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# Development of a Solid State Transformer for HEMP/GMD Common Mode Current Mitigation

Tim Donnelly and Lee Rashkin
*Sandia National Laboratories*

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# Outline

- Background
- Demonstration of HEMP/GMD on a conventional transformer
- Proposed SST for HEMP/GMD mitigation
- SST Design
  - Four-leg inverter
  - Dual active bridge
  - Controls scheme
- SST Testing
- Conclusion and future work

# Background

The electric power grid plays a vital and growing role in society, and ensuring its reliable operation is essential from a national security standpoint

Unfortunately, high-altitude EMPs (HEMPs) and geomagnetic disturbances (GMDs) both present a potential high-impact risk to the grid

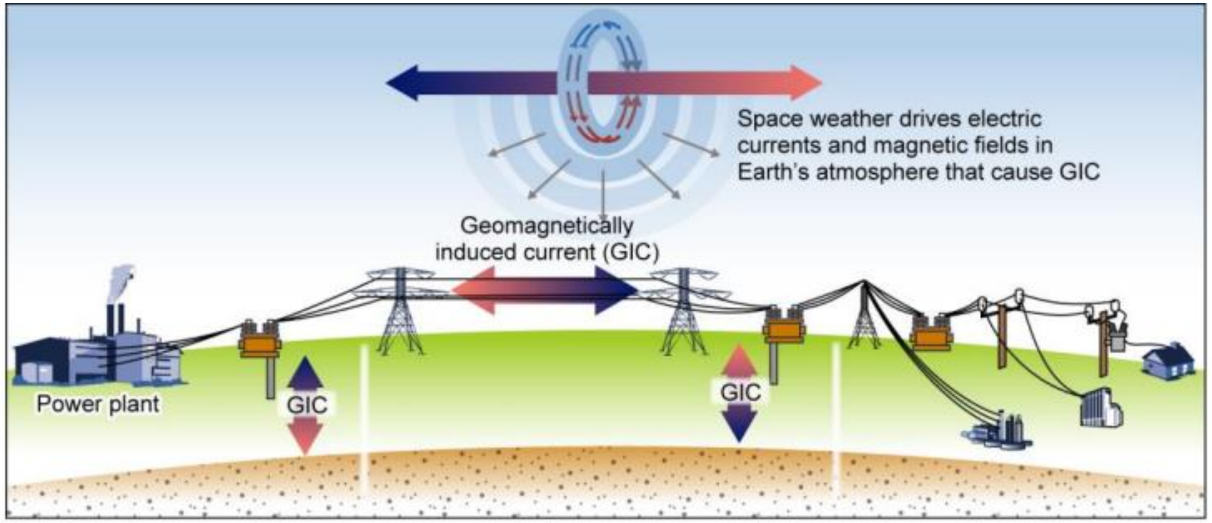



image credit: GAO-19-98

Induced currents → transformer half-cycle saturation

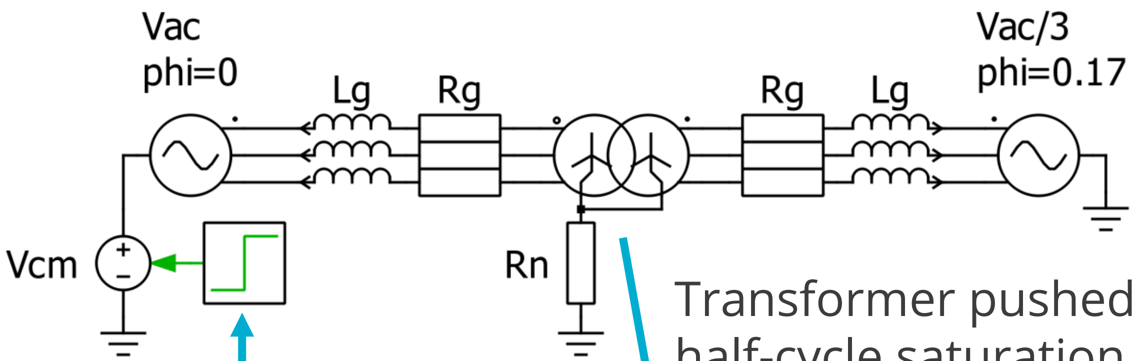
- increased losses, voltage degradation
- thermal damage, cascading failures, blackouts

No panacea currently available

- grid dispatch for <u>small-medium</u> scale events
- passive blocking devices for <u>medium-large</u> scale events
- no clear solution for <u>extreme</u> events (Carrington-level solar storm, high yield nuclear EMP)

New approach/technologies needed to secure *critical infrastructure*

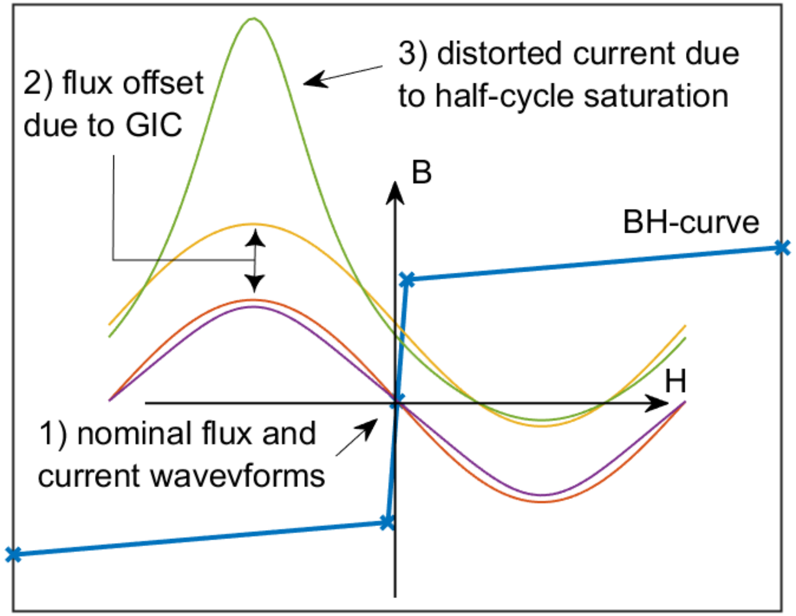
# Conventional Transformer During HEMP/GMD

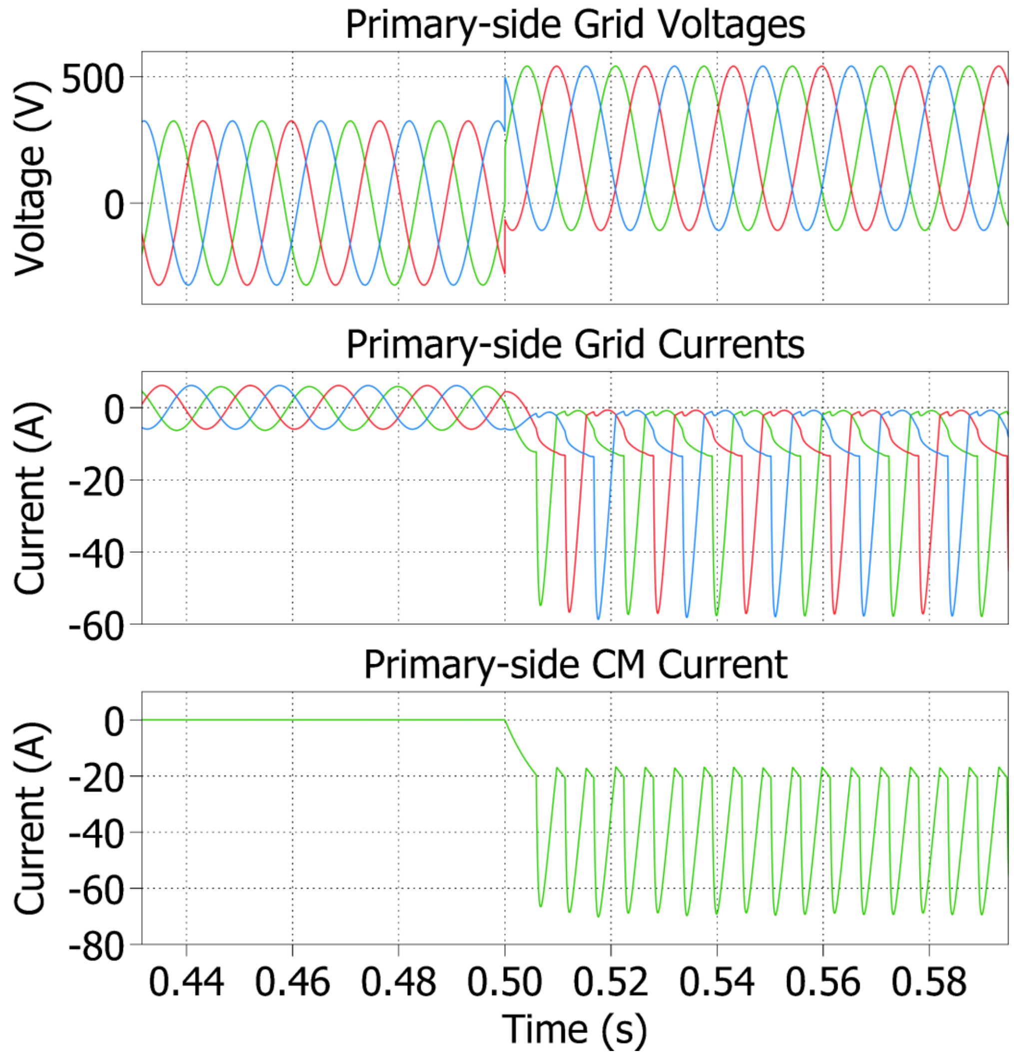



Simulated CM insult

Transformer pushed into half-cycle saturation…

…leading to distorted current

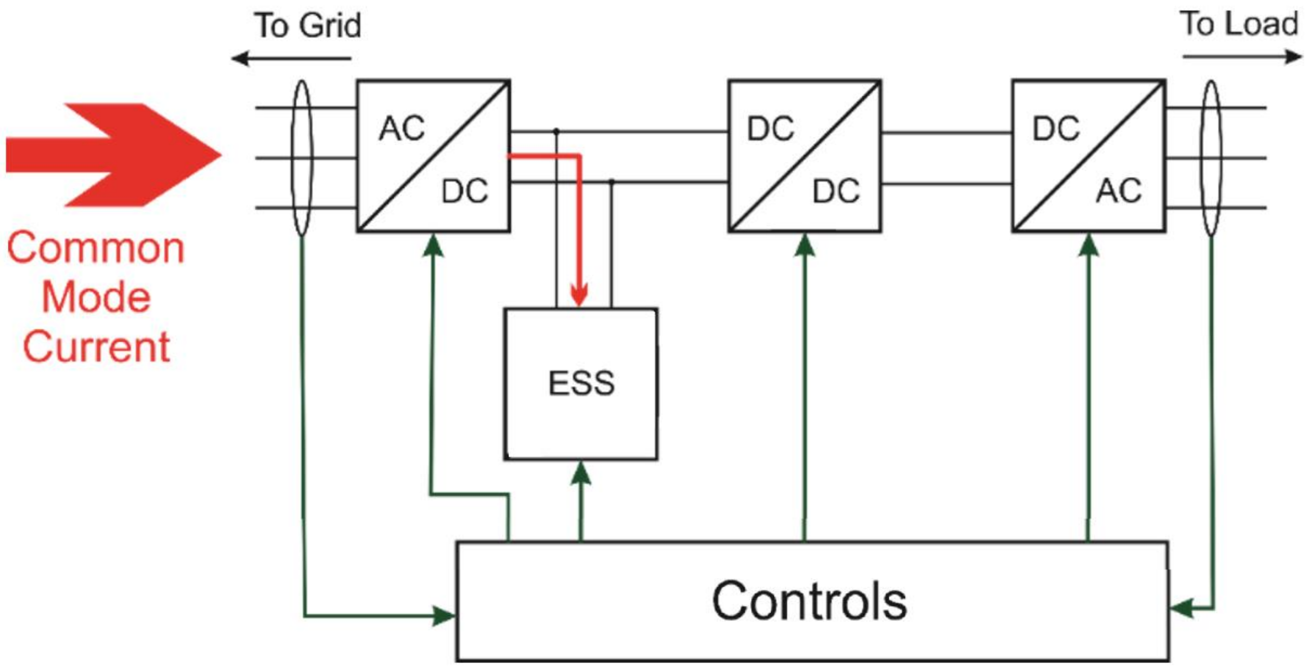


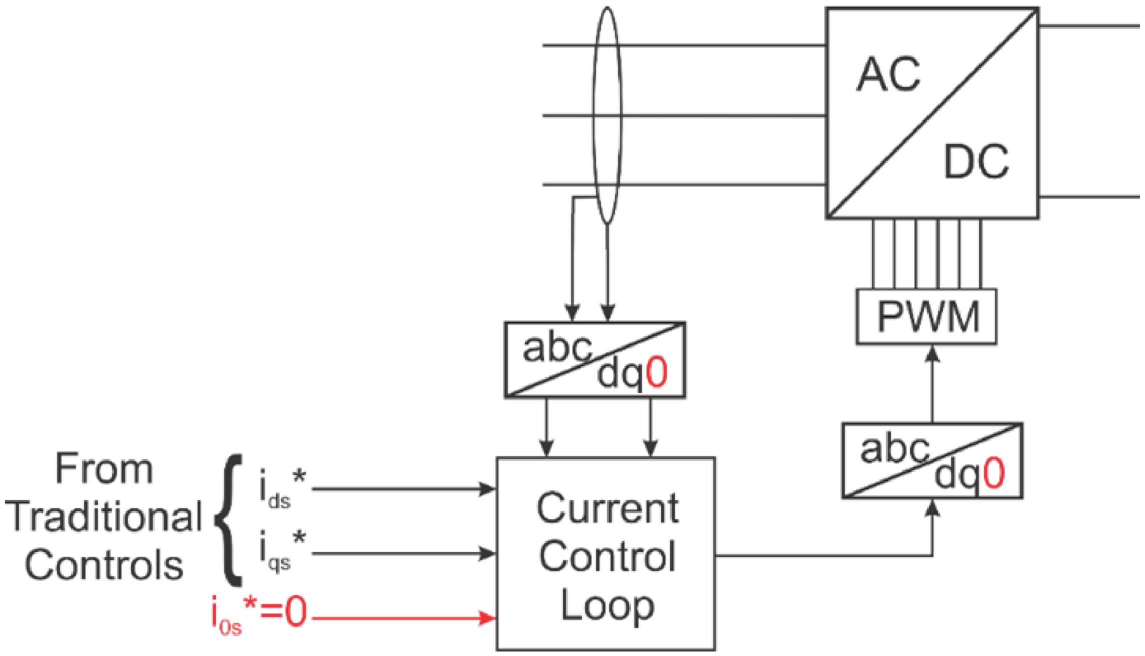



# Solid-State Transformer for HEMP/GMD Mitigation

Approach is to design a solid state transformer (SST) which can replace/protect susceptible magnetic transformers

SST can absorb CM currents caused by a HEMP/GMD, without effecting power delivery



# CM Solid State Transformer Design

Type-IV architecture selected to support dc energy storage and increased control flexibility [1]

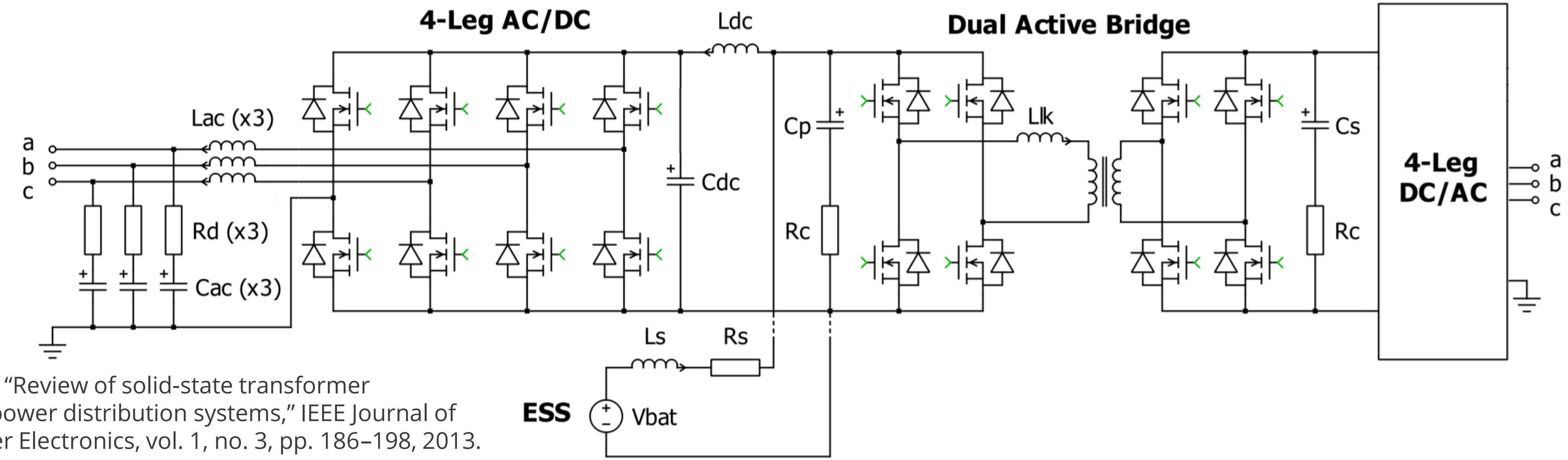
absorb CM insult from HEMP/GMD and prevent disturbance on secondary

4-leg inverter topology selected for input/output converters

enables control of d, q, **and** zero-sequence components

Dual-active bridge (DAB) selected for dc/dc converter

provides galvanic isolation and large step-up/down ratios




[1] X. She, A. Q. Huang, and R. Burgos, "Review of solid-state transformer technologies and their application in power distribution systems," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 1, no. 3, pp. 186–198, 2013.

# Four Leg Inverter

Specifications: 480Vac/120Vac, 10kW, respond to 0.5pu CM insult

3-D space-vector modulation (SVM) scheme required to control DQ0 [2,3]

Hardware designed for 800Vdc, 40kHz switching

DC parameters:

$V_{dc} > 480\sqrt{2}$

$V_{dc} = 800V$

$L_{dc}, = 0.5mH$

$C_{dc} = 1.8mF$

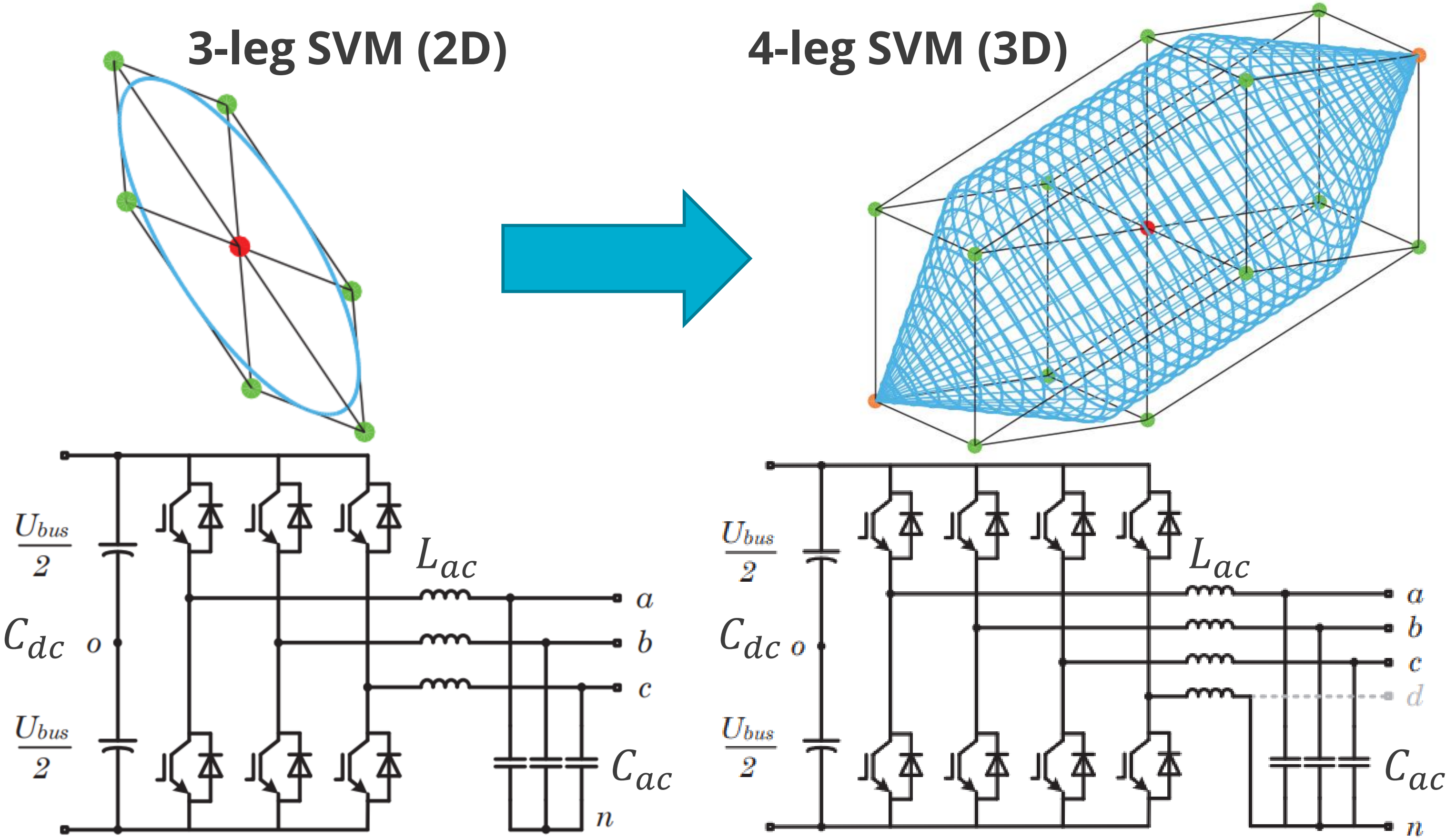
AC parameters:

$F_{sw} \sim 40kHz$

$f_c \approx \sqrt{60Hz * F_{sw}}$

$L_{ac} = 388\mu H$

$C_{ac} = 53\mu F$




[2] M. Perales, M. Prats, R. Portillo, J. Mora, J. Leon, and L. Franquelo, “Three-dimensional space vector modulation in abc coordinates for fourleg voltage source converters,” IEEE Power Electronics Letters, vol. 1, no. 4, pp. 104–109, 2003.
[3] Llonch, M., Heredero-Peris, D., Montesinos-Miracle, D., Rull, J. Understanding the three and four-leg inverter Space Vector. A: European Conference on Power Electronics and Applications. "EPE 2016: ECCE Europe, 18th European Conference on Power Electronics and Applications; Karlsruhe, Germany, 5-9 September, 2016". Karlsrhue: Institute of Electrical and Electronics Engineers (IEEE), 2016, p. 1-10

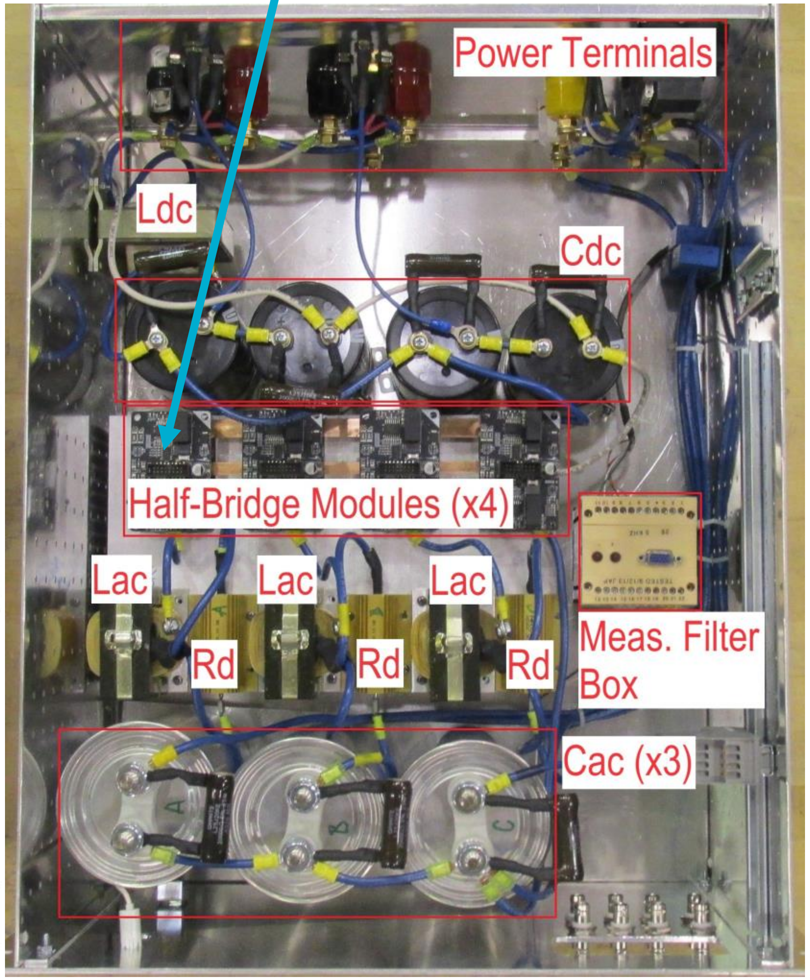
# Four Leg Inverter (Continued)

Inverter design based around 1.2kV Silicon carbide (SiC) half-bridge power modules [4]

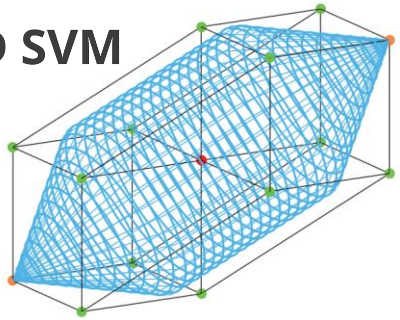
3D SVM implemented on Speedgoat FPGA module [5]

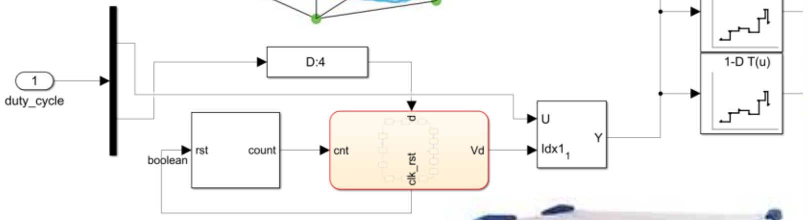
Standalone testing to ensure design meets specifications

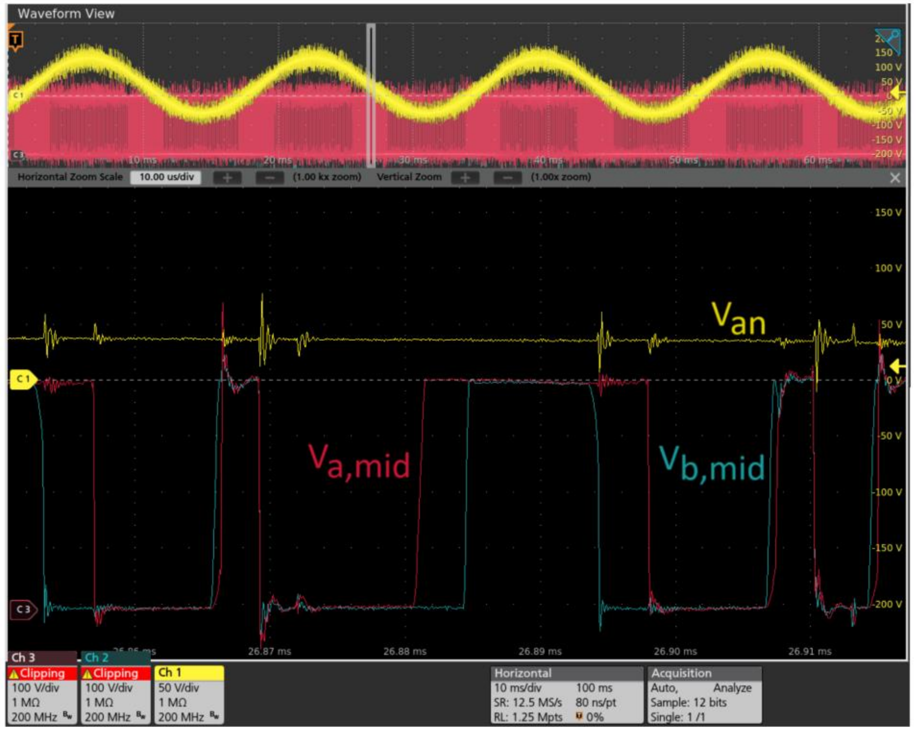
Wolfspeed XM3 power module


**3D SVM**





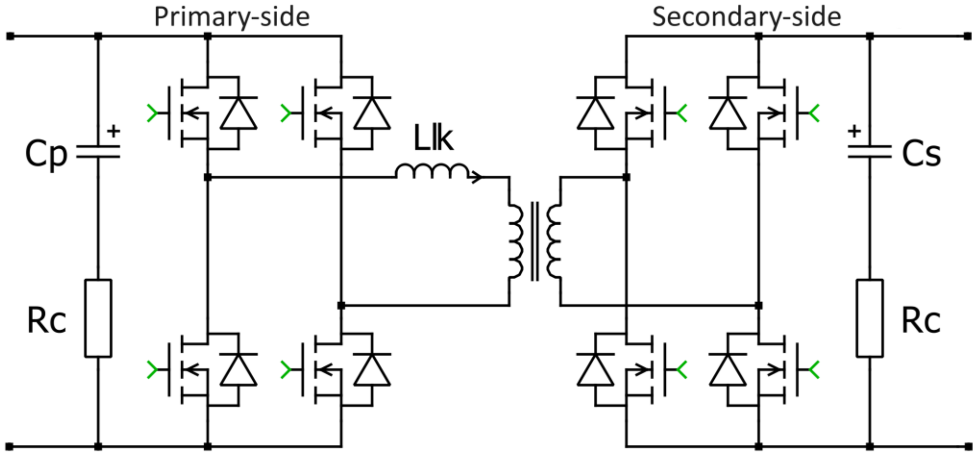

[4] "CAB450M12XM3," www.wolfspeed.com
[5] "Speedgoat IO334 FPGA and Configurable I/O Module," www.speedgoat.com

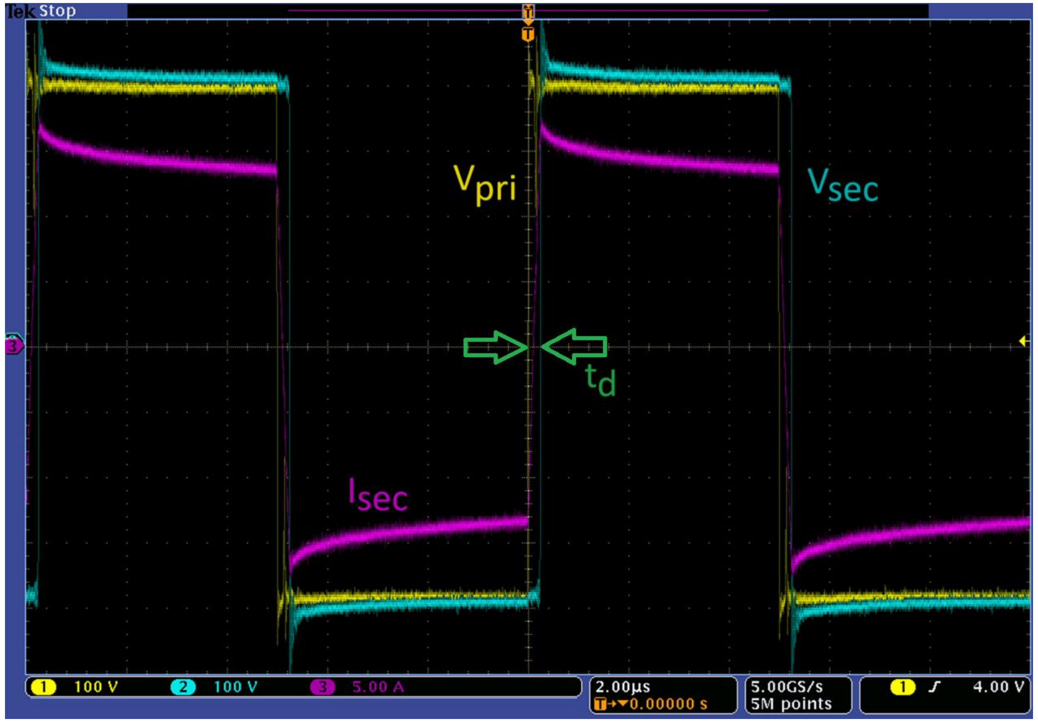
# Dual Active Bridge

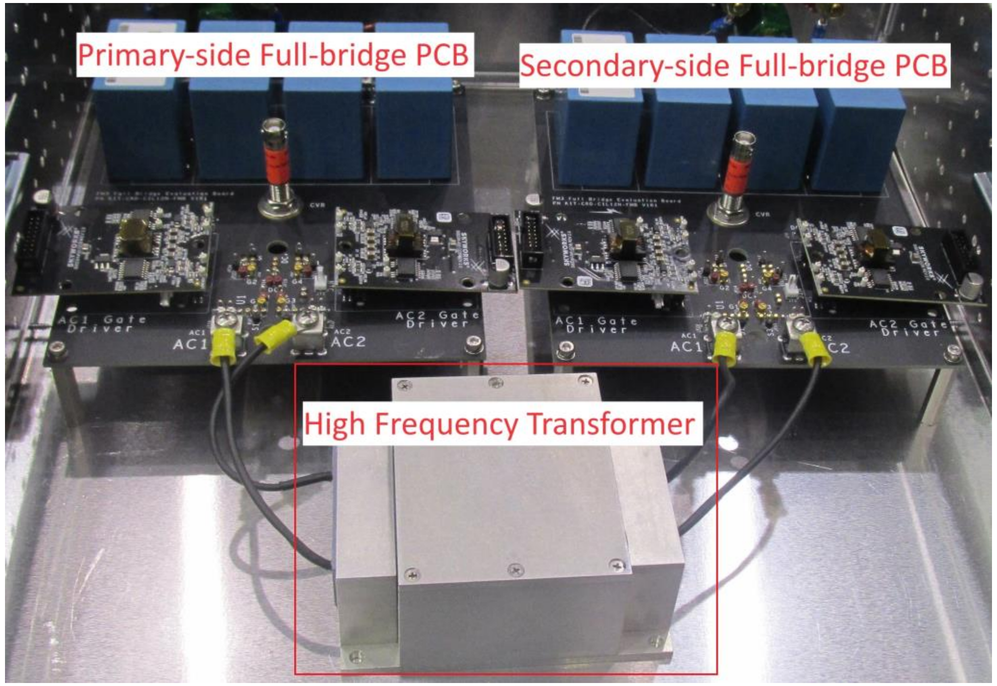
Dual active bridge (DAB) based around high frequency planar transformer [6]

Designed to operated at 800Vdc (input), 100kHz

Phase-shift controller [7] regulates output voltage




[6] “Payton planar,” www.paytongroup.com
[7] B. Zhao, Q. Song, W. Liu, and Y. Sun, “Overview of Dual-Active-Bridge Isolated Bidirectional DC–DC Converter for High-Frequency-Link Power-Conversion System,” IEEE Transactions on Power Electronics, vol. 29, no. 8, pp. 4091–4106, 2014

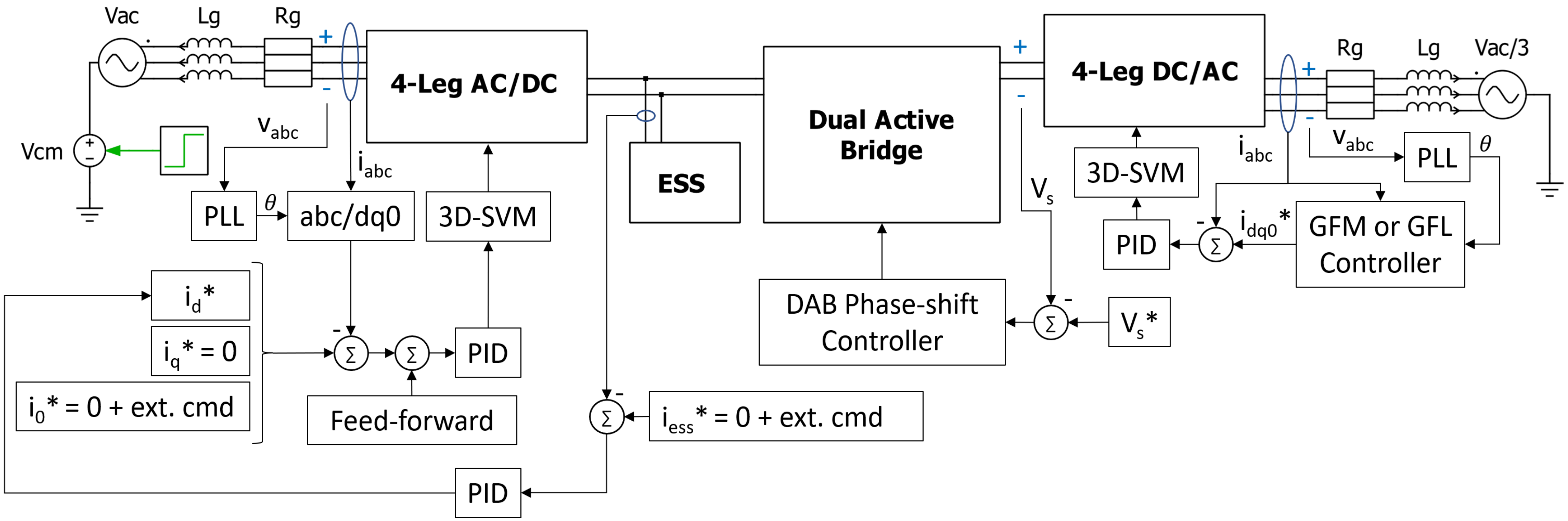
# SST Controls

Controls are designed to transfer ac power from primary to secondary while absorbing CM insults

Primary-side AC/DC responsible for controlling CM current and drawing enough power to supply downstream load

DAB responsible for maintaining constant DC voltage for secondary inverter

Secondary inverter can be configured to be grid forming (GFM) or grid following (GFL)

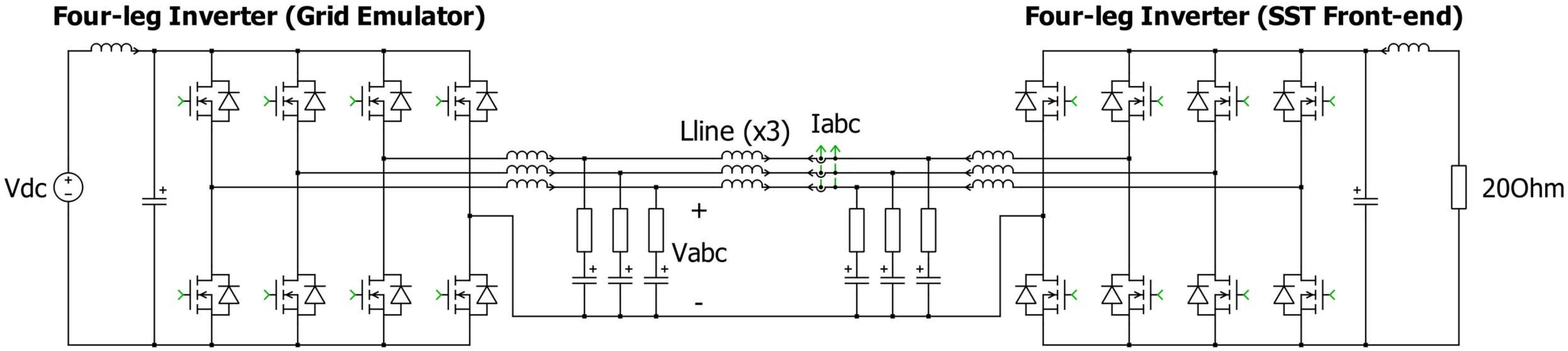


# CM Mitigation Test Setup

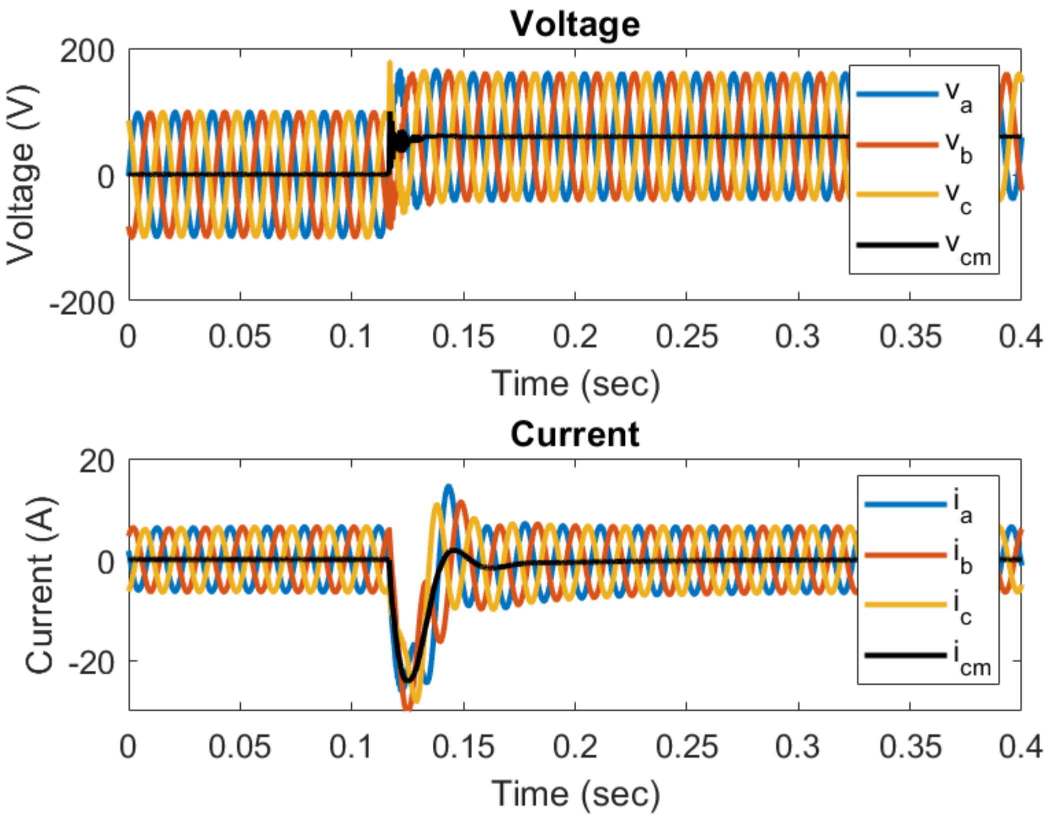
Back-to-back testing conducted to verify four-leg inverter can respond to CM insult

Left inverter acts as source (grid) and outputs AC waveforms and simulated CM insult

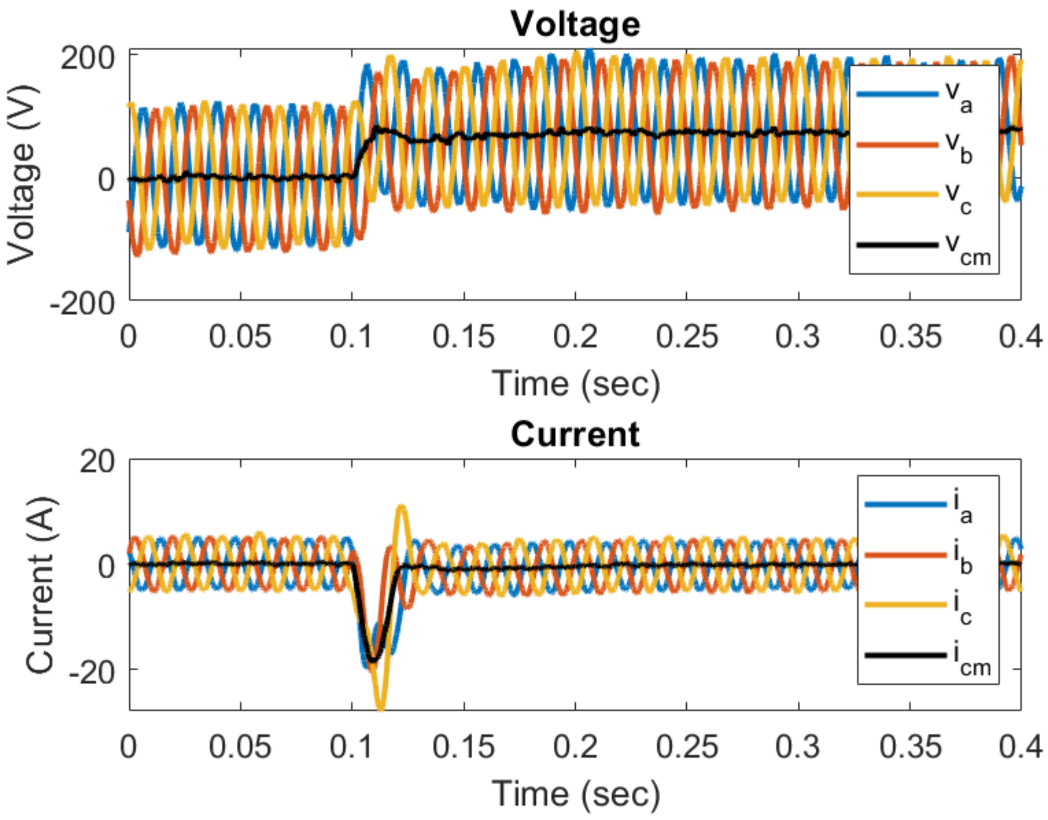
Right inverter acts as SST front-end and responds to CM insult (returns CM current to zero)



# CM Mitigation Results




**Simulation**



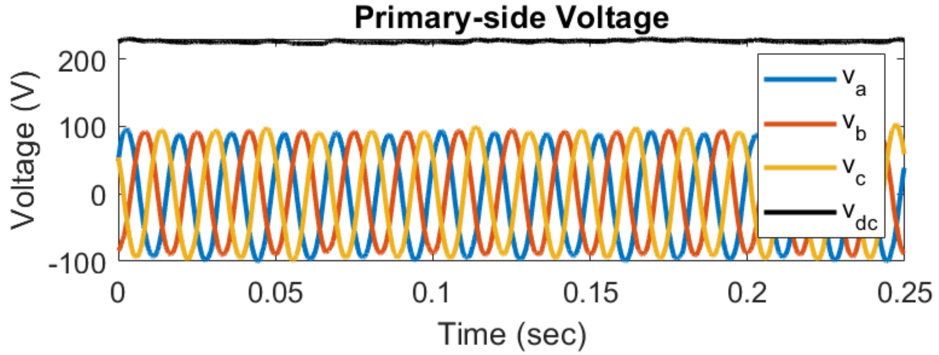

**Hardware**

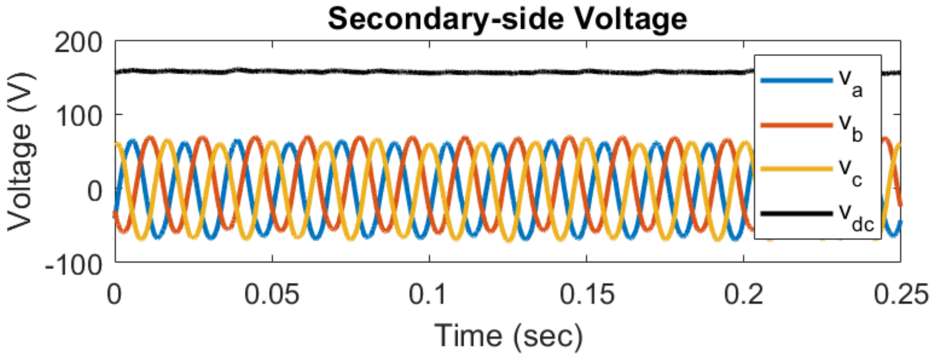
# Full SST Assembly and Testing

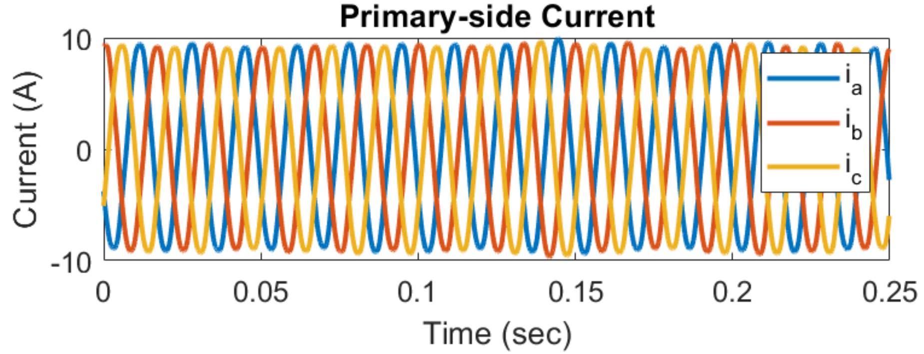
Full SST assembled in rack with cooling, measurement ports, wiring, etc.

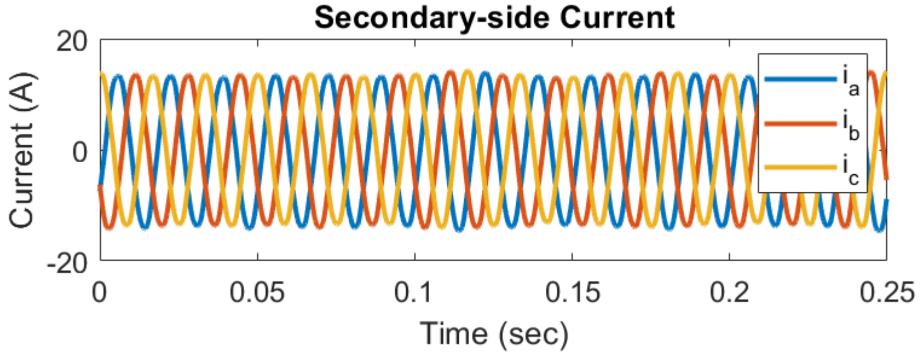
Nominal ac/ac capabilities of SST tested against grid simulator

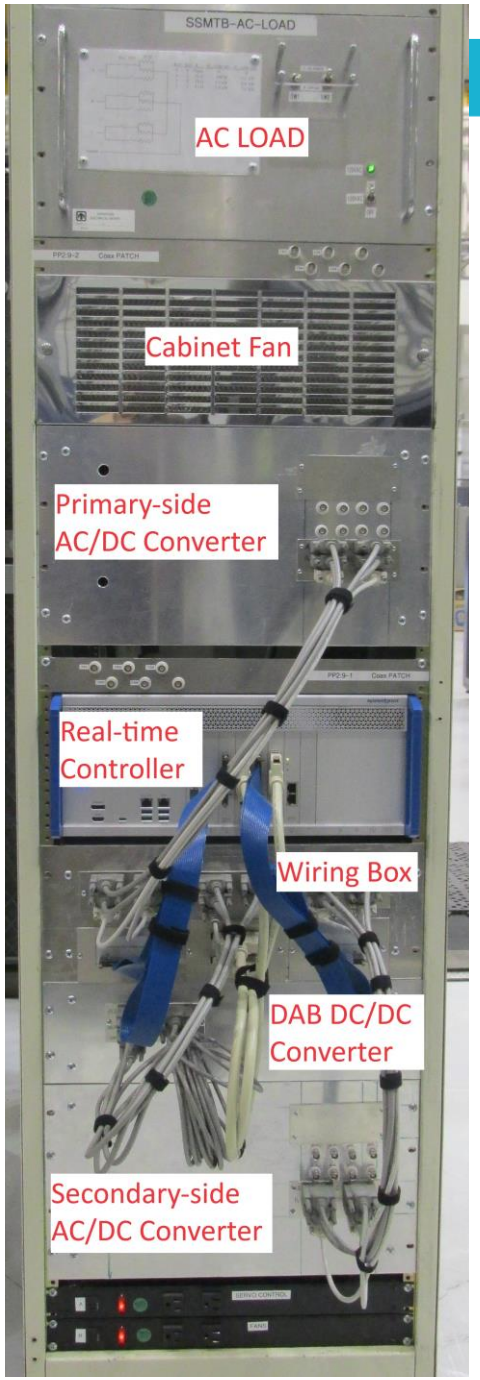
Further testing expected to evaluate performance of SST (efficiency, improved controls response, GFM/GFL output behavior, etc.)



# Conclusions and Future Work

Work presented on the design and testing of an SST for HEMP/GMD CM mitigation

SST is shown to function as an effective ac/ac converter during normal operations, and respond successfully to mitigate CM current during a simulated CM insult

Future work will explore:

- Dynamic response of full SST to simulated CM insult (including energy storage requirements)
- How the SST compares to a conventional magnetic transformer during HEMP/GMD
- How the SST can be deployed in the grid to maximize overall system resilience

# Backup

# Secure Scalable Microgrid Testbed at Sandia [10]

SSM SECURE SCALABLE MICROGRIDS
It's the end of the grid as we know it

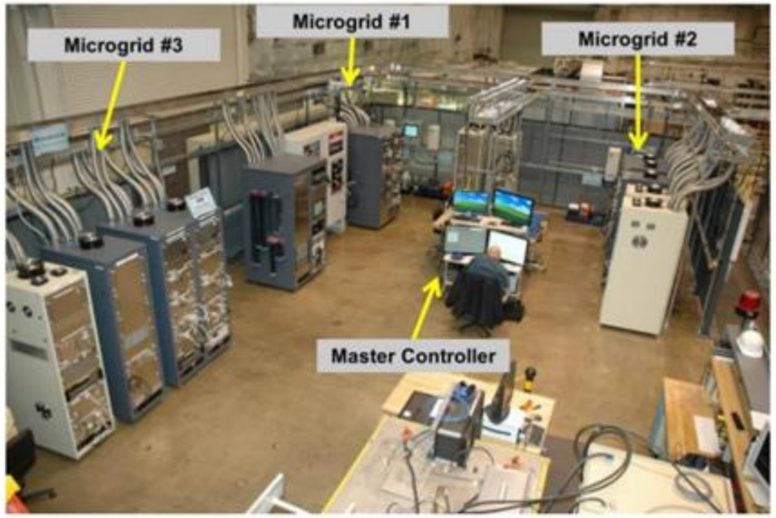
Microgrid testbed facility at Sandia National Laboratories

AC, DC, and hybrid microgrid configurations

Networked control and measurement capabilities for repeatable experiments

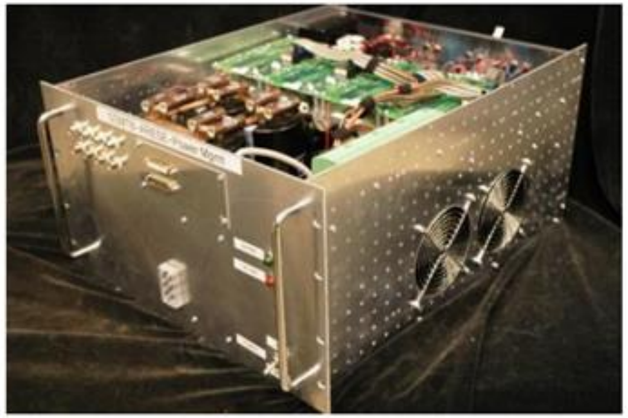
Equipment:
- Real-time control computers
- Data acquisition system
- Custom built power converters
- Energy storage emulators
- Programmable loads
- High power supplies
- Grid simulators

Multiple Microgrid Testbed

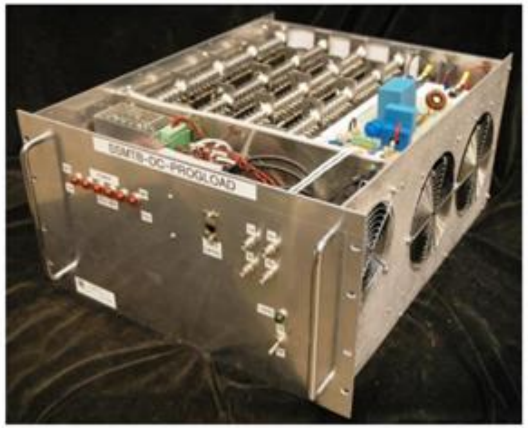



Mechanical Source Emulators


Energy Storage Emulators



High Power Digital Resistor



[10] S. Glover, J. Neely, A. Lentine, J. Finn, F. White, P. Foster, O. Wasynczuk, S. Pekarek, and B. Loop, "Secure Scalable Microgrid Test Bed at Sandia National Laboratories," in 2012 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER)