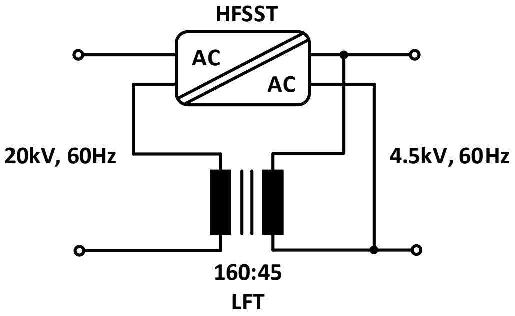
Professor Alex Q. Huang
Dula D. Cockrell Centennial Chair in Engineering
Director, Semiconductor Power Electronics Center (SPEC)
University of Texas at Austin
aqhuang@utexas.edu

Project Overview

- Project summary:
  - Develop and demonstrate a modular Hybrid Solid State Transformer (H-SST) 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.



6MVA 138kV/35kV LPT based on 500kVA HSST



500kVA HSST

- Total value of award (federal + cost share): $2.16m($1.73m/$433k)
- Period of performance: 3/18/2019-3/217/2021
- Project lead and partners

TEXAS The University of Texas at Austin — United Technologies — Argonne NATIONAL LABORATORY — TEMPLE UNIVERSITY — SIEMENS — CONTROL TRANSFORMER, INC. A ParkOhio Company

Project Plan

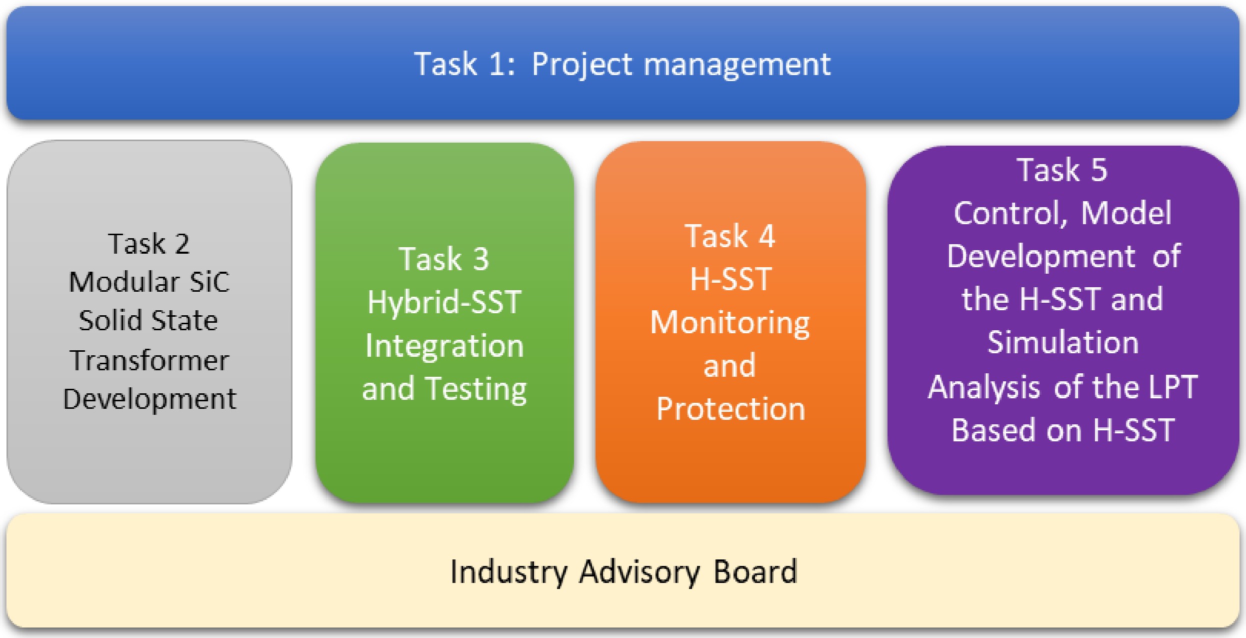


Fig. 18: Organization and task Structure of the proposed project

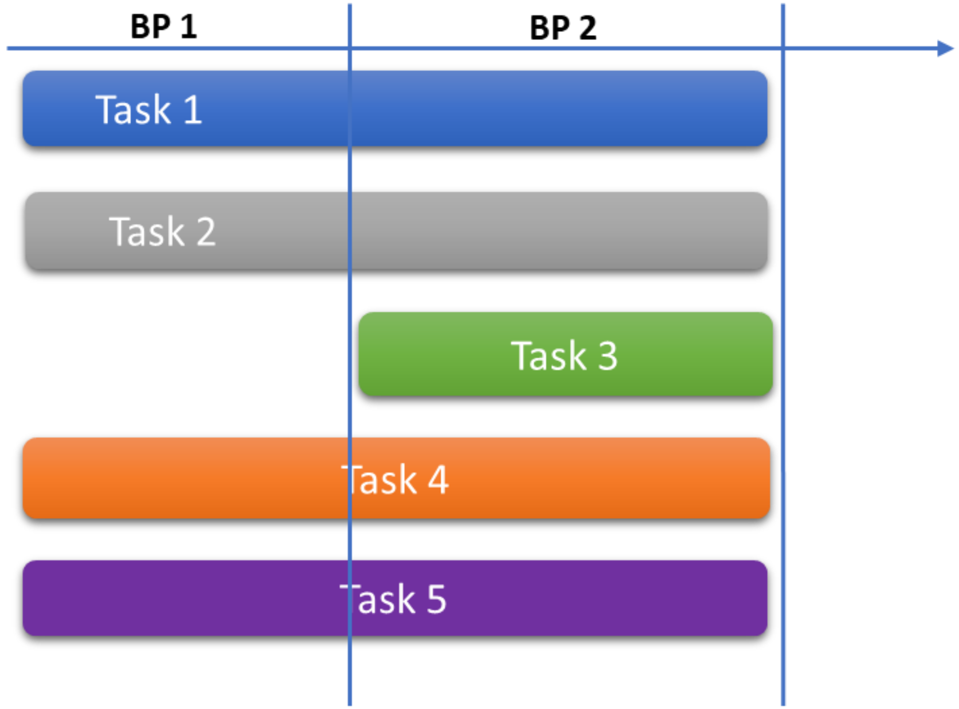
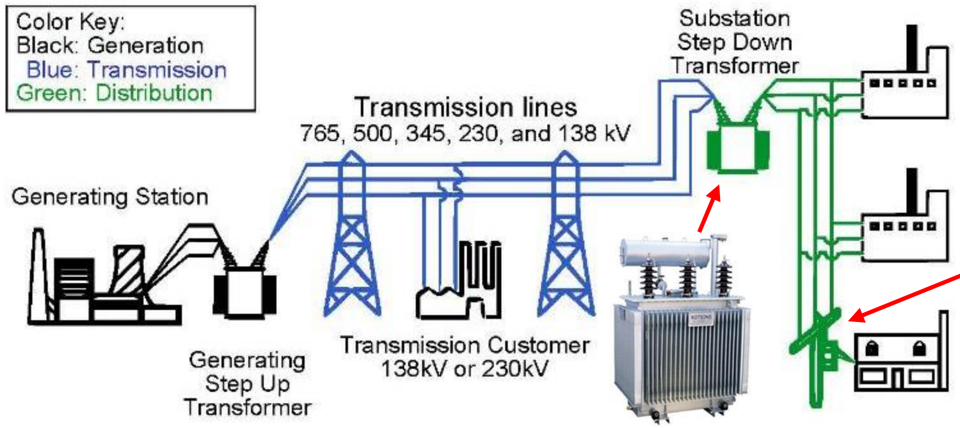
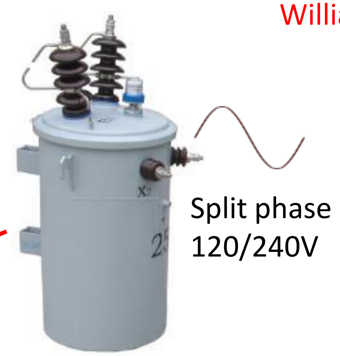


Fig. 19: High level schedules of each task

Need for advanced control function and flexibility



Electricity grid in North America. Source: [1]



Split phase
120/240V

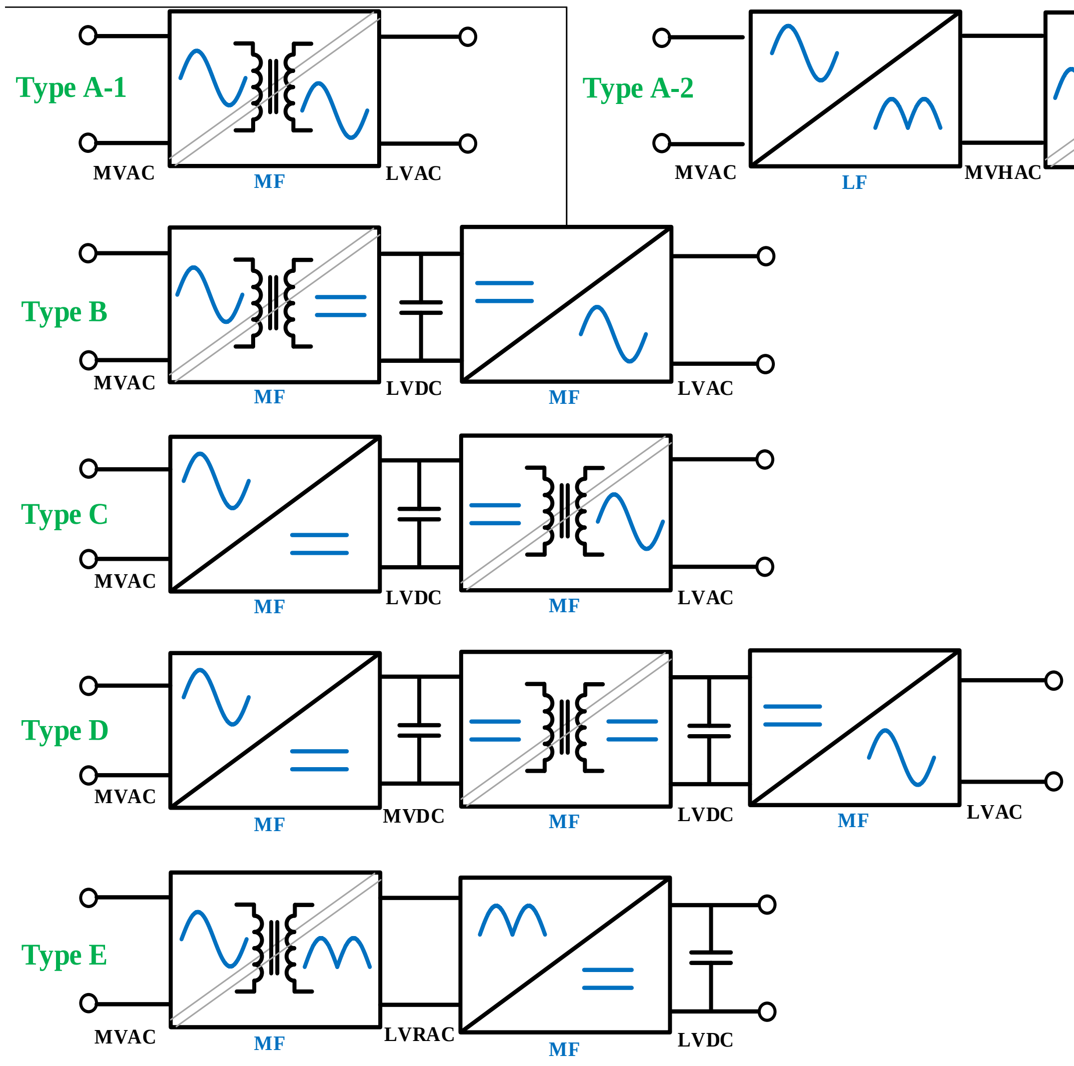
Distribution grid transformer (pole mounted)

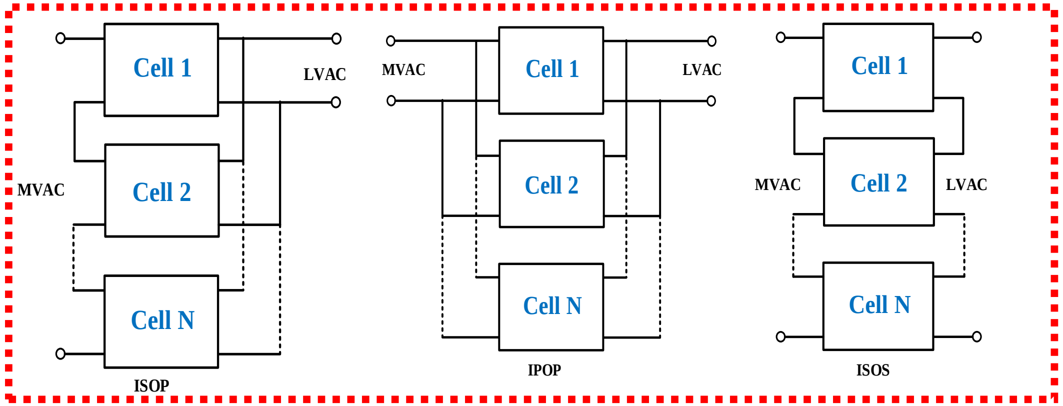
Transformer History: invented in 1886 by William Stanley

- Designed for unidirectional power flow and century-old transformer technology with little controllability
- Requires a wide spectrum of products for power quality improvement (SVC, active filter, voltage regulator, DVR, etc.)
- Strong coupling and won't isolate harmonics/other disturbances
- Not friendly for integration of renewable energy source (DC-typed sources need more conversion stages, synchronization), EV, electronic load

[1] Electricity grid simple- North America" by United States Department of Energy, SVG version by User:J Jmesserly - http://www.ferc.gov/industries/electric/indus-act/reliability/blackout/ch1-3.pdf Page 13 Title:"Final Report on the August 14, 2003 Blackout in the United States and Canada" Dated April 2004. Accessed on 2010-12-25. Licensed under Public domain via Wikimedia Commons http://commons.wikimedia.org/wiki/File:Electricity_grid_simple-_North_America.svg#mediaviewer/File:Electricity_grid_simple-_North_America.svg

Power Electronics Solutions: Solid State Transformer



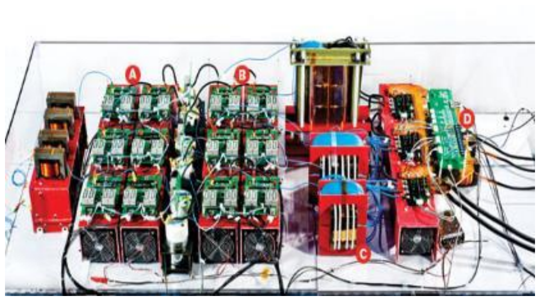


Modular Based Configuration, in which low voltage converters or devices are connected in series to share the voltage and power. Each of the cell can be type A to type E.

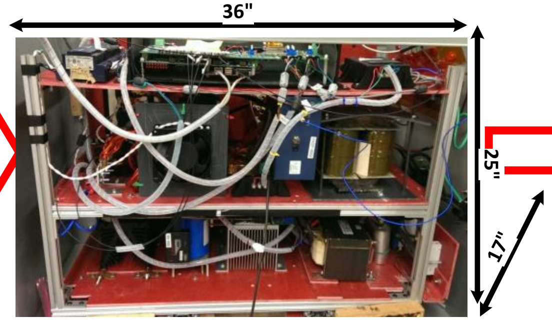
Xu She, Alex Huang, "Review of Solid state Transformer in the Distribution system: From components to Field application," in Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, 2012, pp. 4077-4084.

Previous SST Prototypes: Distribution grid focus

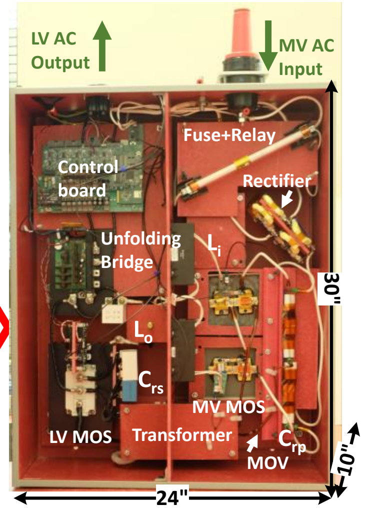
60Hz Transformer



Gen- 1 SST: Si-based (6.5 kV IGBT 3kHz)



Gen- 2 SST: SiC-based (15 kV SiC MOSFET 10 kHz)



Gen- 3 SST: SiC @ 40 kHz

Modular Type D

Type D

Type A-2

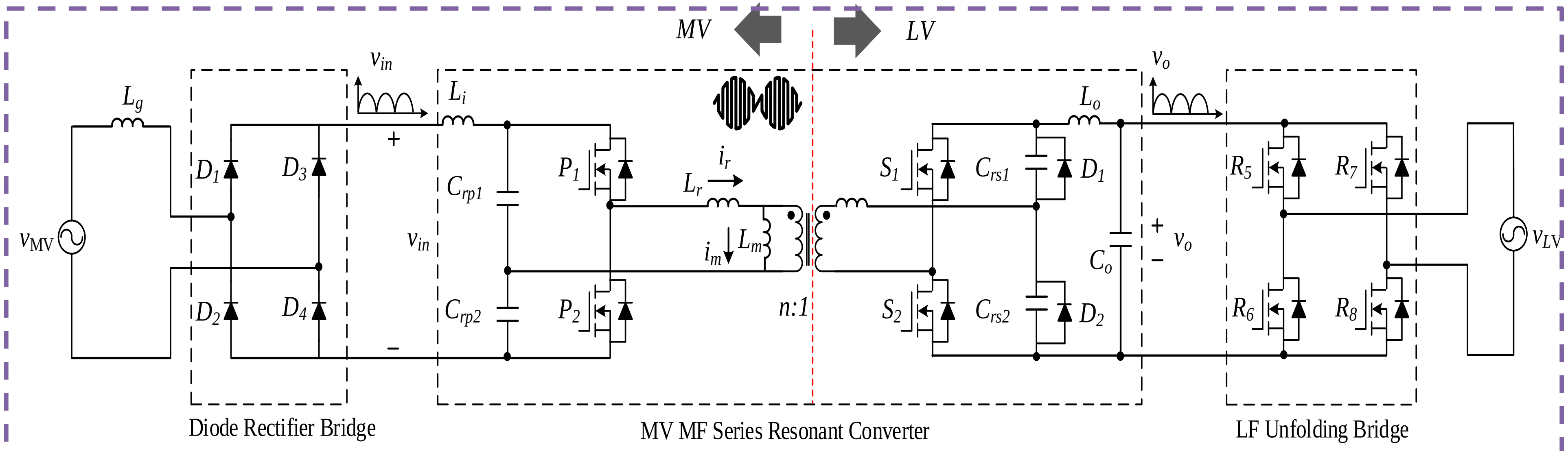
Controls

Topology /magnetics

Wide Bandgap Devices

7.2 kV single phase transformer for residential node (US market)

SST based on Direct AC-AC Conversion (Type A-2)



Type A-2: (Uni-directional)

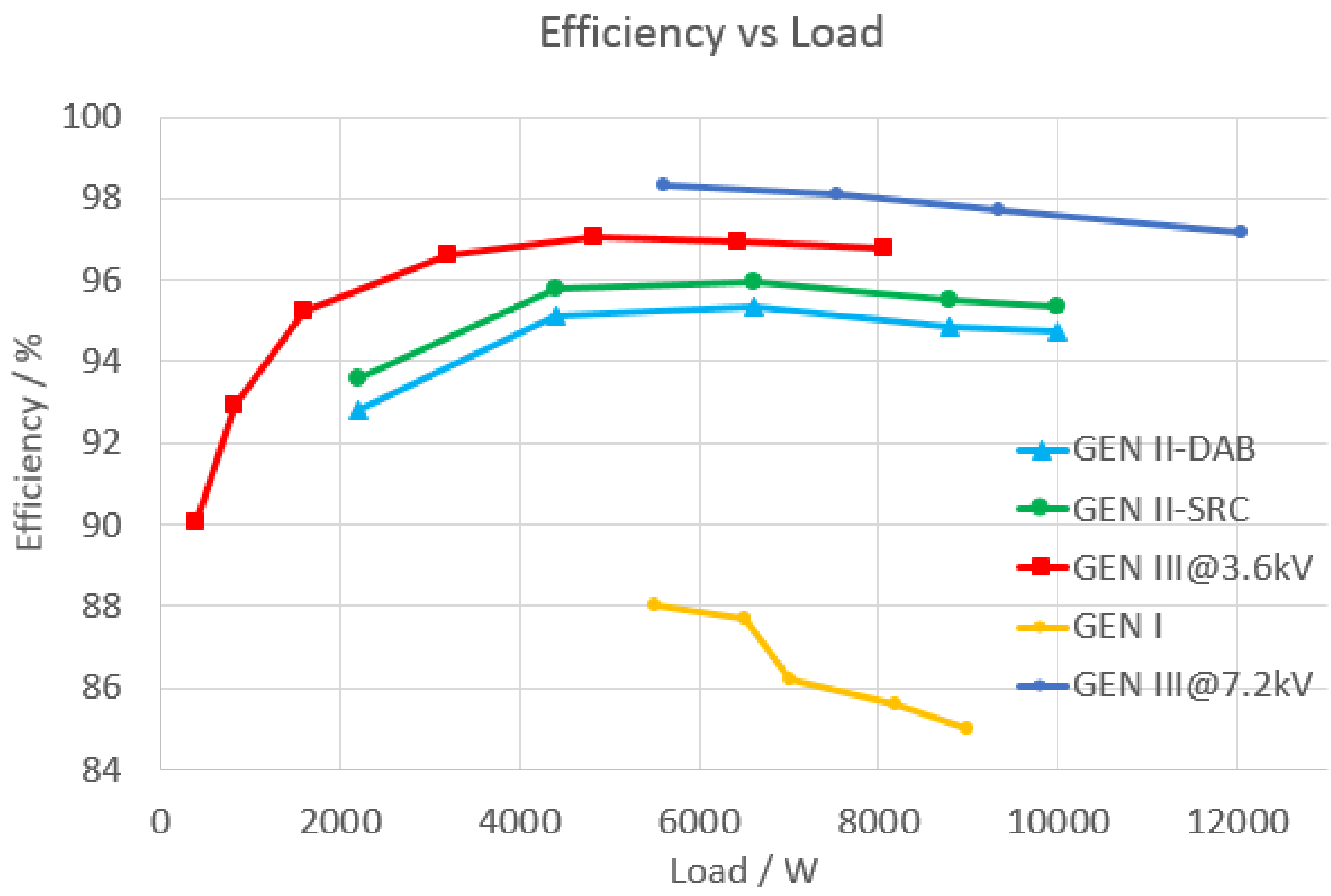
- Use diode bridge to replace MOSFET bridge: cost effective if only unidirectional power flow is needed. Only two HV SiC MOSFETs needed

Advantages

- High efficiency: one stage of high frequency power conversion ⟶ Efficiency
- High power density: 40kHz~100kHz+no dc capacitors ⟶ Power Density
- Only two MF MV MOSFETs and ZVS guaranteed ⟶ Reliability + Efficiency
- Current limit capability under over load conditions ⟶ Functionality
- Minimized system stored energy ⟶ Safety

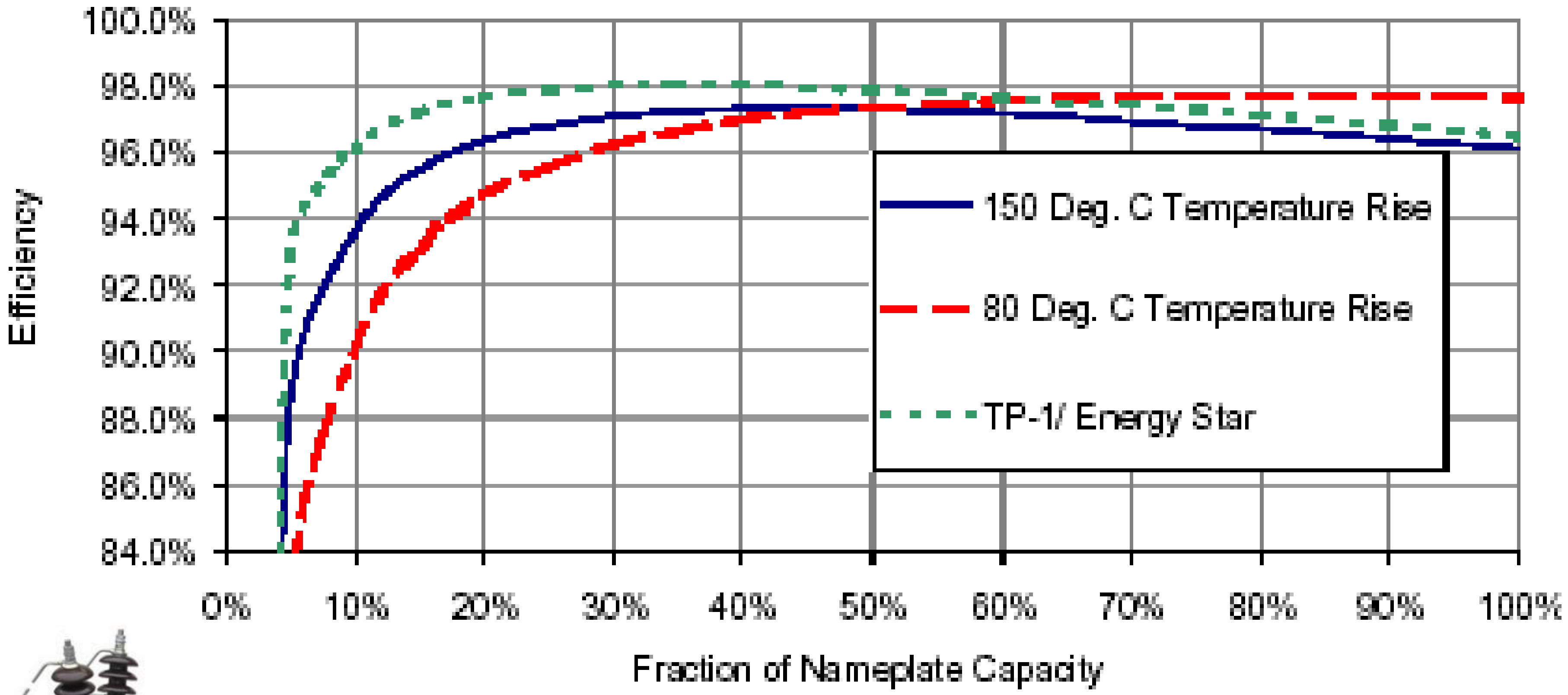
Q. Zhu, L. Wang, A. Huang, K. Booth and L. Zhang, "7.2 kV Single Stage Solid State Transformer Based on Current Fed Series Resonant Converter and 15 kV SiC MOSFETs," in *IEEE Transactions on Power Electronics*.

Measured Efficiency (MV AC- LV AC)



Input: 7.2 KV
Output: 240V

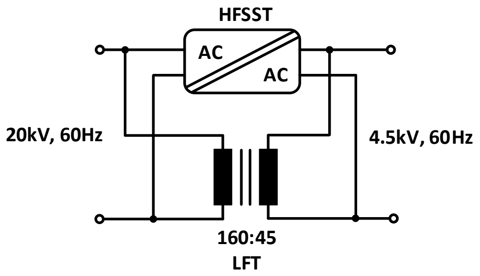
60 Hz transformer efficiency



Conclusion: single phase SST is approaching similar LFT efficiency!
Challenge: How to sale this to transmission application

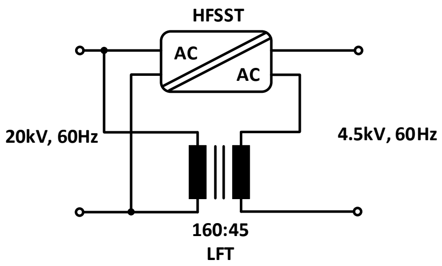
Hybrid SST: trade-off between power level and functionality

C1: Input parallel and output parallel



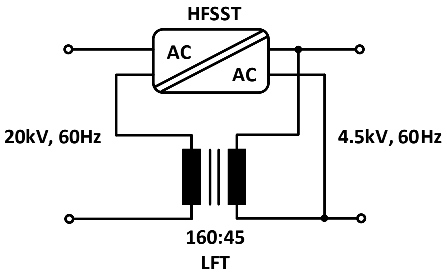
- ✓ Flexible partial power control
- ❖ V1/V2=n1/n2
- ❖ No voltage regulation
- ❖ 20kV devices
- ❖ 100kV insulation

C2: Input parallel and output series



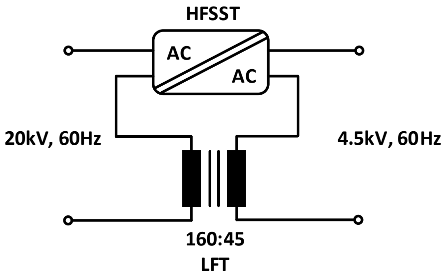
- ✓ Partial power
- ✓ Voltage regulation
- ❖ 20kV devices
- ❖ 100kV insulation

C3: Input series and output parallel



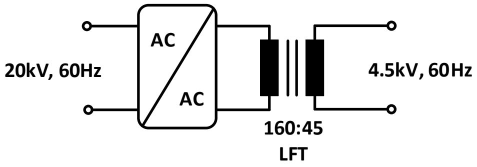
- ✓ Partial power
- ✓ Voltage regulation
- ✓ No 20kV devices
- ❖ 100kV insulation

C4: Input series and output series



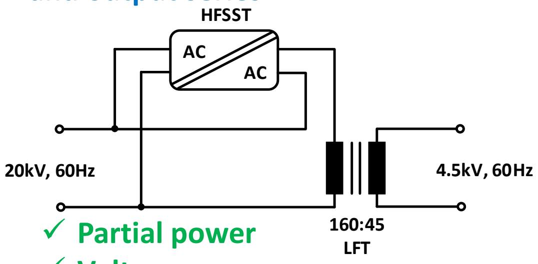
- ✓ Partial power
- ✓ No 20kV devices
- ❖ V1/V2=n1/n2
- ❖ No voltage regulation
- ❖ 100kV insulation

C5: Primary side cascaded



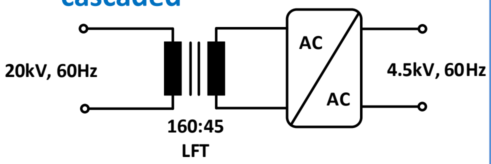
- ✓ Voltage regulation
- ✓ No transformer
- ❖ 20kV devices
- ❖ No partial power

C6: Primary side input parallel and output series



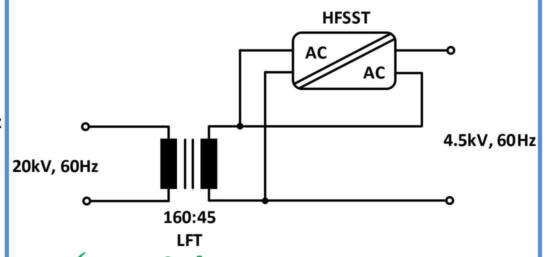
- ✓ Partial power
- ✓ Voltage regulation
- ❖ 20kV devices
- ❖ 100kV insulation

C7: Secondary side cascaded



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

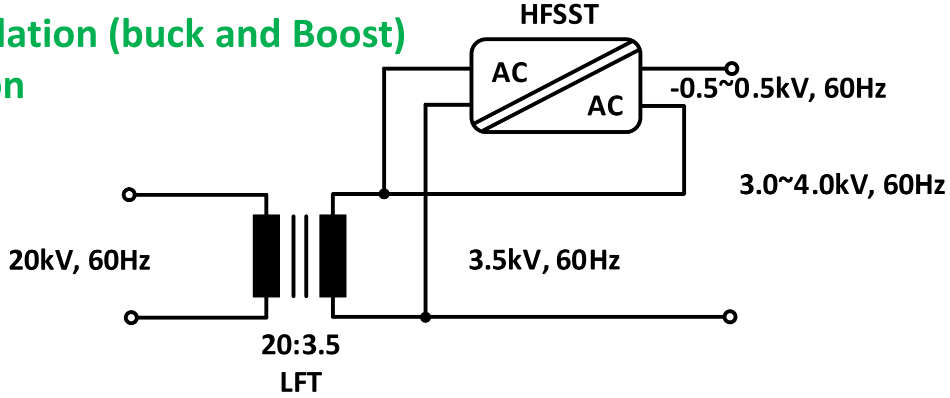
C8: Secondary side input parallel and output series



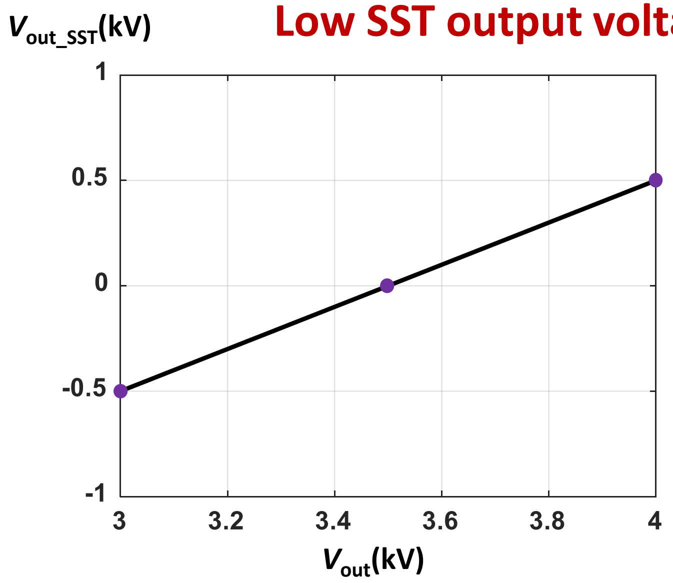
- ✓ Partial power
- ✓ Low voltage insulation
- ✓ Voltage regulation
- ✓ No 20kV devices

Preferred Hybrid-SST Solution: Secondary side IPOS configuration

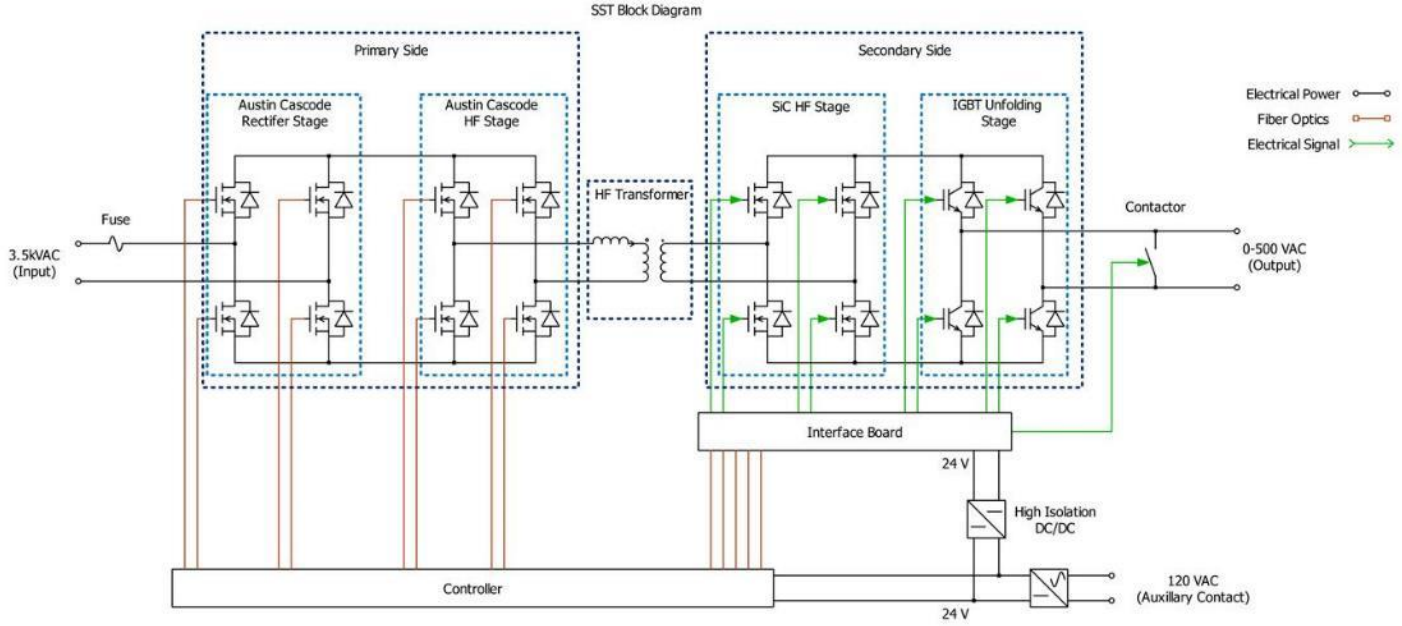
- ✓Partial power
- ✓Low voltage insulation (buck and Boost)
- ✓Voltage regulation
- ✓No 20kV devices



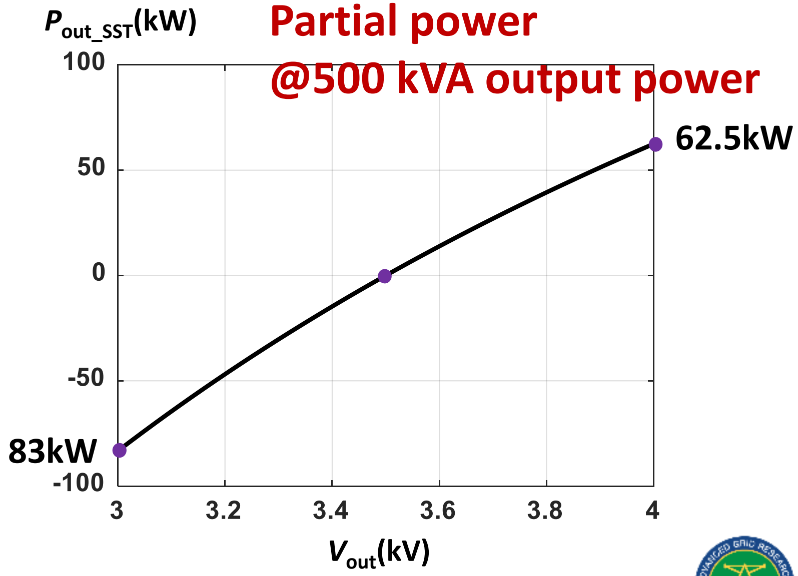
Low SST output voltage



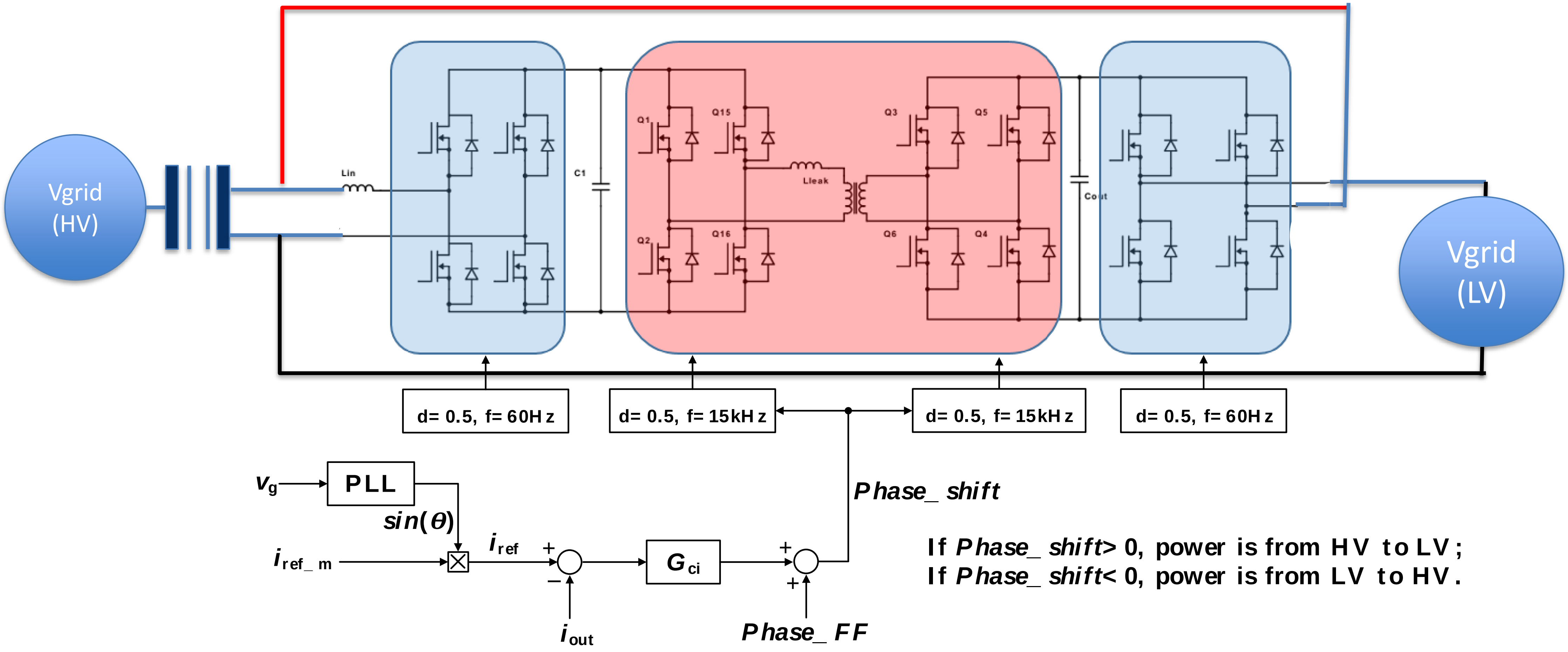
Proposed DAB SST



Partial power @500 kVA output power



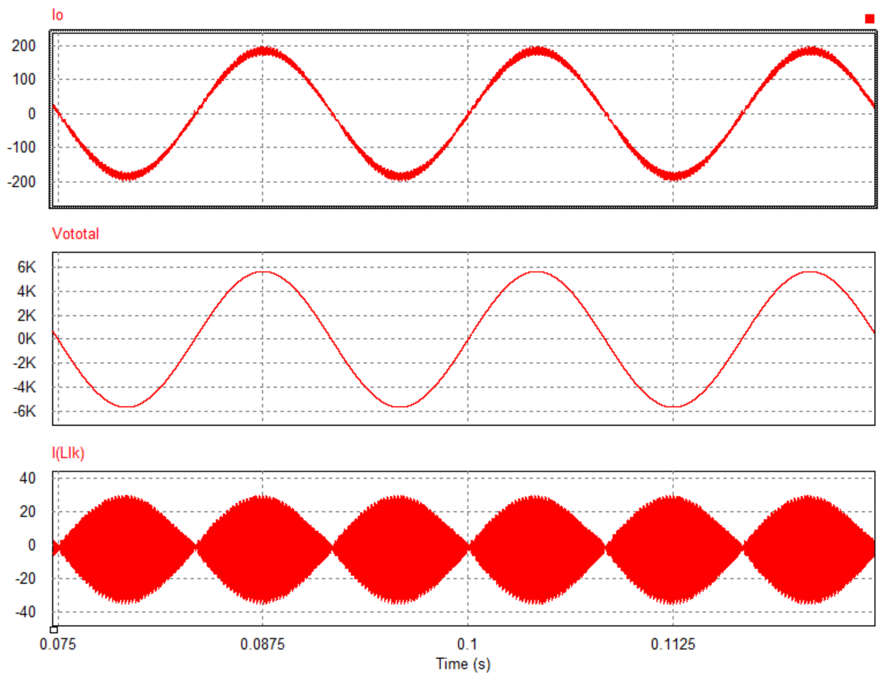
HSST Control Strategy: Constant Frequency with Single Phase-Shift



If *Phase_shift* > 0, power is from HV to LV;
If *Phase_shift* < 0, power is from LV to HV.

Simulation Results (1): Power from HV Side to LV Side

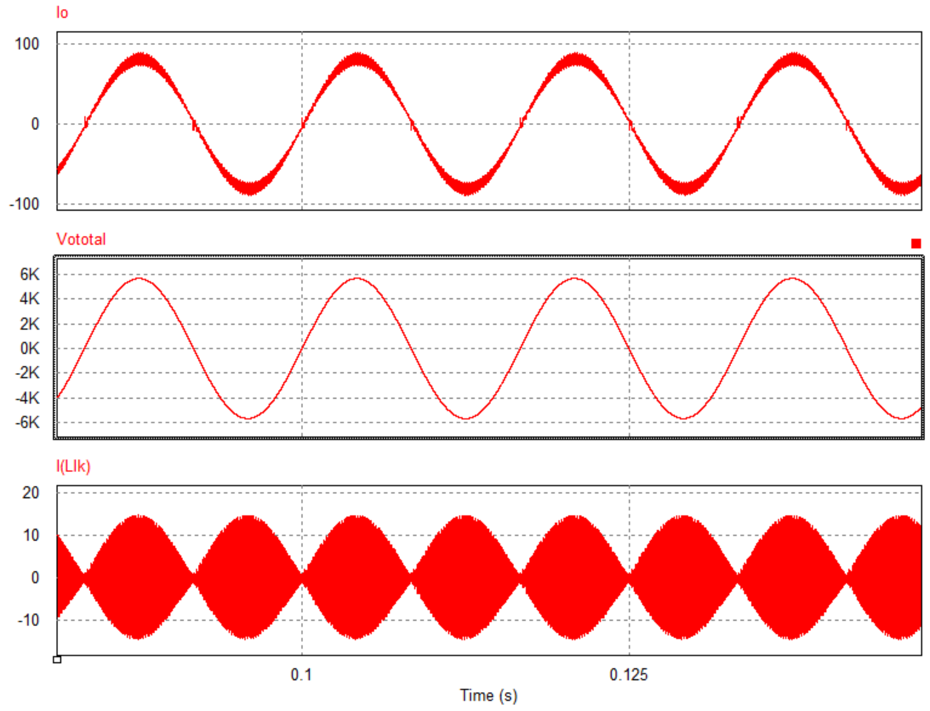
- Power from HV side to LV side, full power, 500kW
- Control: constant frequency (15kHz) with constant phase shift (9.93°),



Vin=20kV,
Vinsst=3.5kV
Vout=4.0kV,
Voutsst=0.5kV

$P \propto \text{Phase\_Shift}$

- Power from HV side to LV side, half power, 250kW
- Control: constant frequency (15kHz) with constant phase shift (0.5*9.93°),

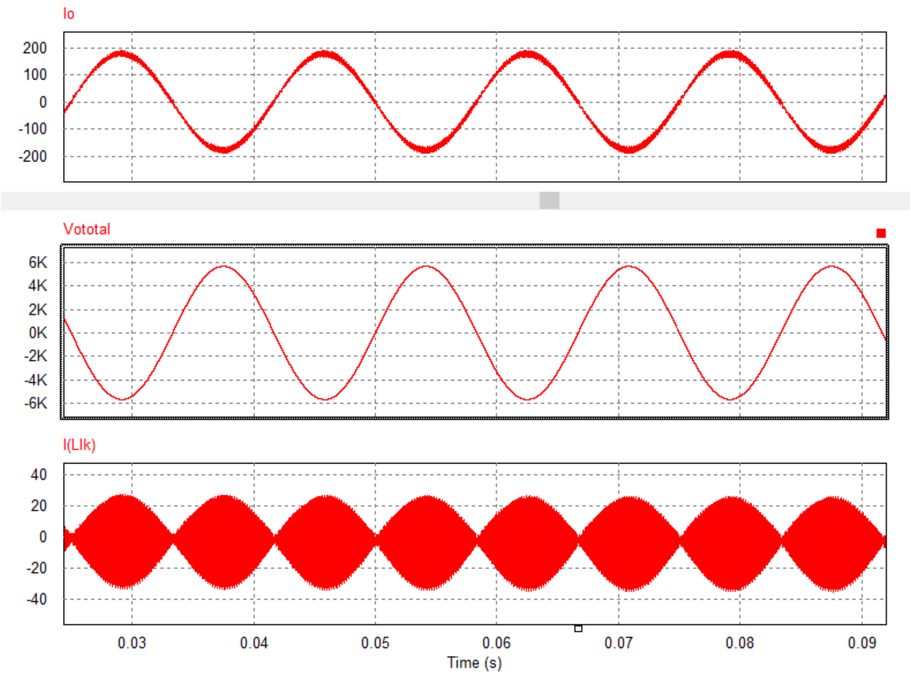


Vin=20kV,
Vinsst=3.5kV
Vout=4.0kV,
Voutsst=0.5kV

$P \propto \text{Phase\_Shift}$

Simulation Results (2): Power from HV Side to LV Side

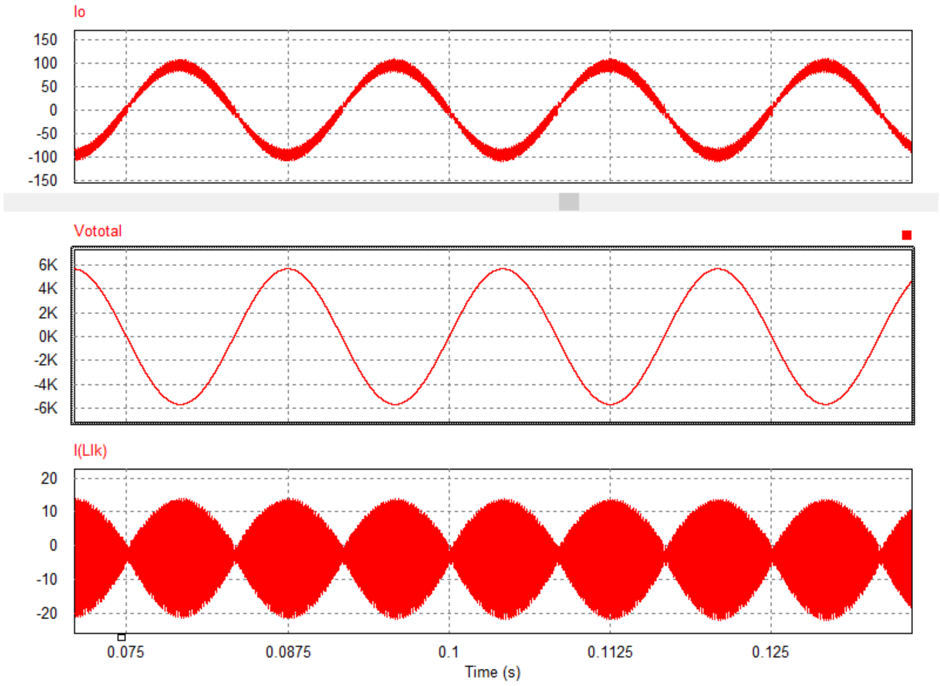
- Power from LV side to HV side, full power, 500kW
- Control: constant frequency (15kHz) with constant phase shift (-9.0°),



Vin=20kV,
Vinsst=3.5kV
Vout=4.0kV,
Voutsst=0.5kV

$P \propto \text{Phase\_Shift}$

- Power from LV side to HV side, half power, 250kW
- Control: constant frequency (15kHz) with constant phase shift (-0.5*9.0°),

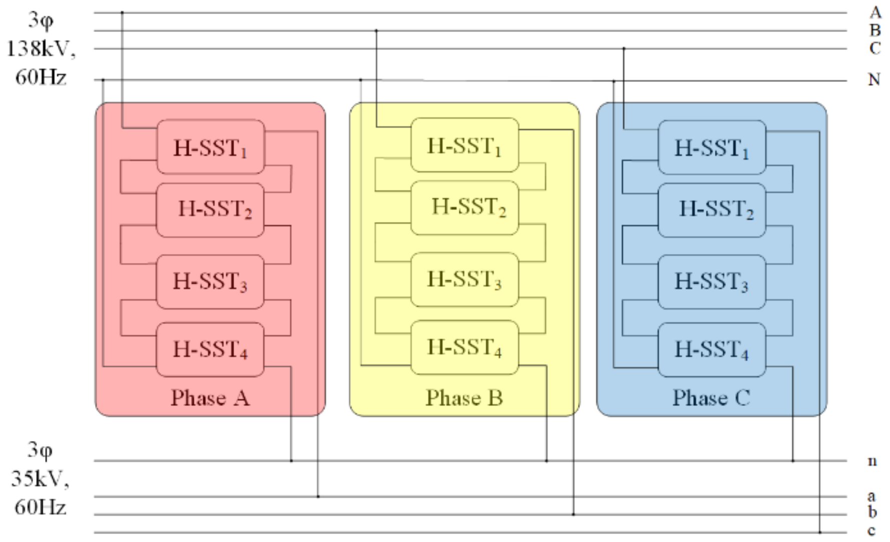


Vin=20kV,
Vinsst=3.5kV
Vout=4.0kV,
Voutsst=0.5kV

$P \propto \text{Phase\_Shift}$

HSST: Standardized Design for Multiple LPT Constructions

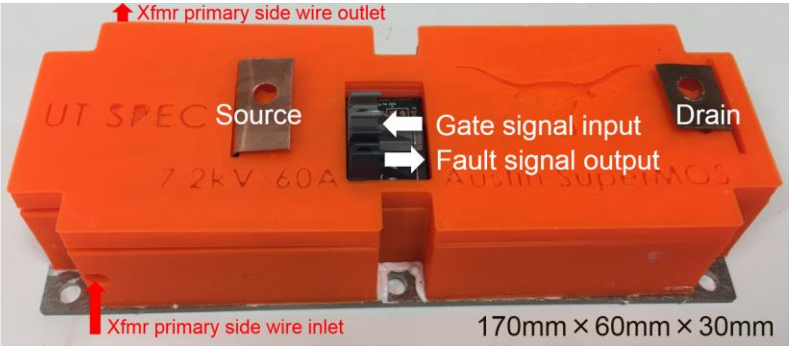
- **6 MVA 138kV/35 kV LPT based on the 500 kVA H-SST.**



- **Modular configurations utilized to achieve various 138 kV LPTs**

LPT Voltage	**138kV/115kV**	**138kV/69 kV**	**138kV/35 kV**	**138kV/4 kV**
Input configuration	Series and parallel	Series and parallel	series	series
Desirable H-SST input voltage	20 kV	20 kV	20 kV	20 kV
Number of H-SST at the input per phase	4+4+4+4=16	4+4=8	4	4
Output configuration	Series	Series	series	parallel
Desirable H-SST output voltage	4 kV	5 kV	5 kV	4 kV
Number of H-SST at the output per phase	16	8	4	4
Minimum LPT power rating	24 MVA	12 MVA	6 MVA	6 MVA

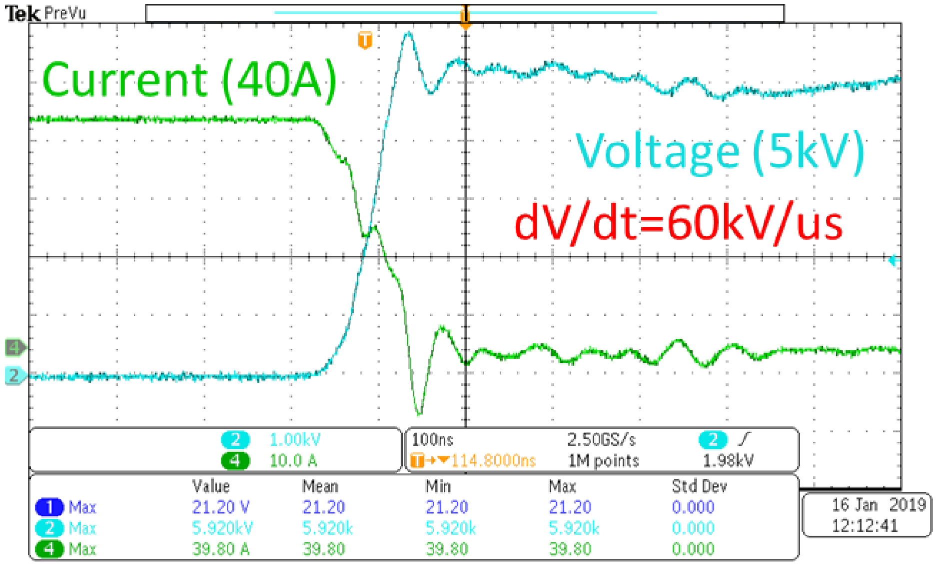
7.2kV/60A Austin SuperMOS (1)



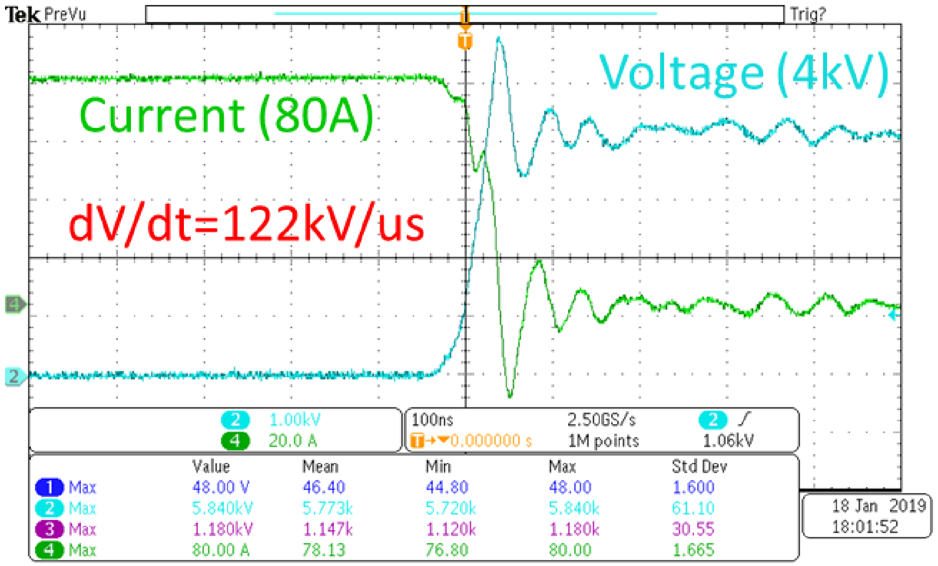
Picture of the 7.2kV/60A Austin SuperMOS

Features:

- High blocking voltage with low on-resistance (<200 mΩ)
- High speed switching (dV/dt >120kV/us) with low capacitances
- Simple to drive and easy to be parallel
- ZVS switching achievable
- Integrated gate driver DESAT protection, UVLO protection, and Over temperature protection
- Integrated isolated power supply with 20kV insulation capability

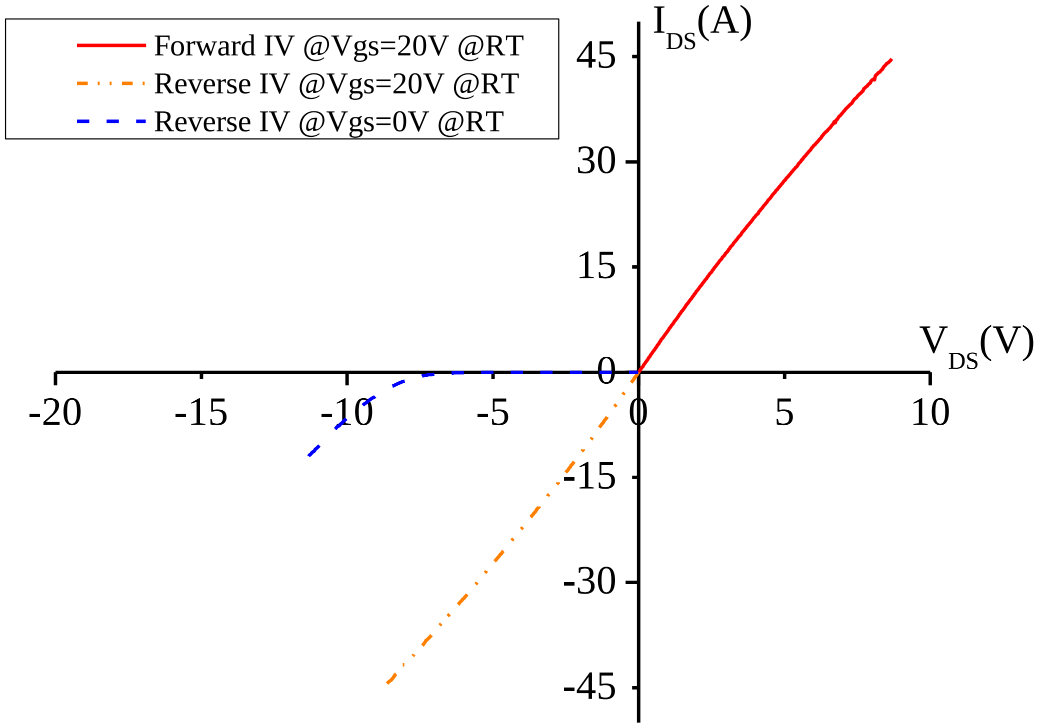


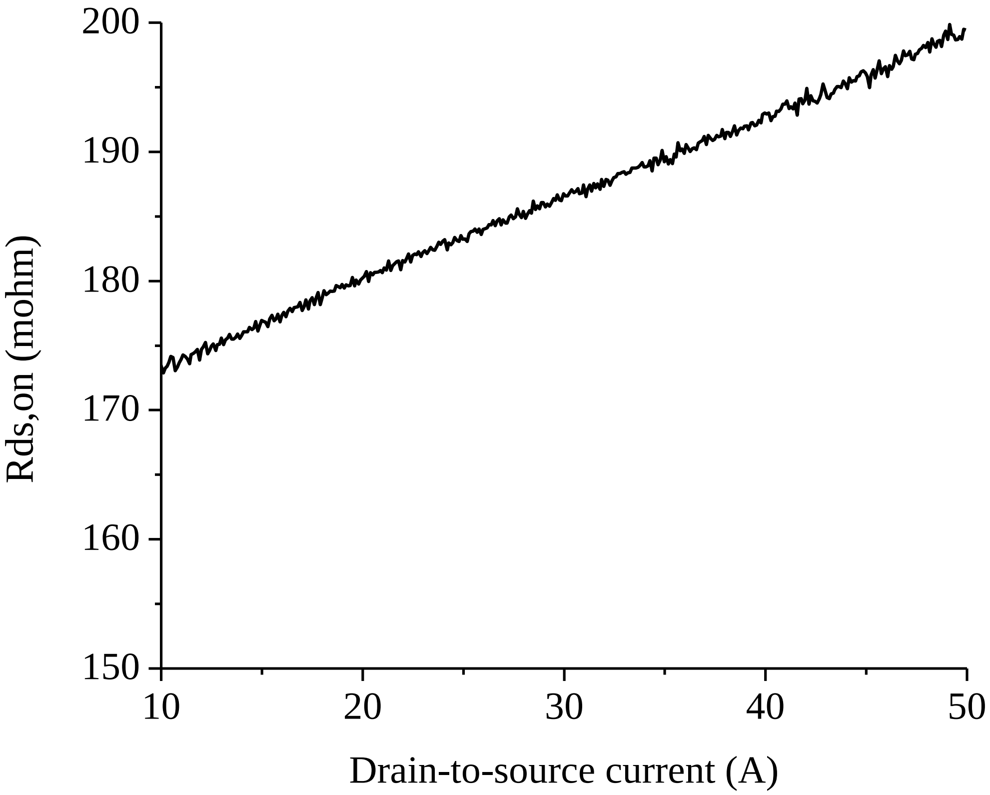
Turn-off waveform at 5kV/40A



Turn-off waveform at 4kV/80A

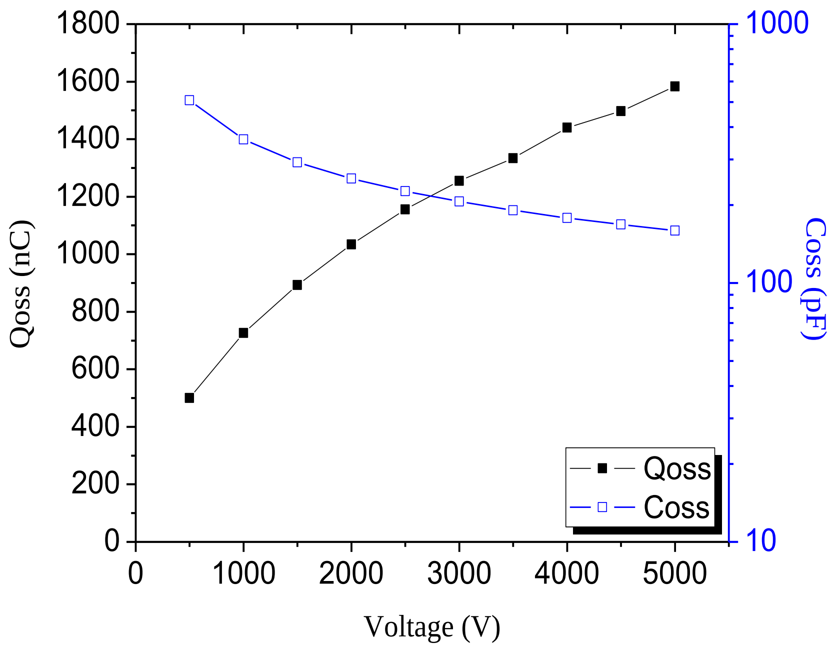
7.2kV/60A Austin SuperMOS (2)





- **I-V curves of the 7.2kV/60A Austin SuperMOS @RT**
- **Conduction resistance of the 7.2kV/60A Austin SuperMOS under different drain-to-source current @RT**

7.2kV/60A Austin SuperMOS (3)



Output charge and output capacitance of the 7.2kV Austin SuperMOS

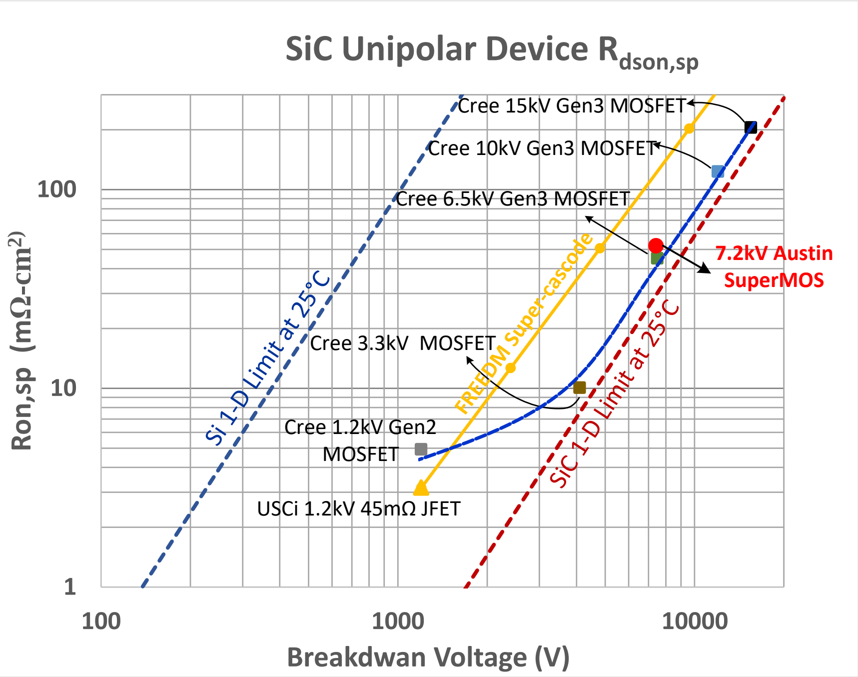
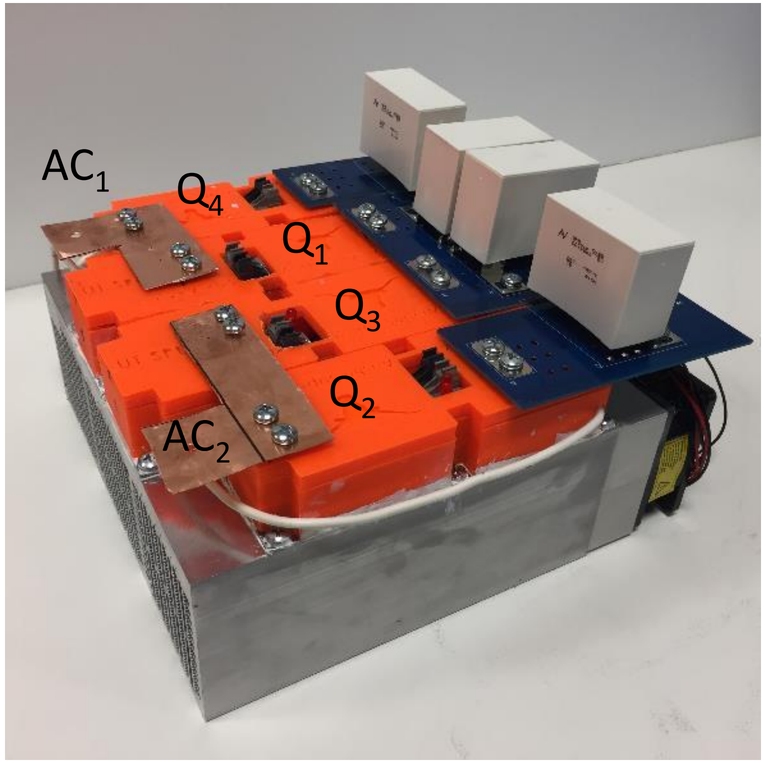


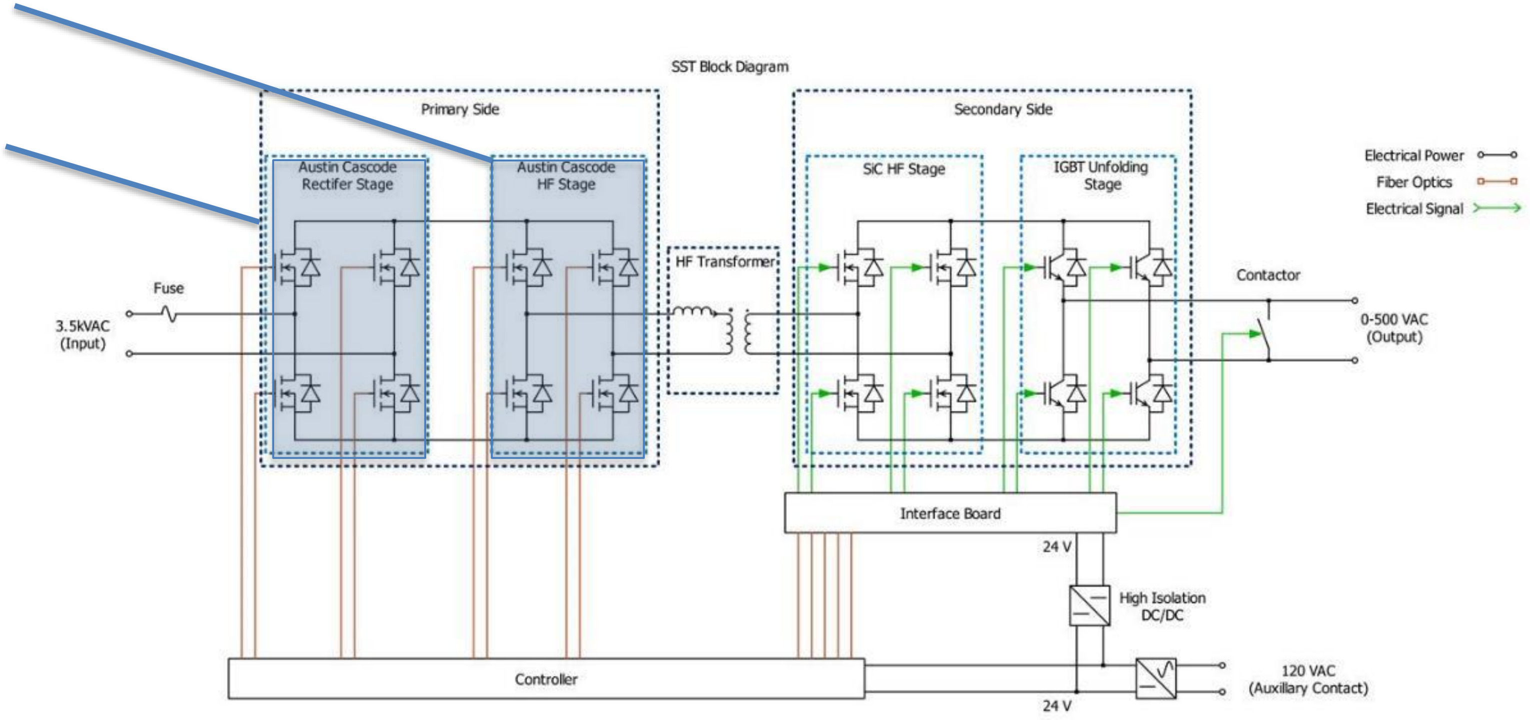
Figure of Merit (FOM) of SiC unipolar devices

Parameter	Value	Parameter	Value
Rated Voltage	**7.2kV**	**E_{on} @5kV/10A**	**15.5mJ**
Rated Current	**60A@100°C 90A@25°C**	**E_{off} @5kV/10A**	**1.2mJ**
R_{dson}	**<200 mΩ @25°C**	**E_{off} @5kV/40A**	**1.8mJ**
Q_{oss}@5kV	**1584nC**	**C_{oss}@5kV**	**159pF**

Primary Side Full Bridge Setup

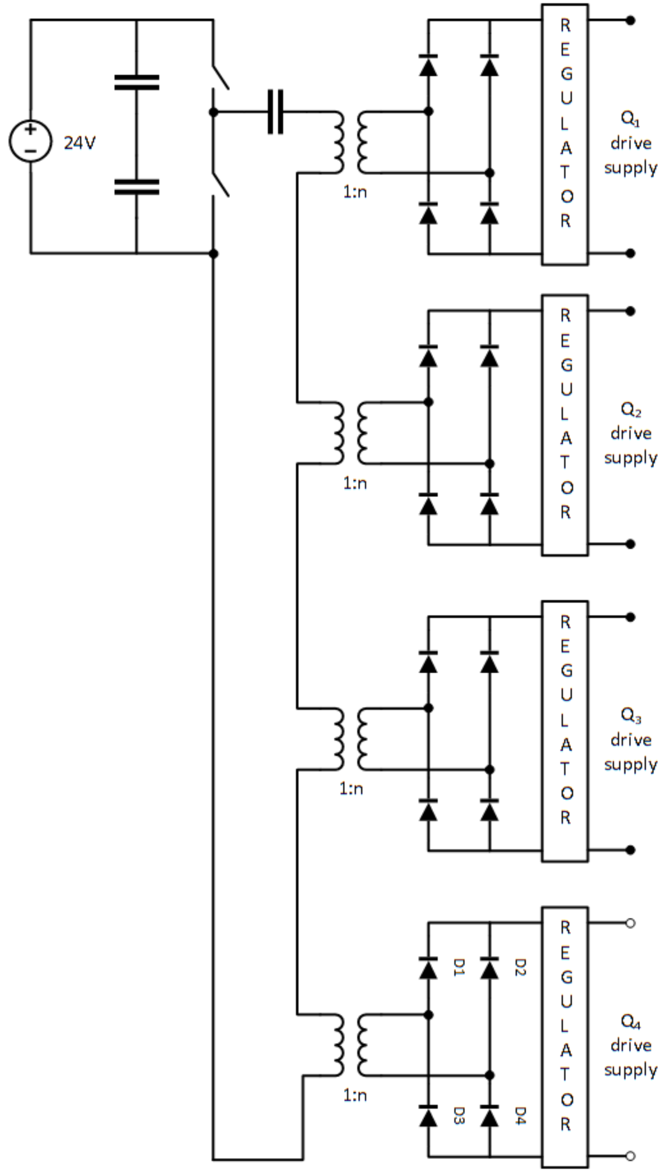
- 3kV film capacitors are used in series to construct the 5kV dc link.
- DC+, DC- and the midpoint cable entry points are located on the bottom layer of the PCB
- Dimensions are 262mm x 240mm x 168mm





Gate Driver Power Supplies with High Isolation Voltage

- **10kV isolation**
- **Series LLC resonant circuit**
- **Secondary side circuit included inside integrated module**
- **Primary winding is a HV wire that loops around 4 toroidal cores included inside 4 SuperMosfet modules of the primary full bridge**
- **Transfer capacitance = 2pF**
- **Input = 15Vdc; Output = 24V dc**
- **High insulation capability realized by 3D printed bobbin which separates the primary hv wire and secondary winding.**
- **Switching frequency = 235kHz**

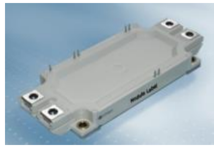


Low Voltage Side Power Stage

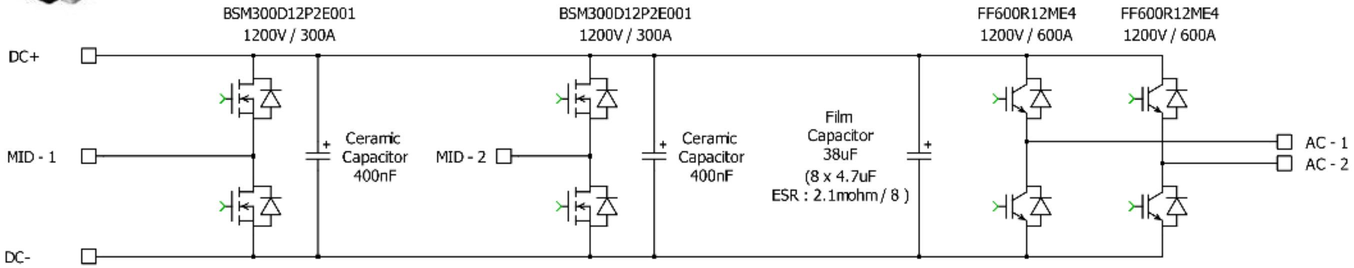
Rohm SiC modules

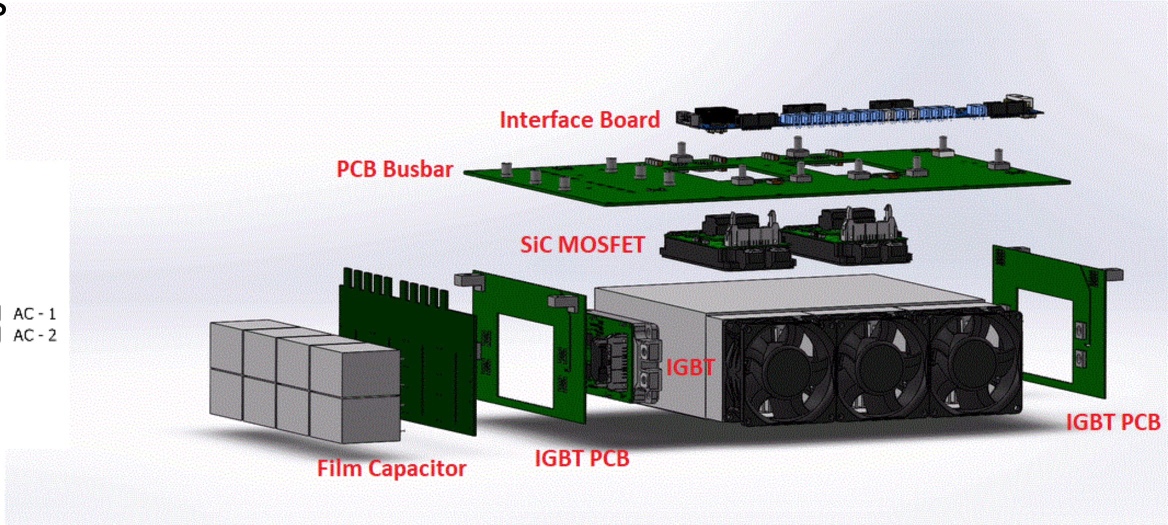
1200V, 8mohm

Infineon IGBT modules



1200V,
200A, 1.2V
600A, 2V



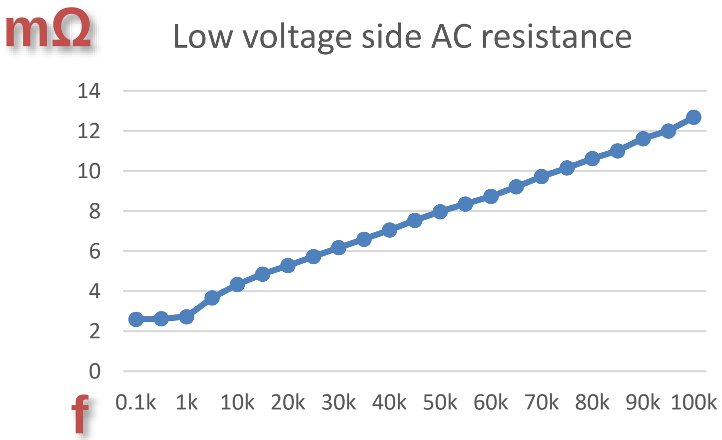


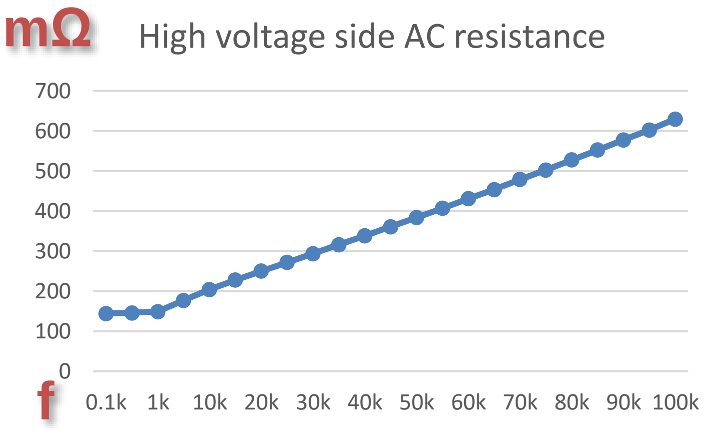
- **Secondary Side dimensions : 400 x 270 x 130mm**
- **Includes Interface Board, which allows for optical control from the controller , thus achieving high level of isolation**
- **Interface Board also responsible for**
    - **Output Contactor Control**
    - **Sensor signal conditioning**
    - **Driver Fault detection and shutdown**

High-power Medium-frequency Transformer

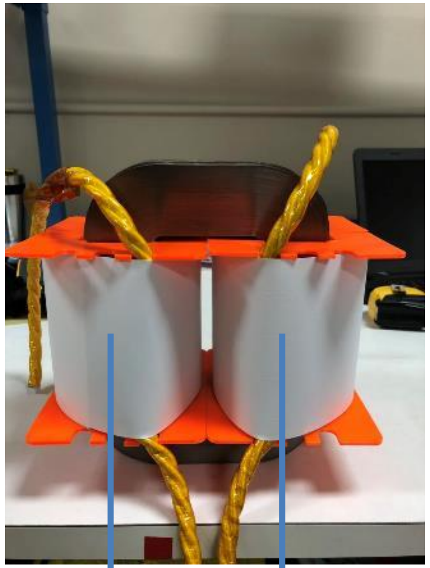
Version 1 transformer

- Core Material:FINEMET®FT-3TL
- 150 * 125 * 170mm
- Turn ratio: 49:7
- Magnetic inductance_HV/LV: 276.5mH/5.88mh
- Leakage inductance_HV/LV: 78.3uH/1.86uH





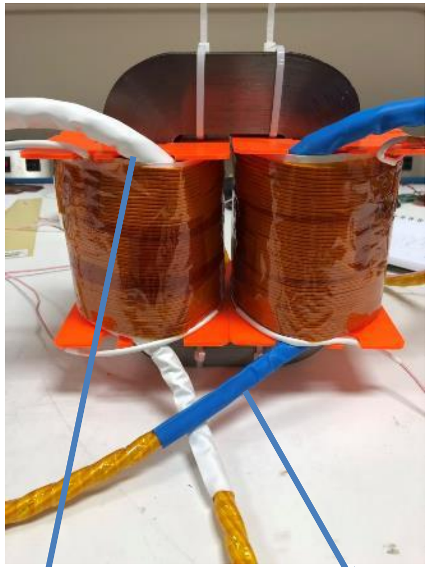
Transformer insulation design and Partial discharge test



Insulation sheet

Dielectric Breakdown
20,292 volts

Dielectric Strength -
1194 volts/mil

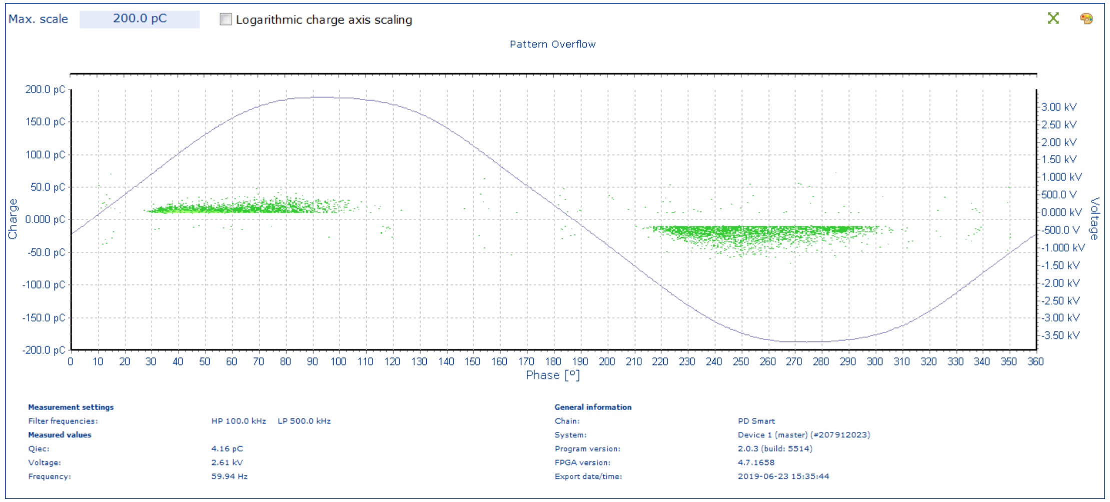


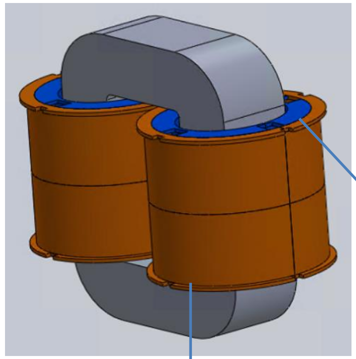
Heat Shrink Thin Wall Tubing

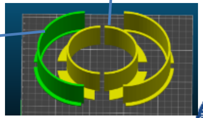
Dielectric Strength>20kV / mm

- **PDIV is 2.5kV,**
- **Improved design for higher insulation voltage is needed.**

AC RMS 2.5kV 60HZ





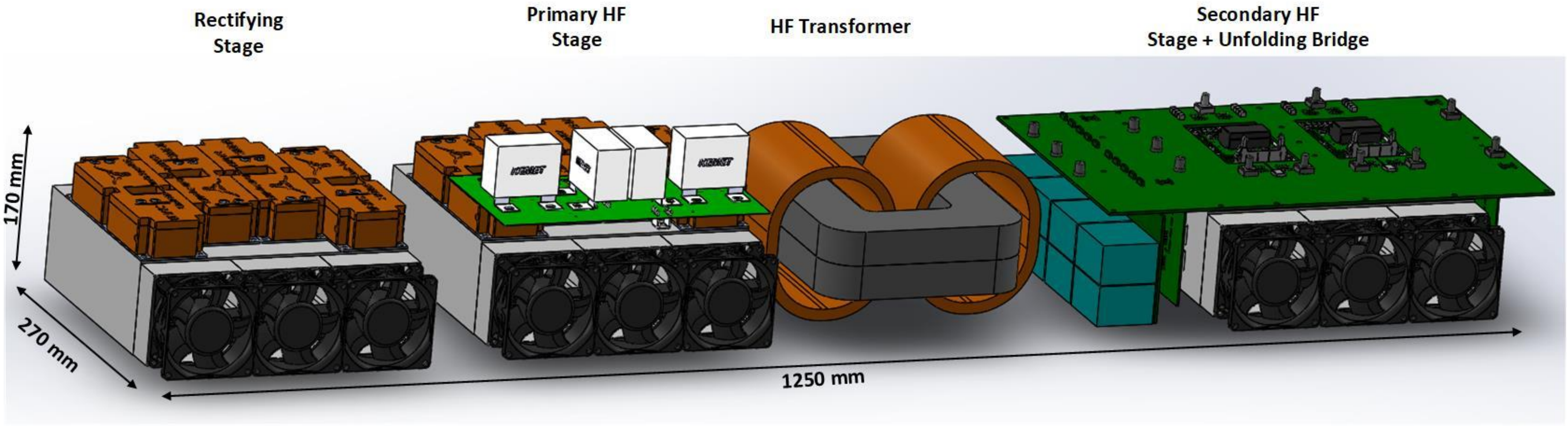


Inner-layer bobbin

Outer-layer bobbin

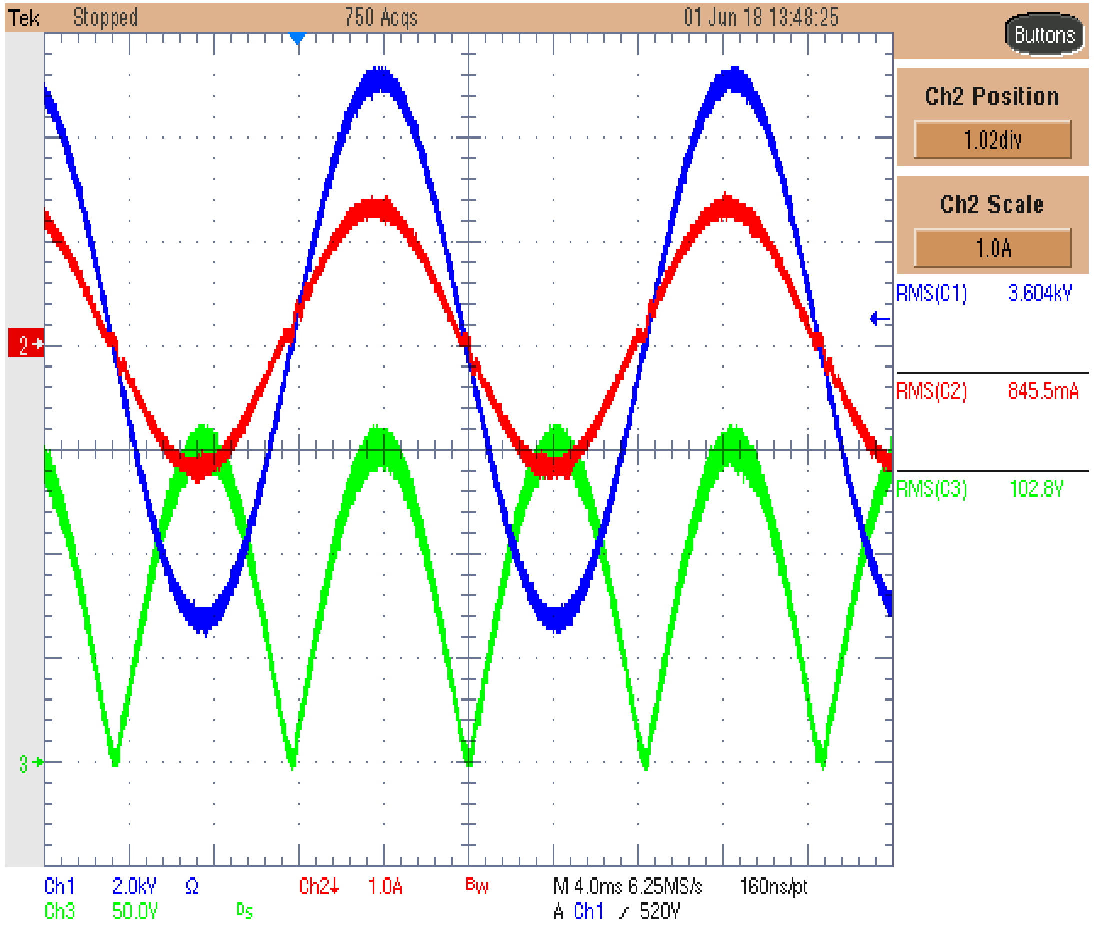
- **Version 2 design is planned**
- **Using inner bobbin to enhance the insulation**

100 kVA DABSST Converter 3D drawings (Alpha Design)

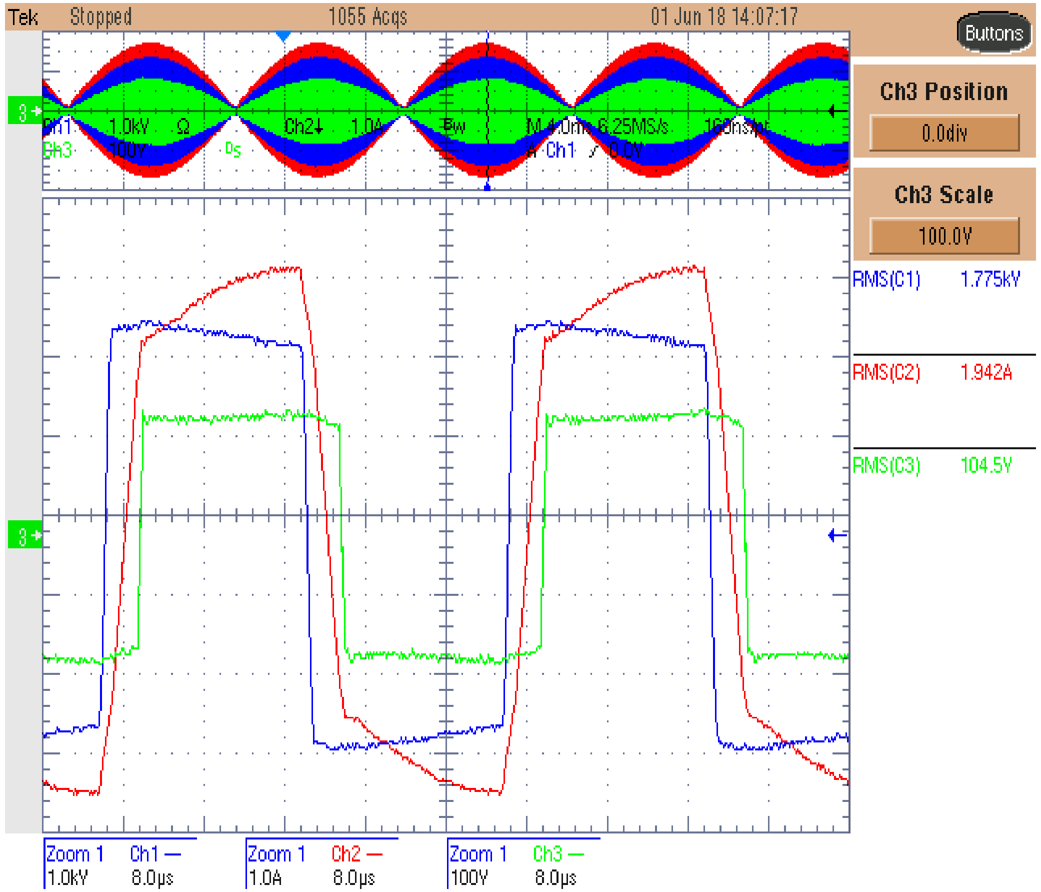


- Tentative Arrangement yields an SST of dimensions : 1250 x 270 x 170 mm
- However, since the LFT is considerably bigger (1575 x 1524 x 2032 mm), the SST should be able to fit in the LFT enclosure itself (drawing on next slide)

Preliminary MV Test Result (Vin=3.6 kV/Vout=103V)

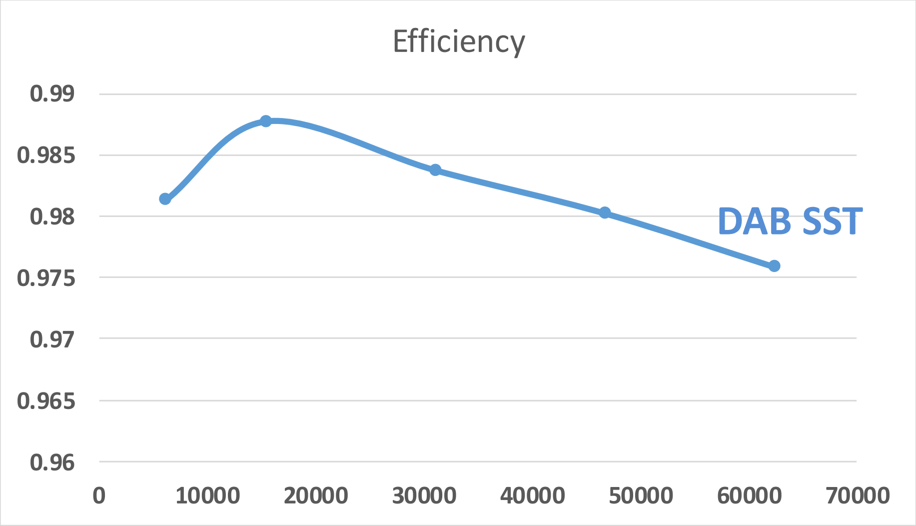


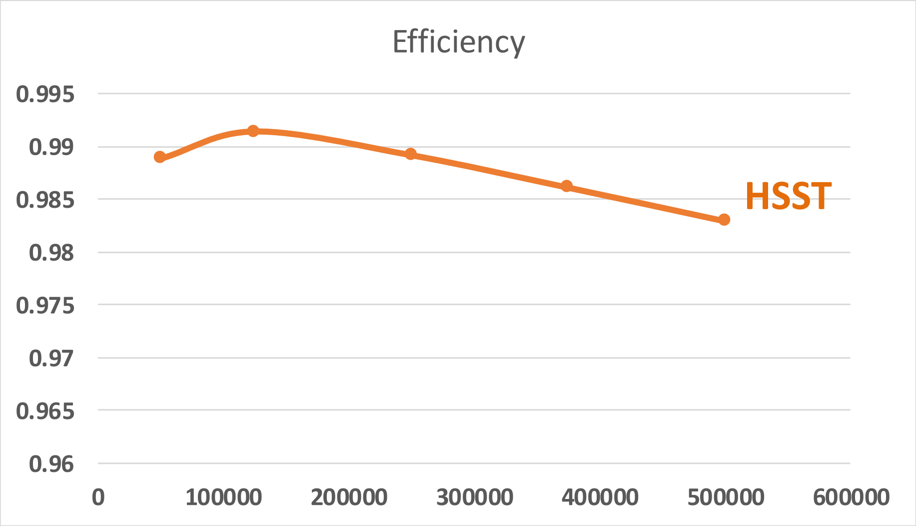
DABSST operation with 3.6kV input (blue 2kV/div.) and 103V output (green 50V/div.) and grid current (red 1A/div.).

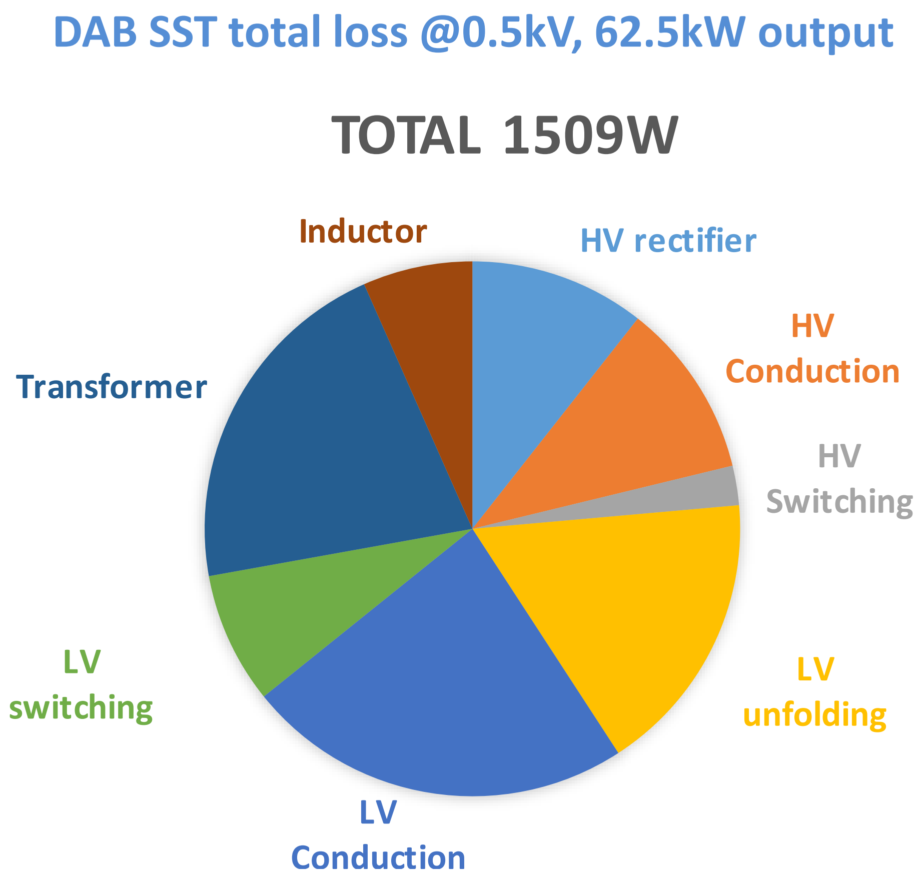


Transformer primary voltage (blue), primary winding current (red) and secondary voltage (green).

Estimated Loss Breakdown and Efficiency

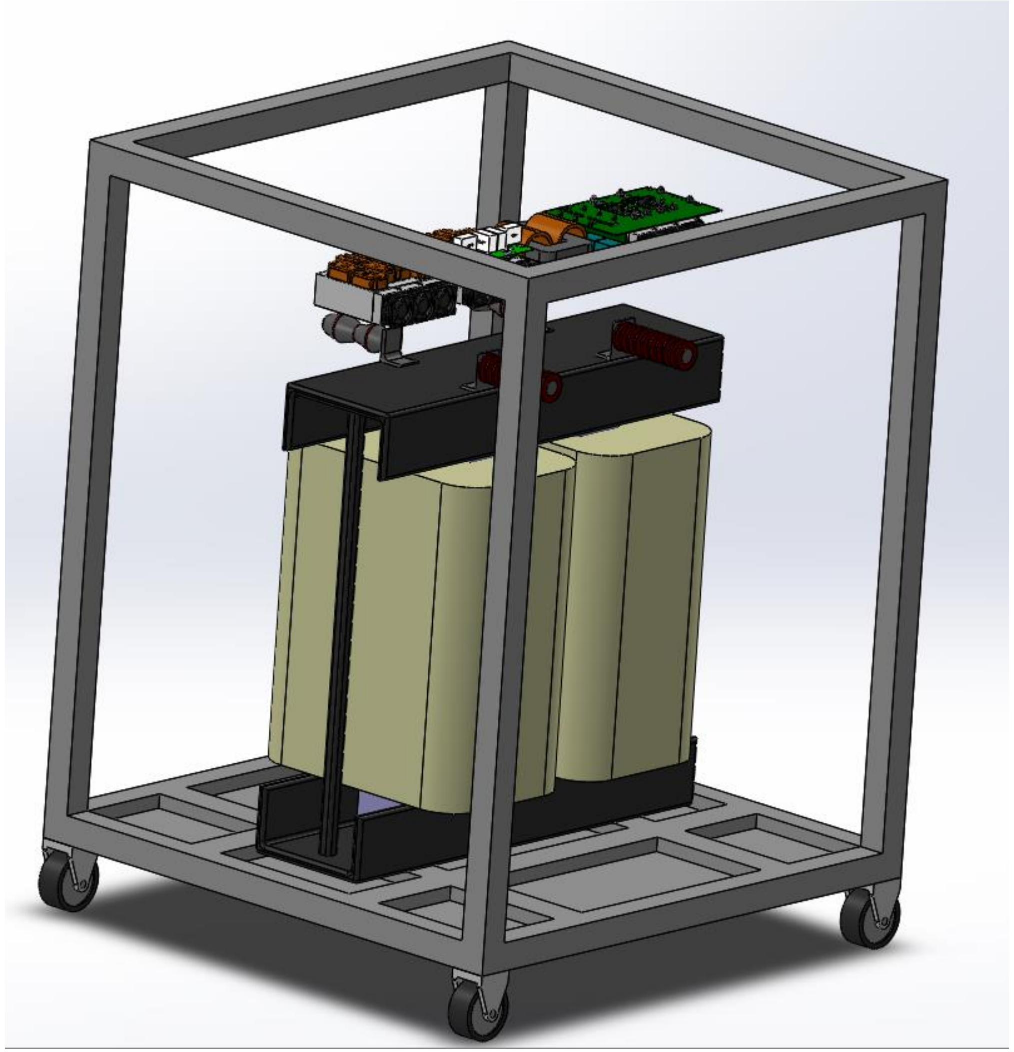






- LFT efficiency estimated based on 500 kVA prototype from Control Transformer

500kVA HSST drawing



- 500 kVA LFT order in place
- 100 kVA DABSST is 80% complete
- DABSST modeling and control finished
- Next step
  - Contract in place for all subs (task 1)
  - Line frequency model of the DABSST (Task 5)
  - System level modeling of LPT (Task 5)
  - HSST monitoring strategy (Task 4)
  - Improved isolation capability of DABSST transformer (Task 2)

DELIVERABLES (*assume 3/18/2019 start date)

Deliverable	Planned Completion Date	Status (8/2019)
Alpha 100 kVA SiC DABSST	9/30/2019	80%
Beta 100 kVA SiC DABSST	3/31/2020	0%
500 kVA Hybrid Solid State Transformer	9/30/2020	50%
Monitoring and failure/fault detection platform	12/31/2019	Started, 10%
Control, modeling and simulation analysis of LPT based on H-SST	12/31/2020	Started, 10%