A Novel Insulation Method and Practical Considerations for MV/MF Transformers in SST Applications

PSMA Magnetics Workshop 2023

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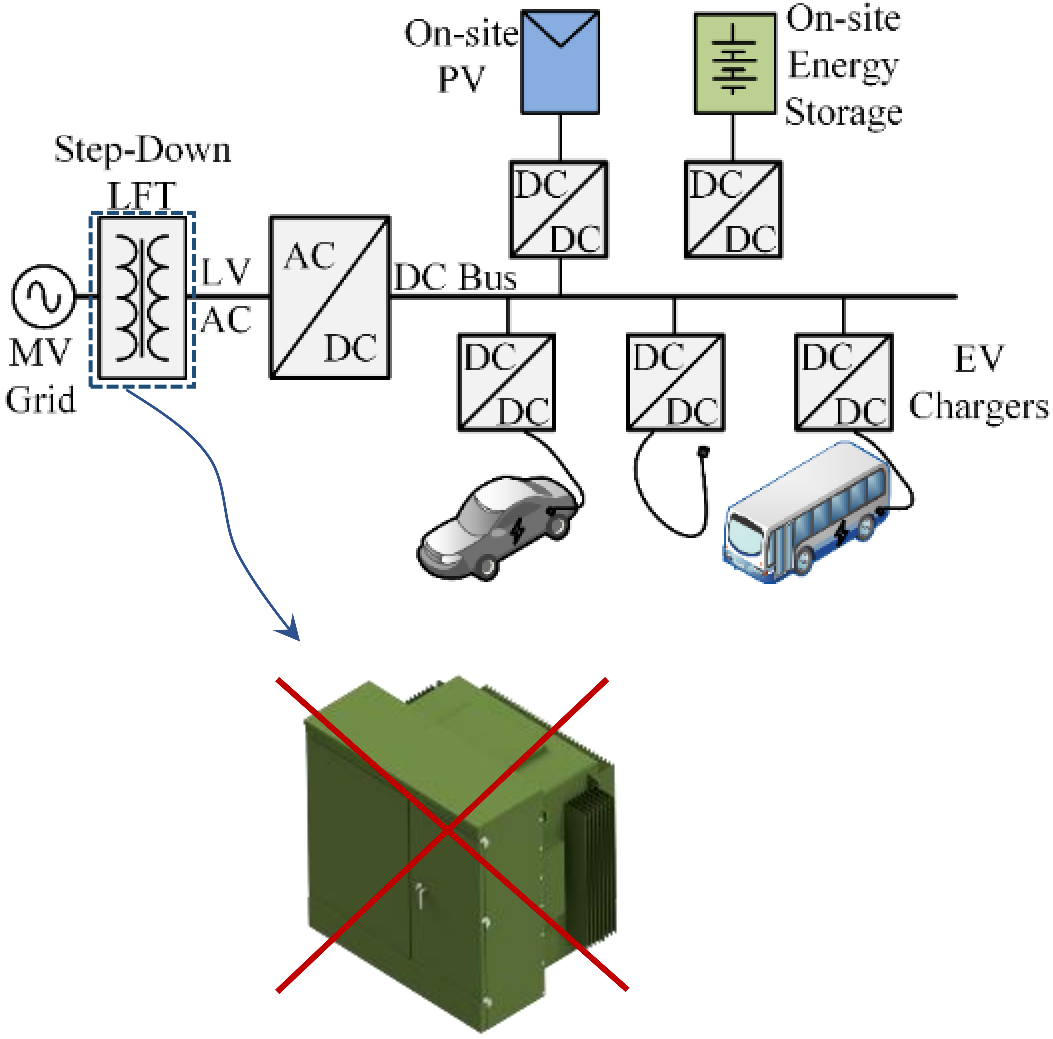
Background: MV AC to LV DC SST Applications

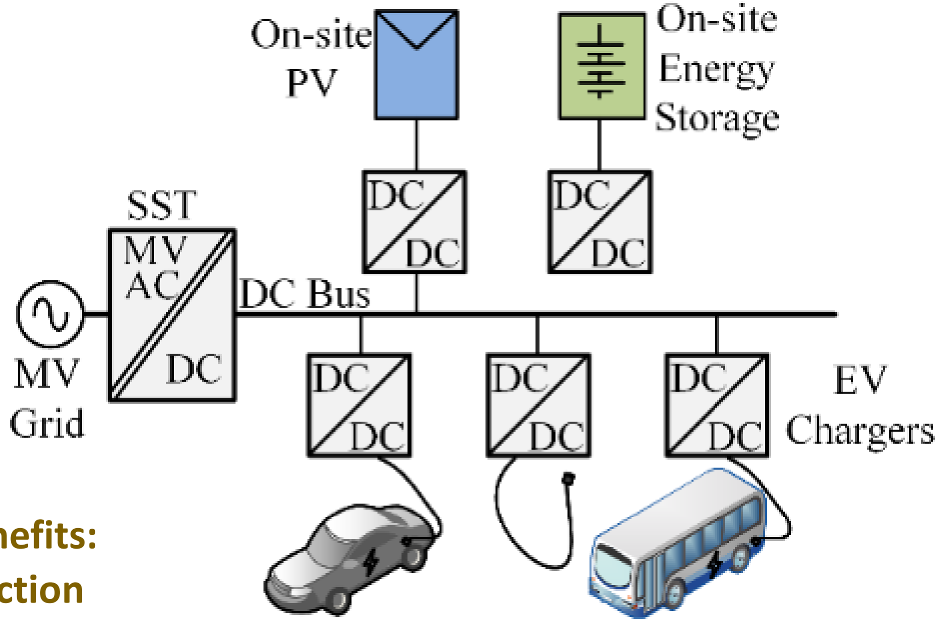
High power grid connected DC loads:

- EV charging Stations & Solar inverters
- Data centers & DC micro-grid Utility interface
- Locomotive drives

EV Charging Station: Grid Connection through **LF Transformer**



EV Charging Station: Grid Connection through **MV SST**

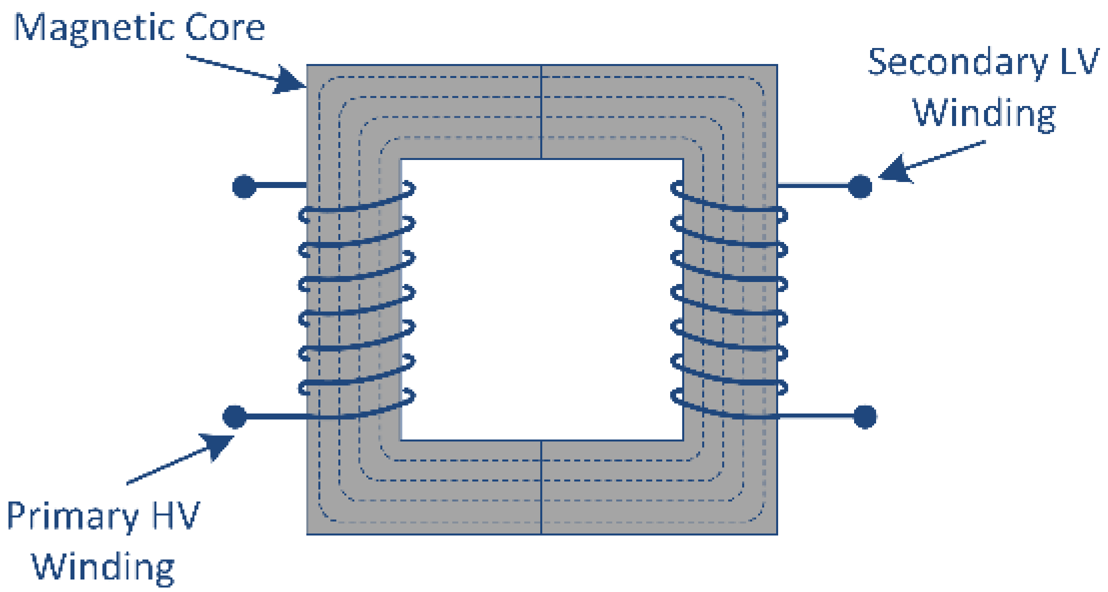


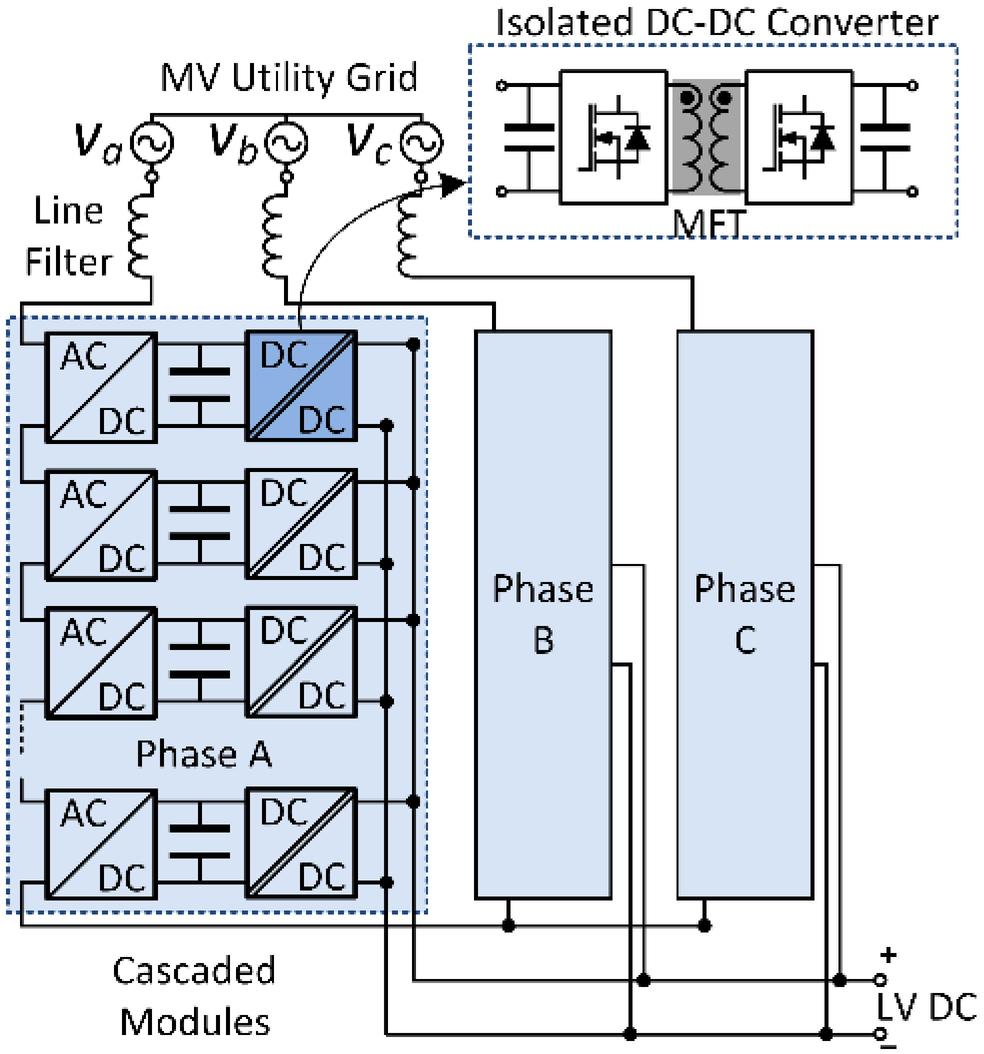
Potential Benefits:
→ **Loss Reduction**
→ **Increased Power Density**

MV/MF Transformer Requirements

- High voltage isolation capability
- Operate with ZVS to enable HF operation for high-power density
- Bi-directional power flow capability

Challenge: Design of high-power density DC-DC module while maintaining MV isolation



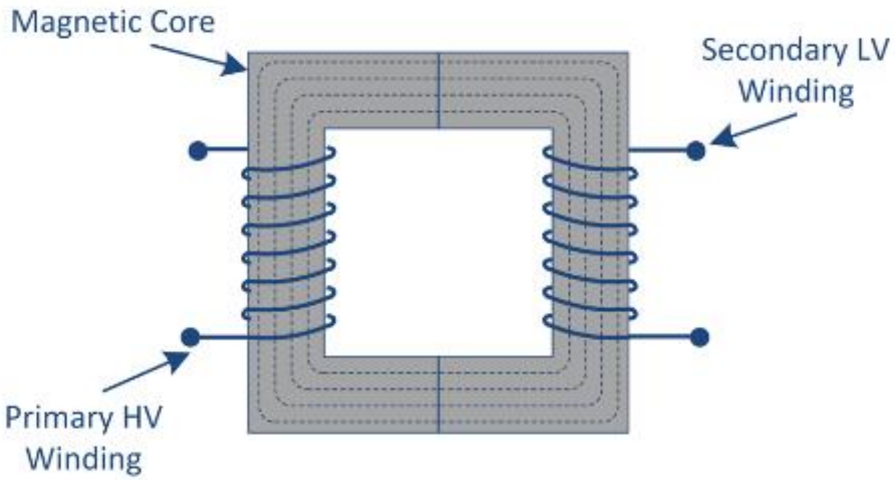


Block Diagram of a Typical AC to DC SST Topology

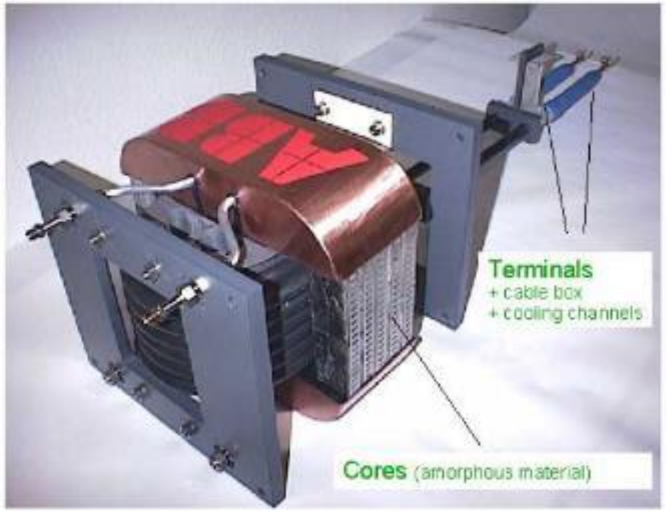
Medium Voltage Insulated Transformers

Three popular approaches to achieve MV isolation:

- Using high voltage cable for windings
- Potting the windings
- Oil-immersed windings
- Other Techniques



High Voltage Cable [1]



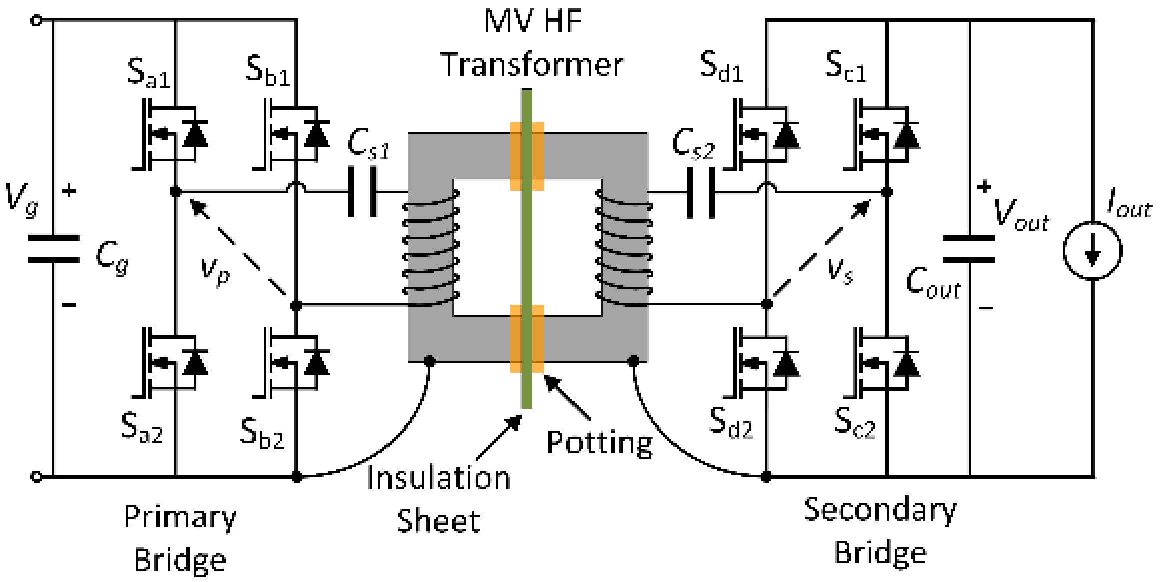
Potted Windings [2]

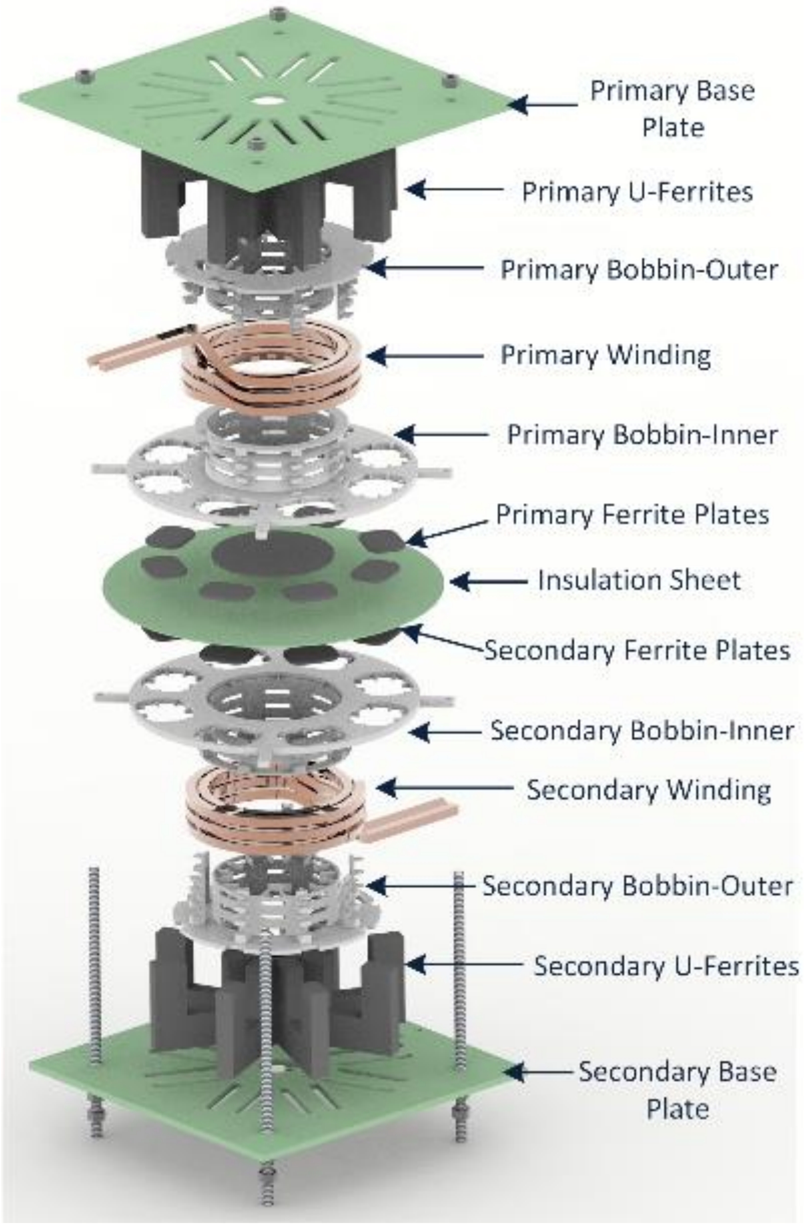
Oil-Immersed Windings [3]

Insulation Concept Summary

Design Considerations [4]:

- Segregating the MV and LV sides (Confines the high electric stress)
- Using an insulation sheet to meet the HV requirements
- Accommodating a lower magnetizing inductance
- Managing the high electric field regions (Ferrite Grinding, Potting)
- Loss estimation and thermal management





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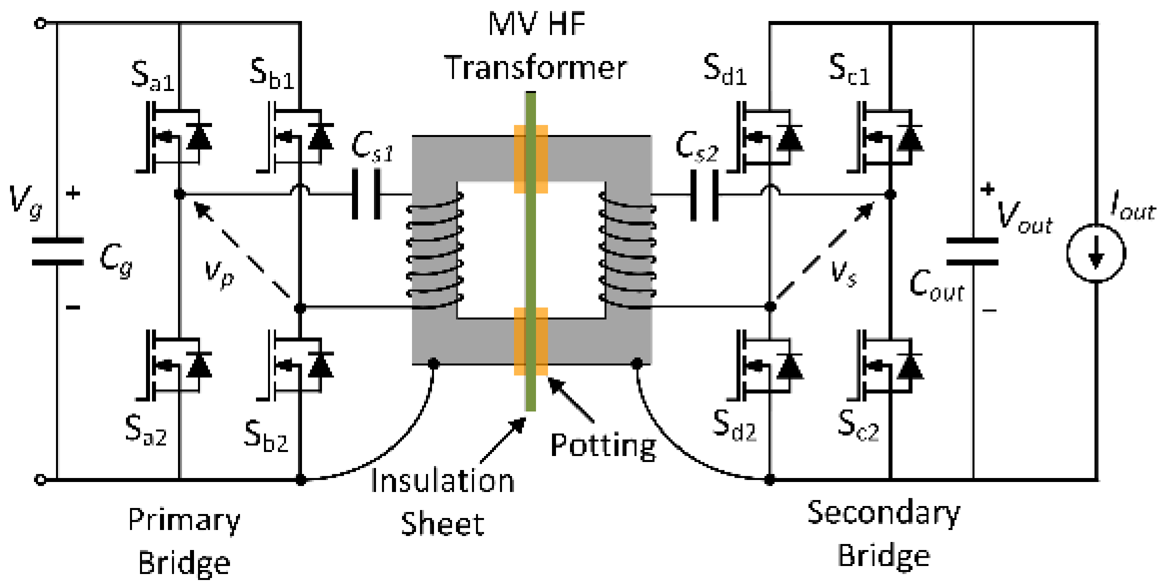
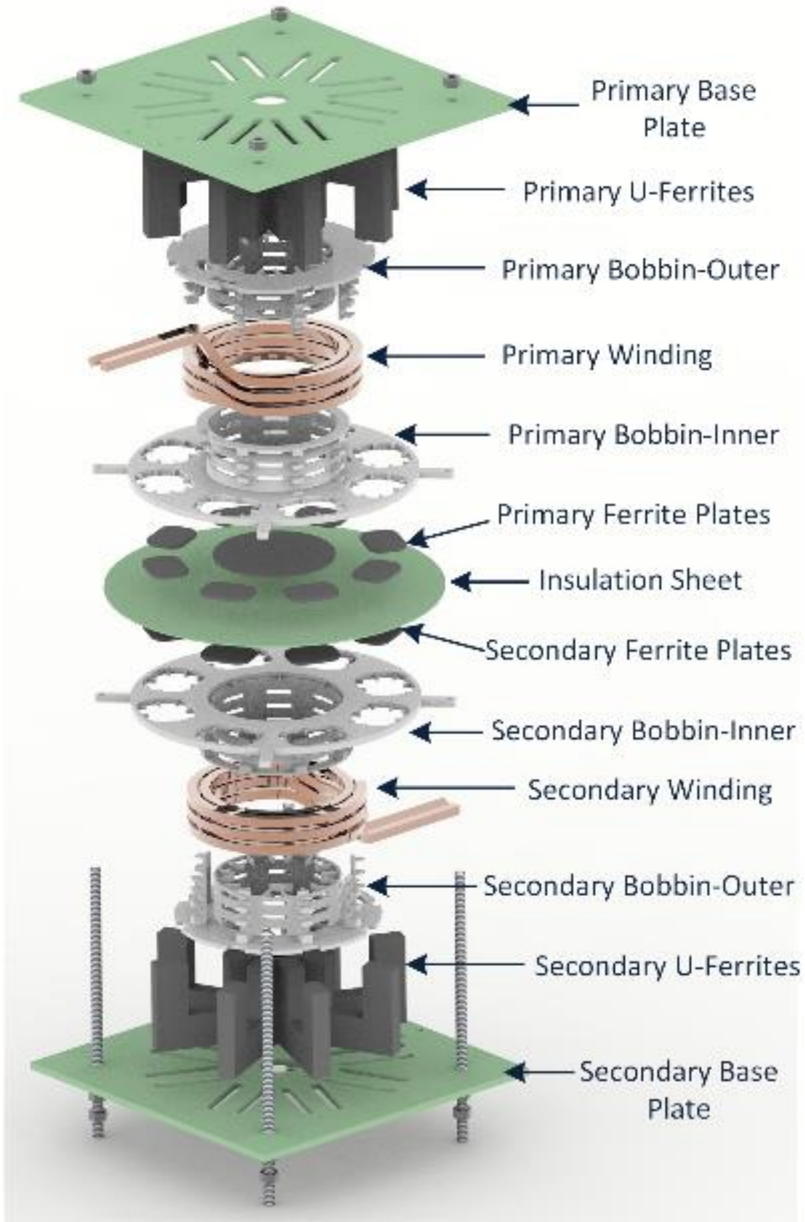
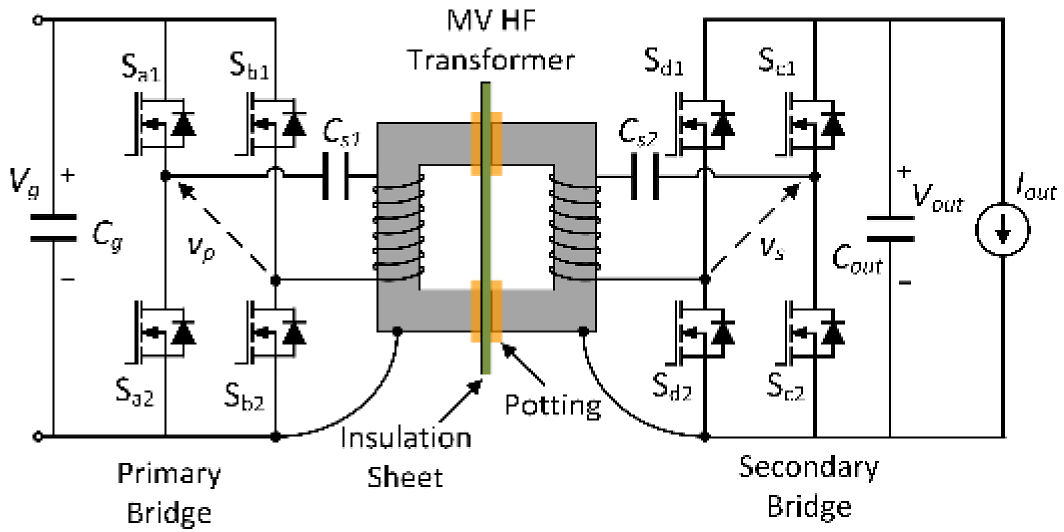


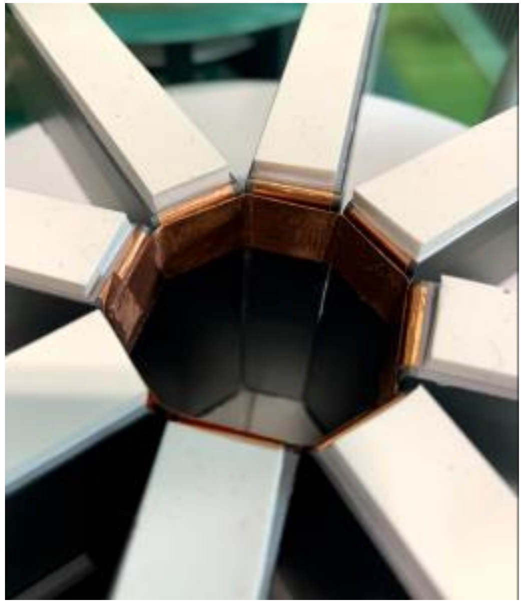


Insulation Concept: MV/LV Segregation

Considerations:

- Adequate spacing between the MV and LV side windings
- Ferrite Potential Management





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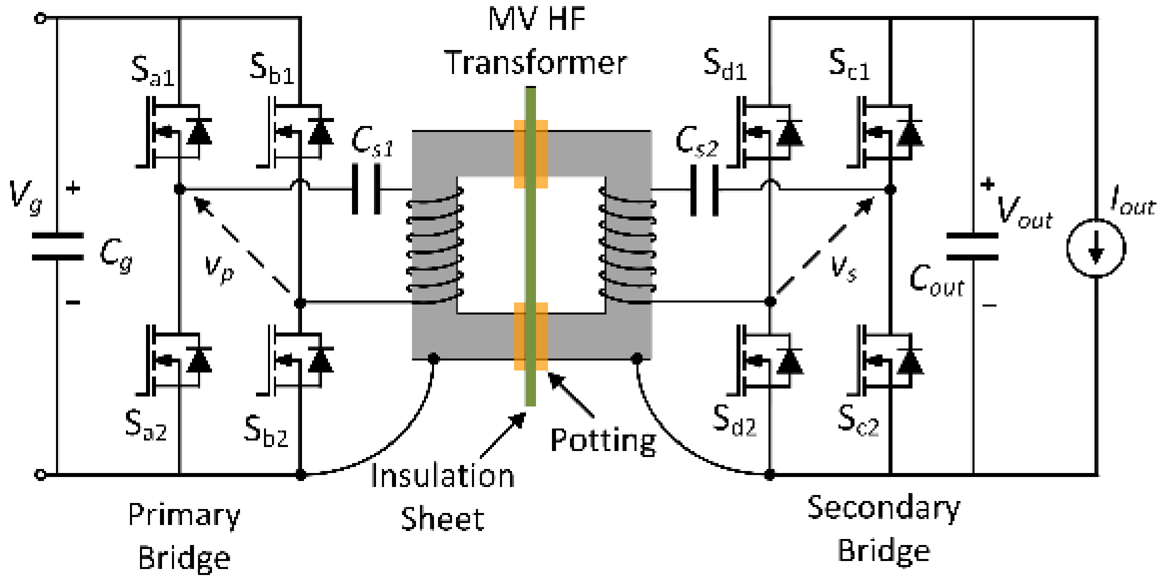
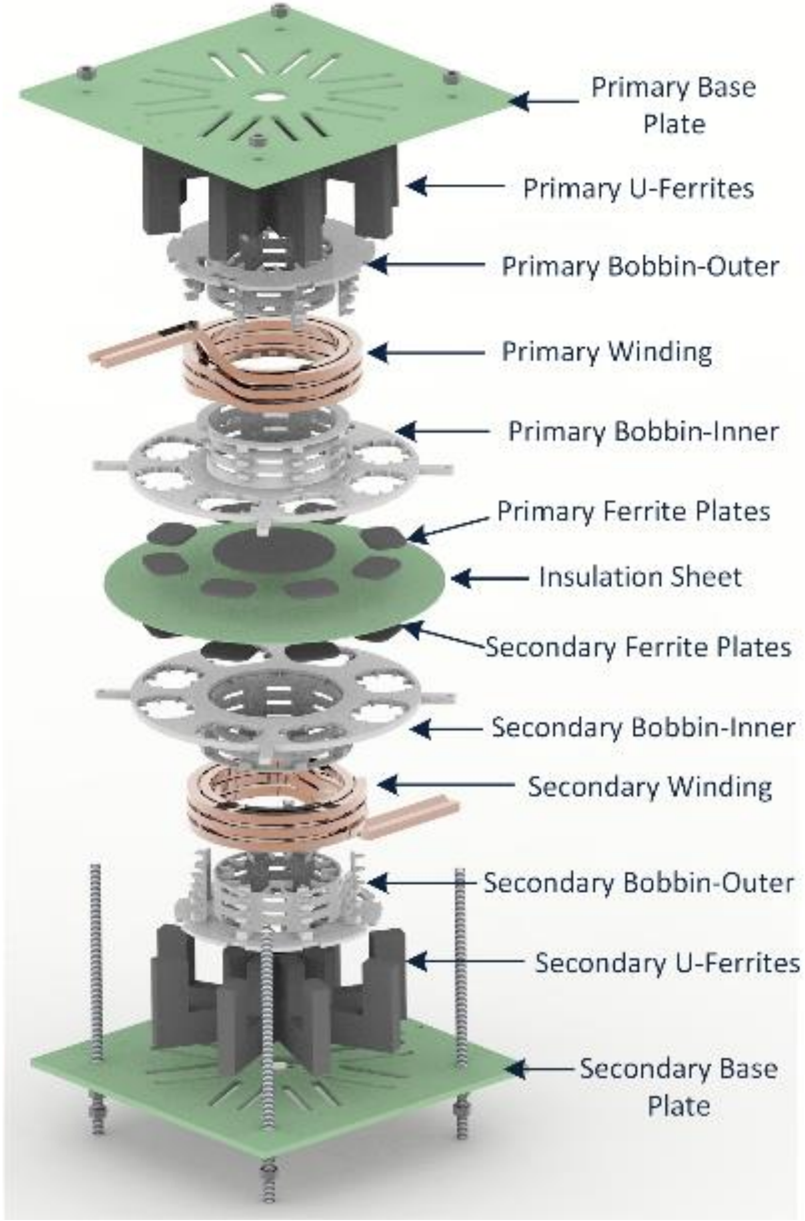
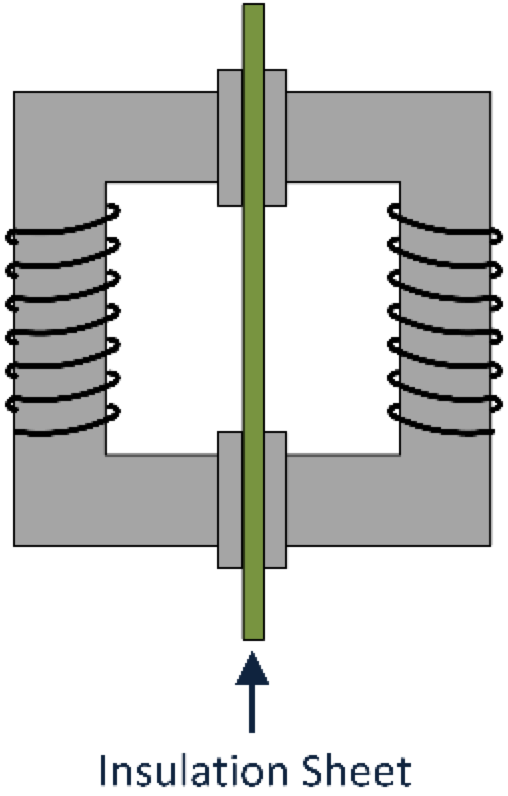


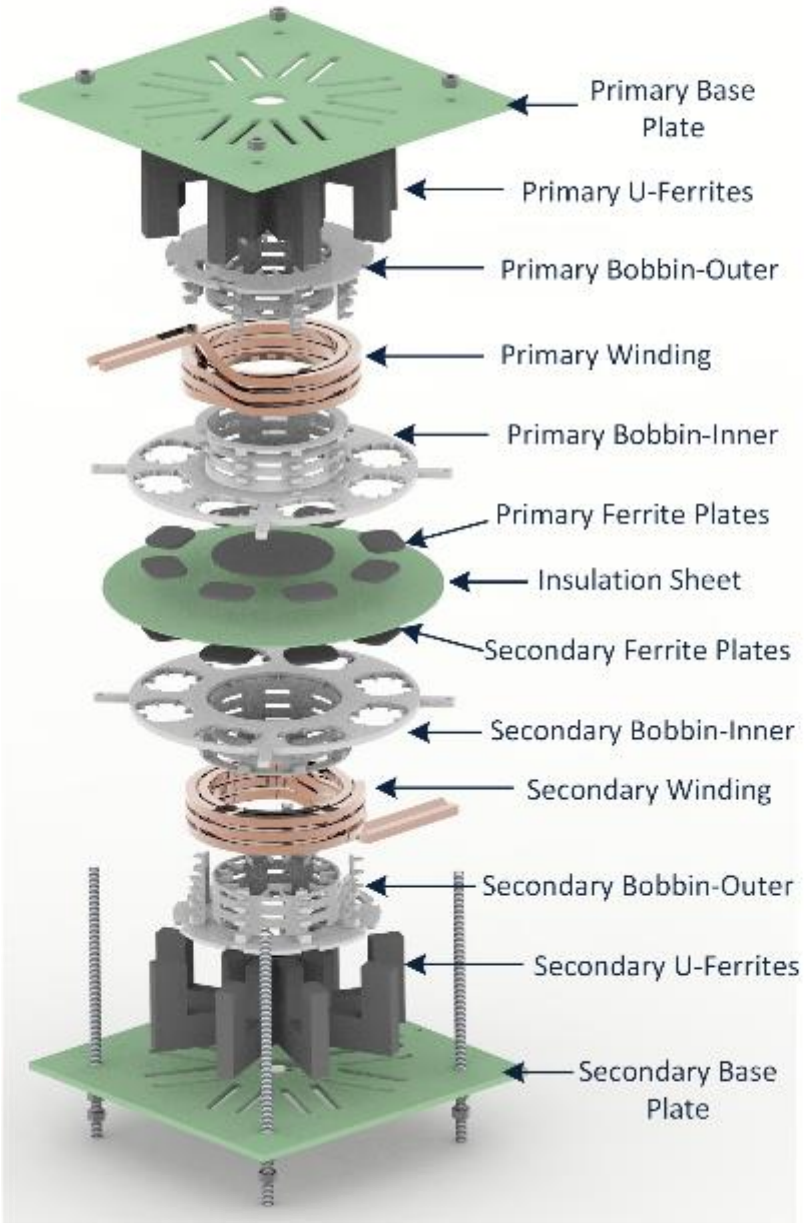


Insulation Concept: Insulation Sheet

High dielectric strength sheet to meet the isolation requirements:

- FR-4.0/21 material, 1.6 mm
- Electric strength: 40 kV minimum
- Dielectric constant: 5.20





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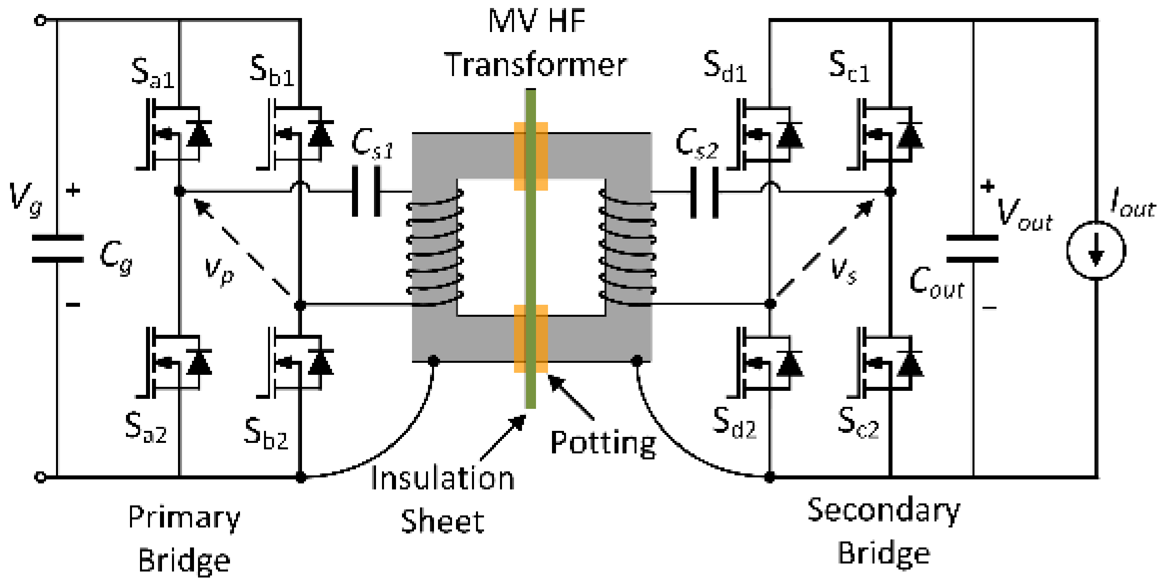
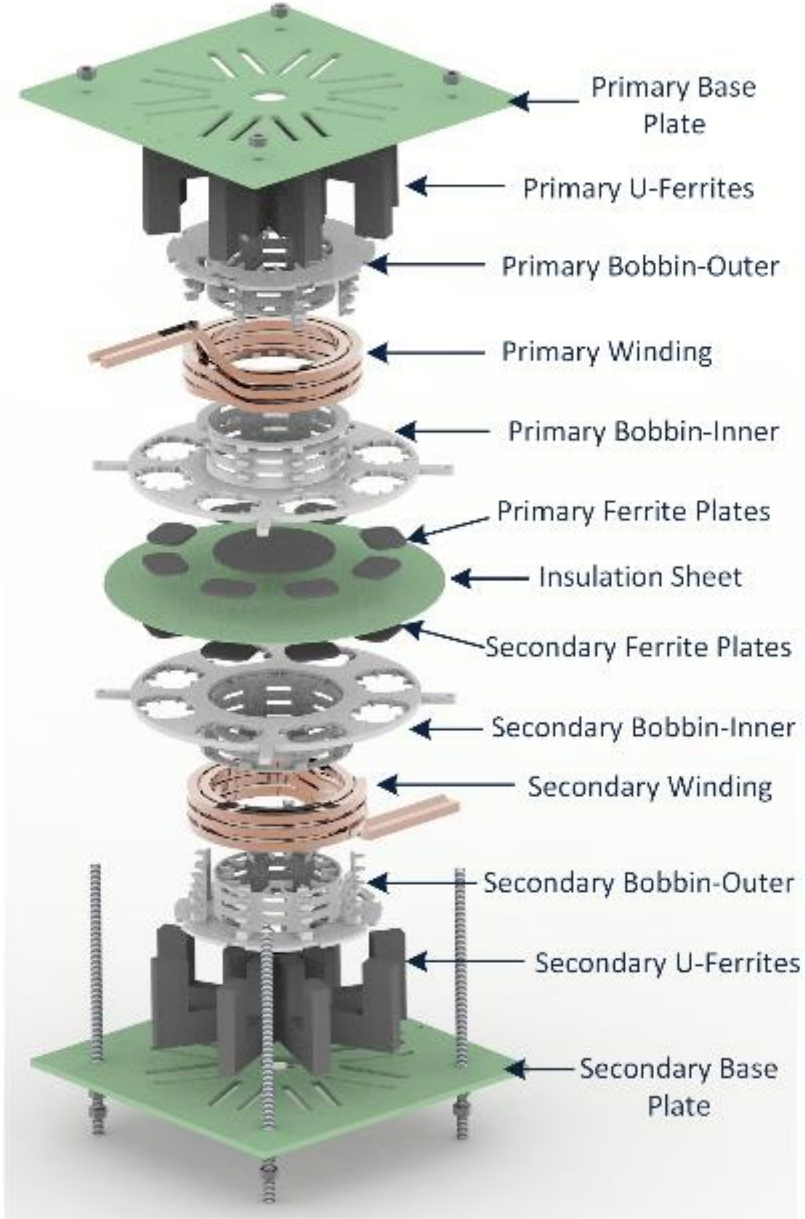
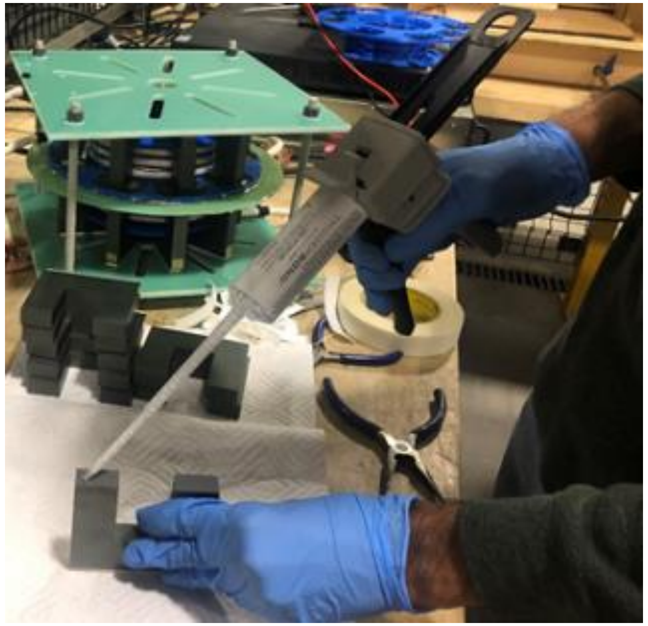




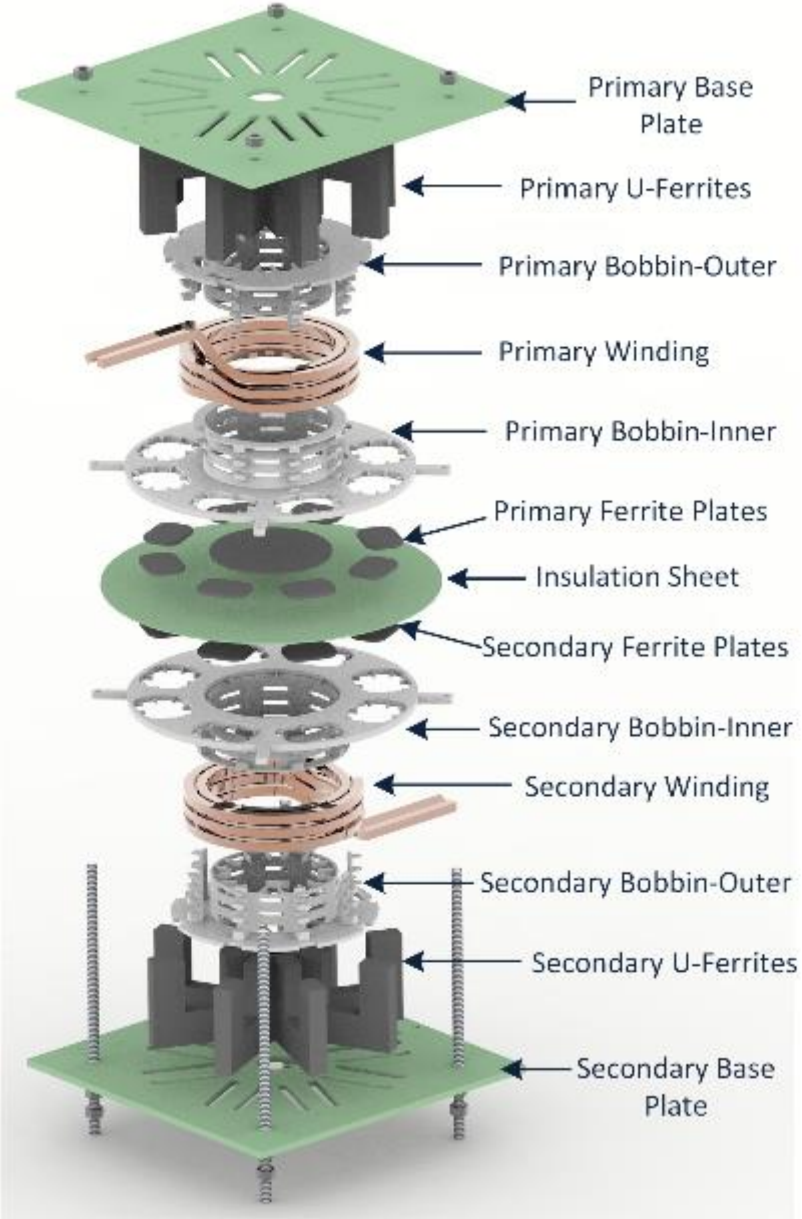
Insulation Concept: Low Magnetizing Inductance

Meeting the target magnetizing inductance:

- Custom Ferrite Disks
- Ferrite Glue



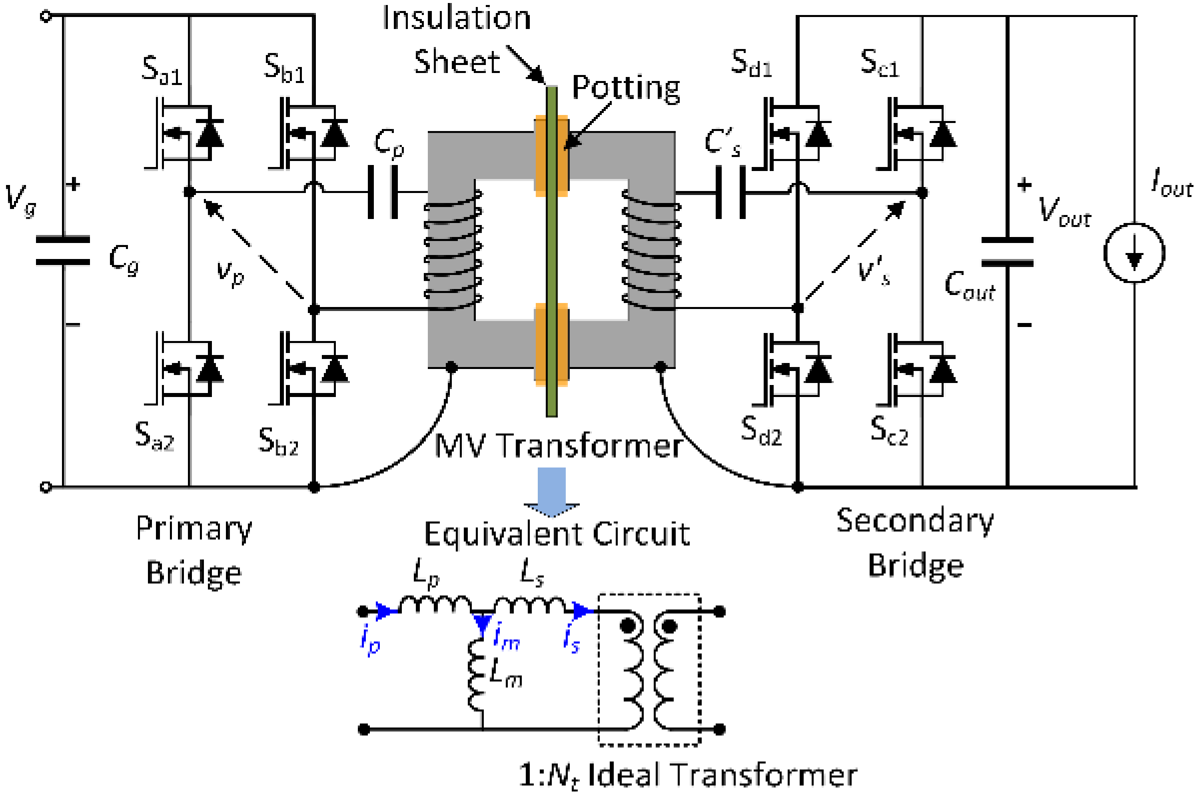
Circuit parameter	Value
Turns ratio, N_t	1
Series inductance, $L_p = L_s = L$	10.4 µH
Series capacitance, $C_p = C_s = C$	1.5 µF
Magnetizing inductance, L_m	105.7 µH
Switching frequency, f_s	50 kHz



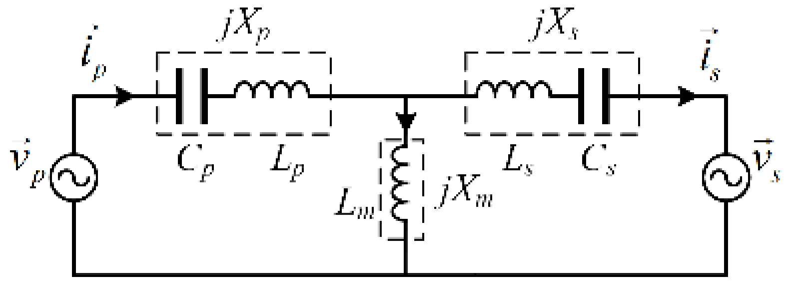
Insulation Concept: Low Magnetizing Inductance

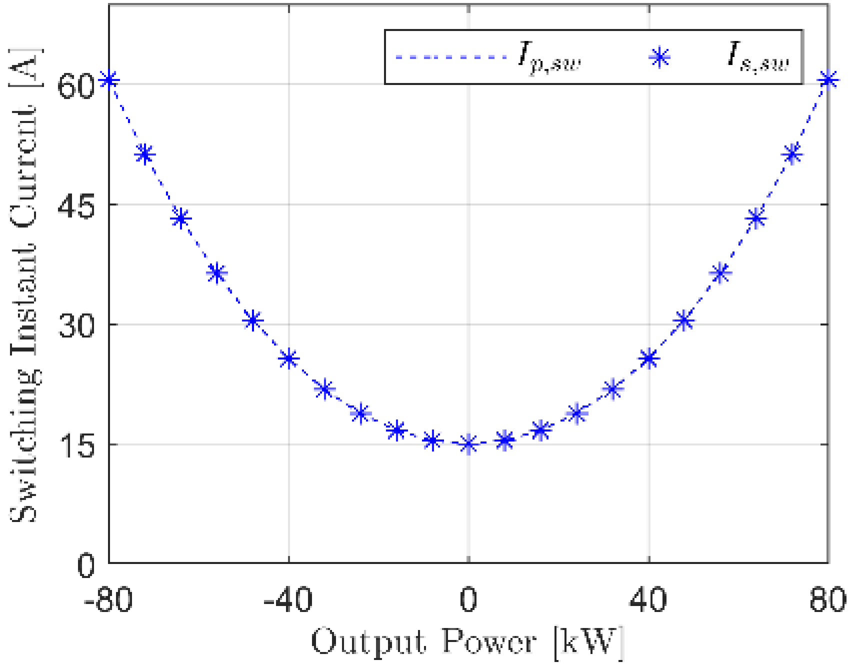
Low Magnetizing Inductance Impact:

- **Higher Circulating Currents**
- Seamless Power Transitions and Zero-voltage Switching



FHA Equivalent Circuit Referred to Primary





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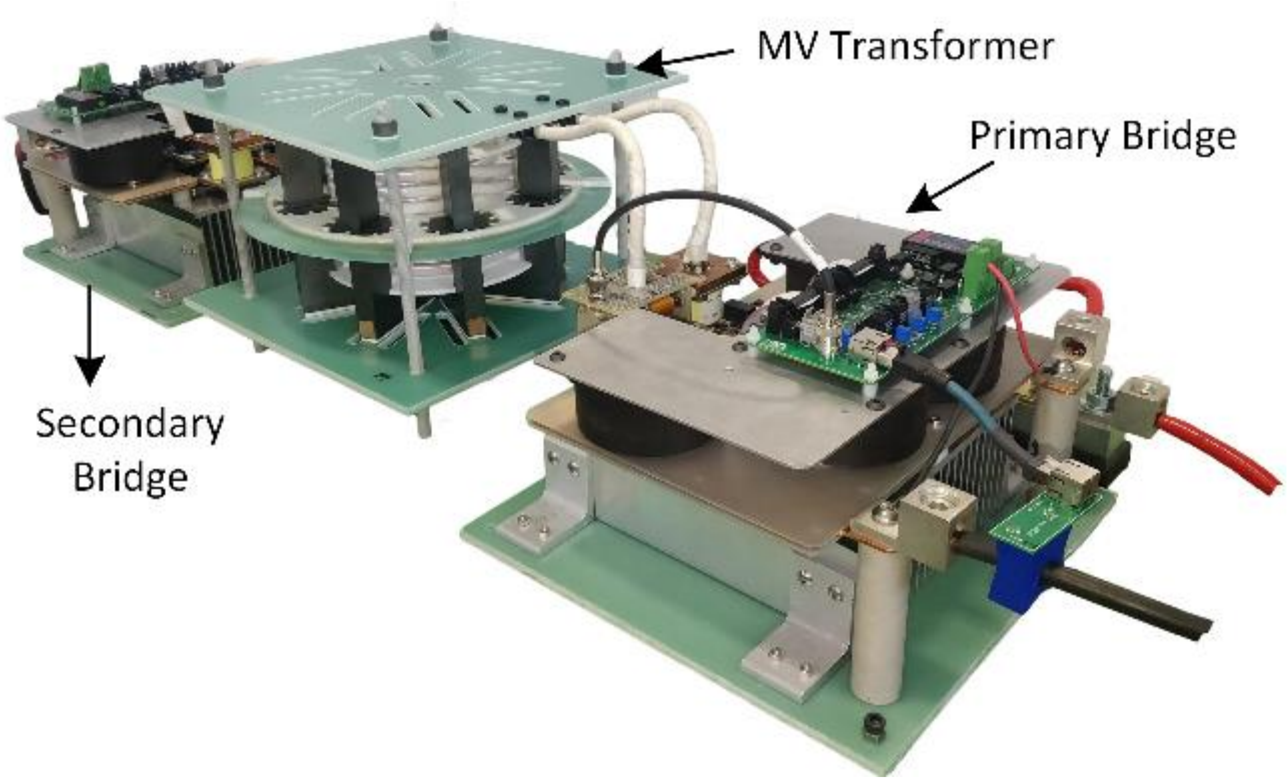

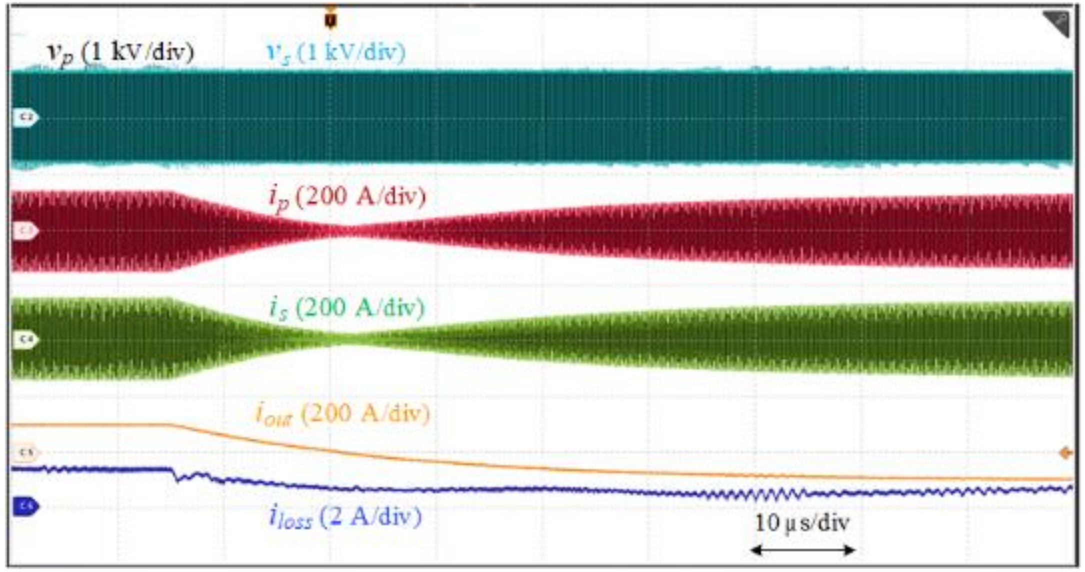

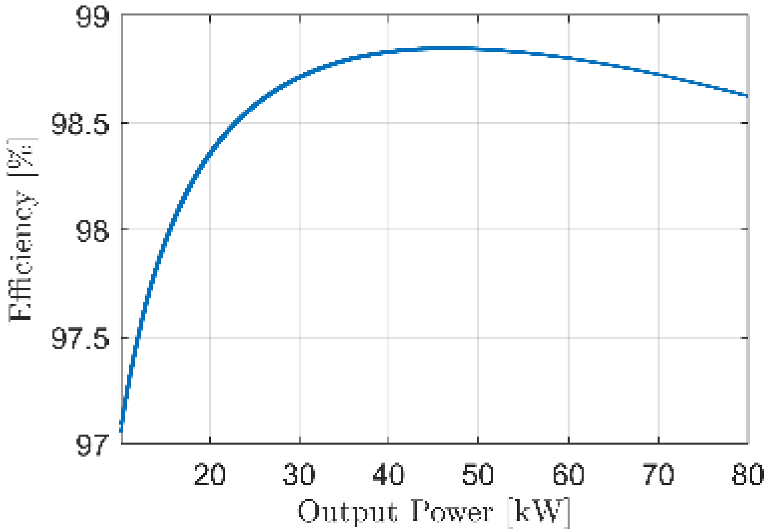

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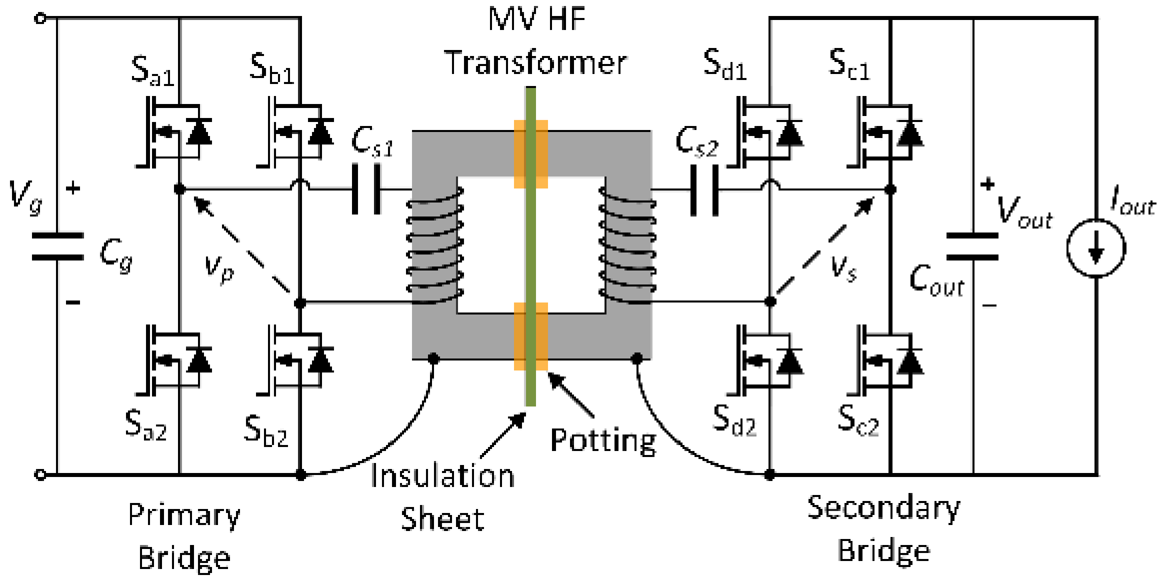
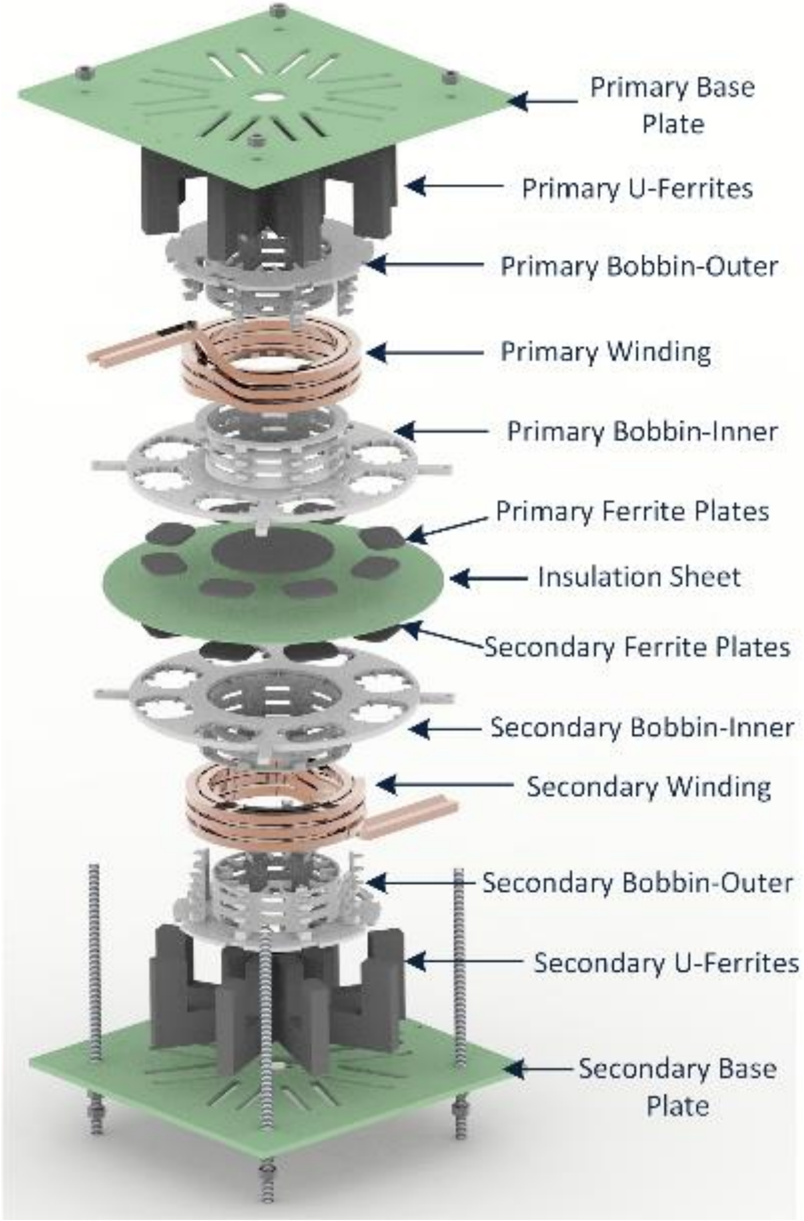
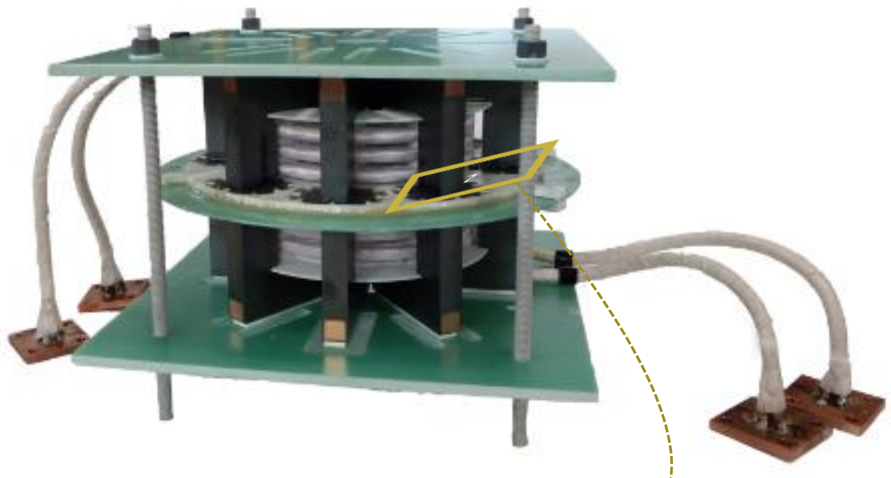


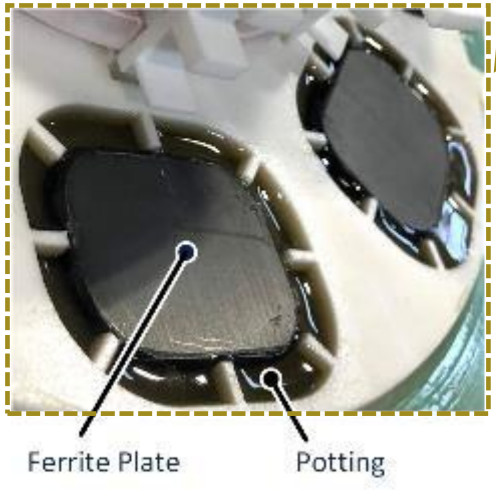


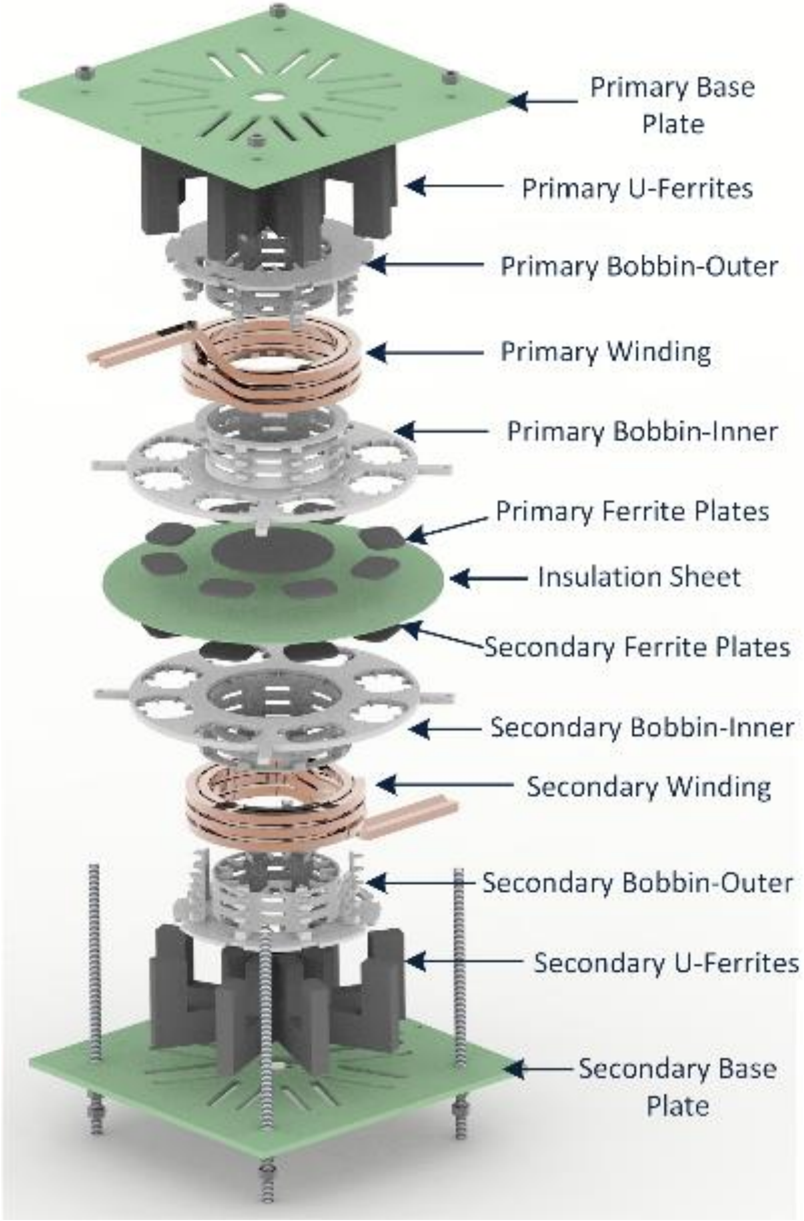
Insulation Concept: High Electric Field Regions

Managing and reducing concentrated electric field stress:

- Ferrite Grinding
- Vacuum Potting







Insulation Concept: High Electric Field Regions

Managing concentrated electric field stress:

- **Ferrite Grinding**
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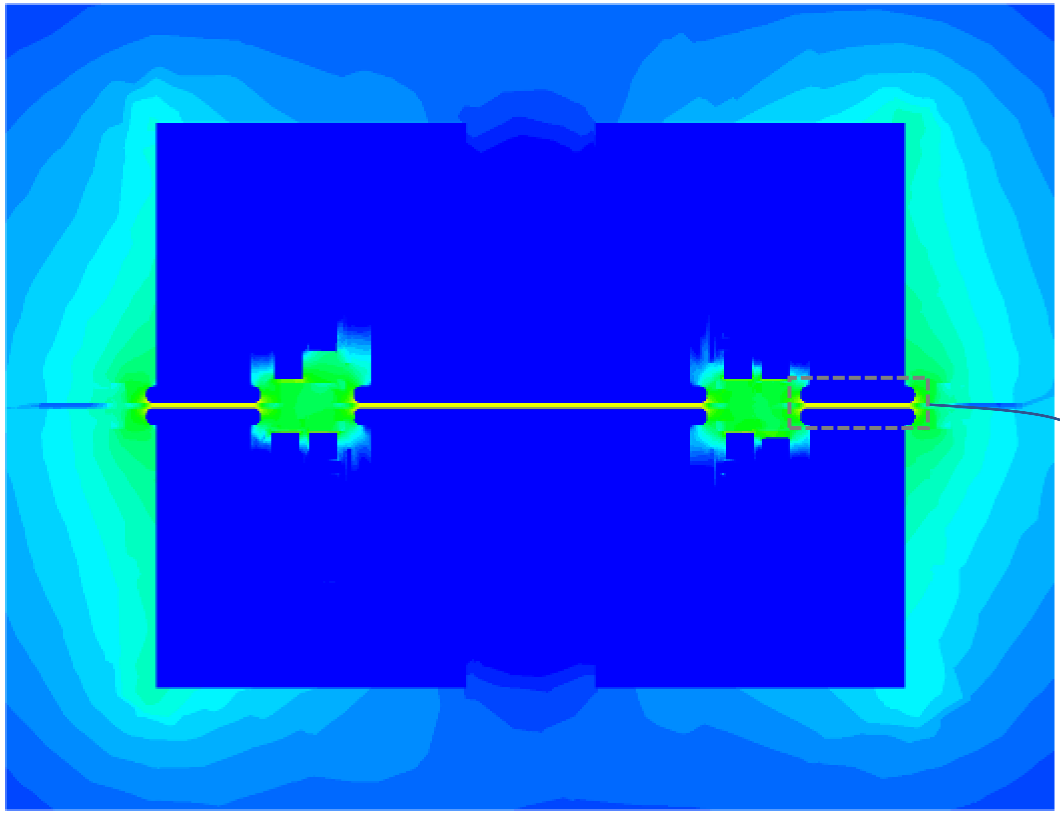
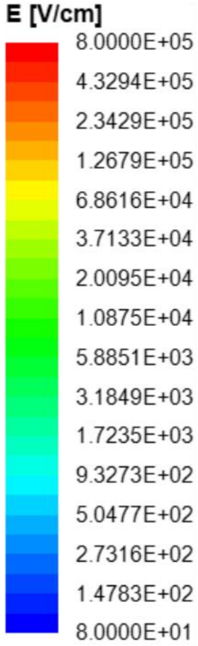
Electric Field Distribution Under 10 kV Voltage
Stress Between Two Halves of the Transformer



Before Ferrite Grinding

After Ferrite Grinding



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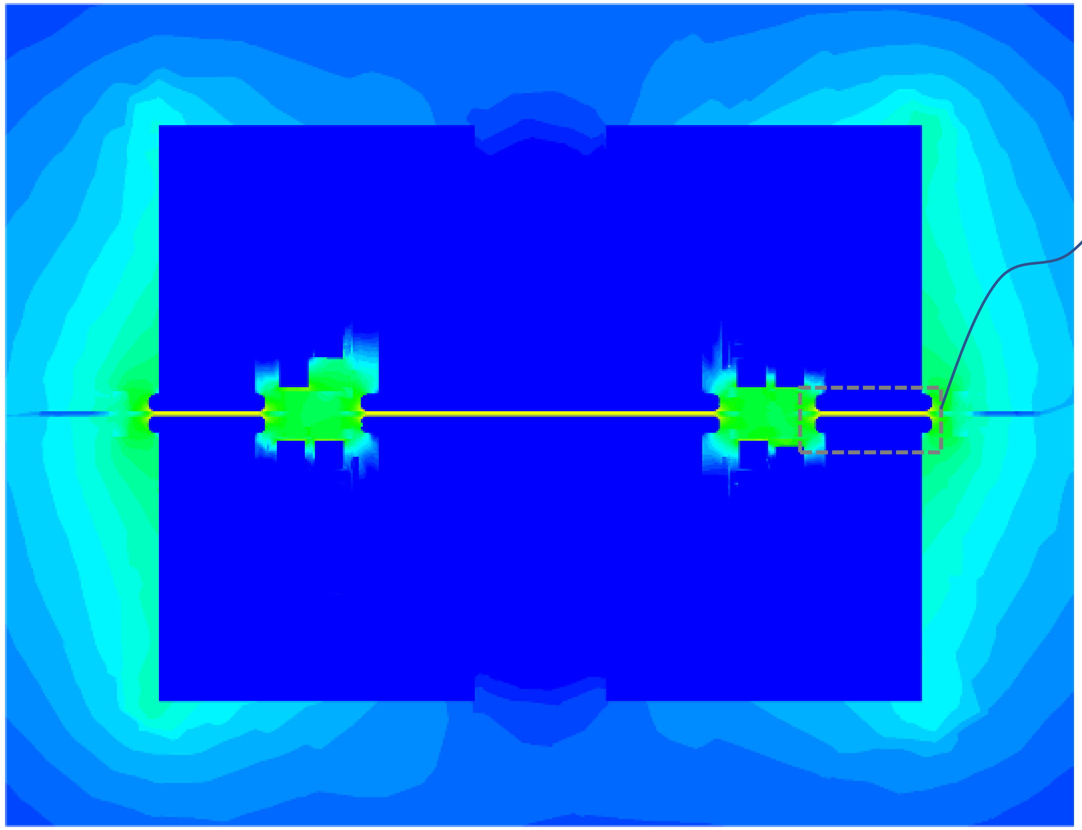
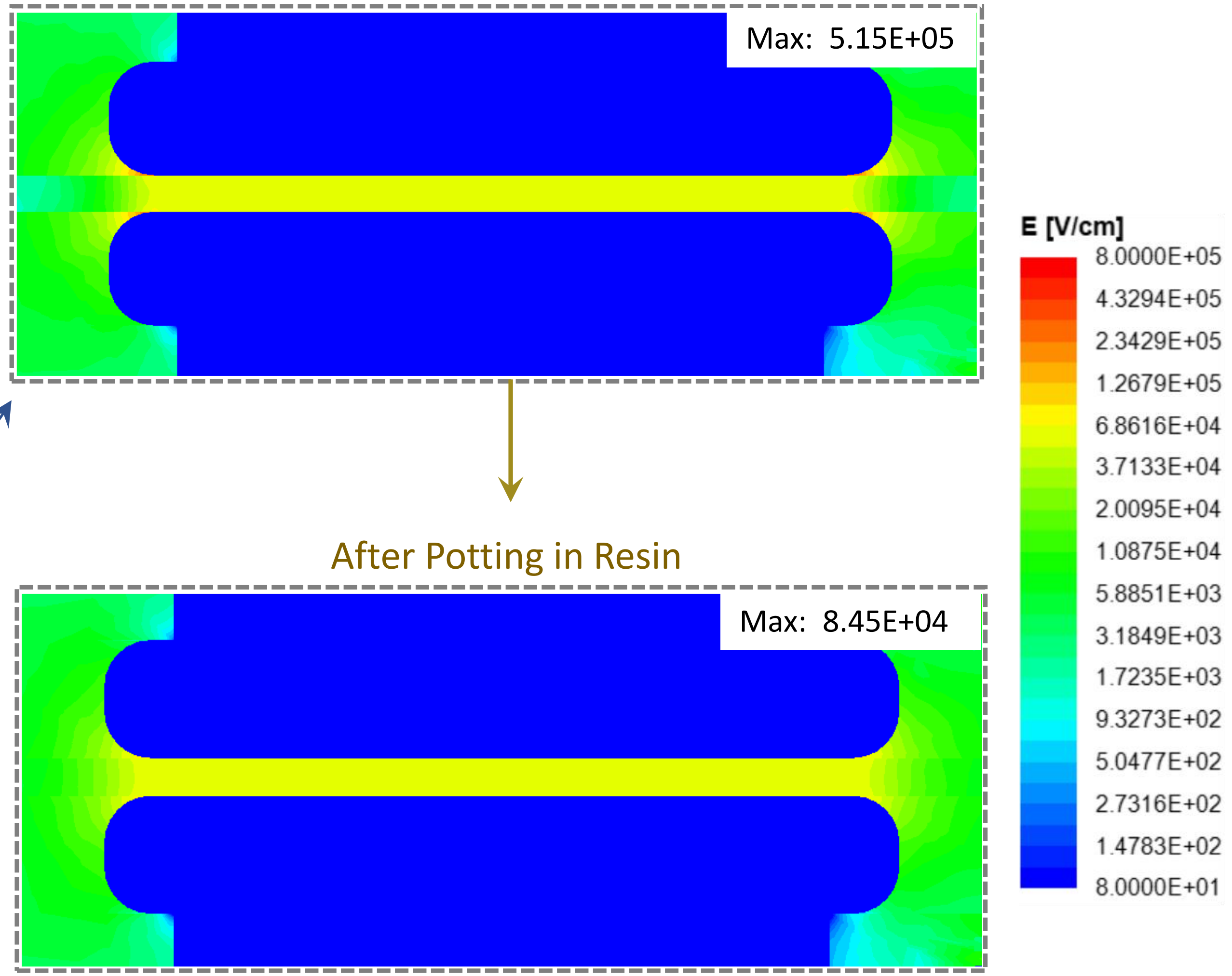


Before Potting in Resin

After Potting in Resin



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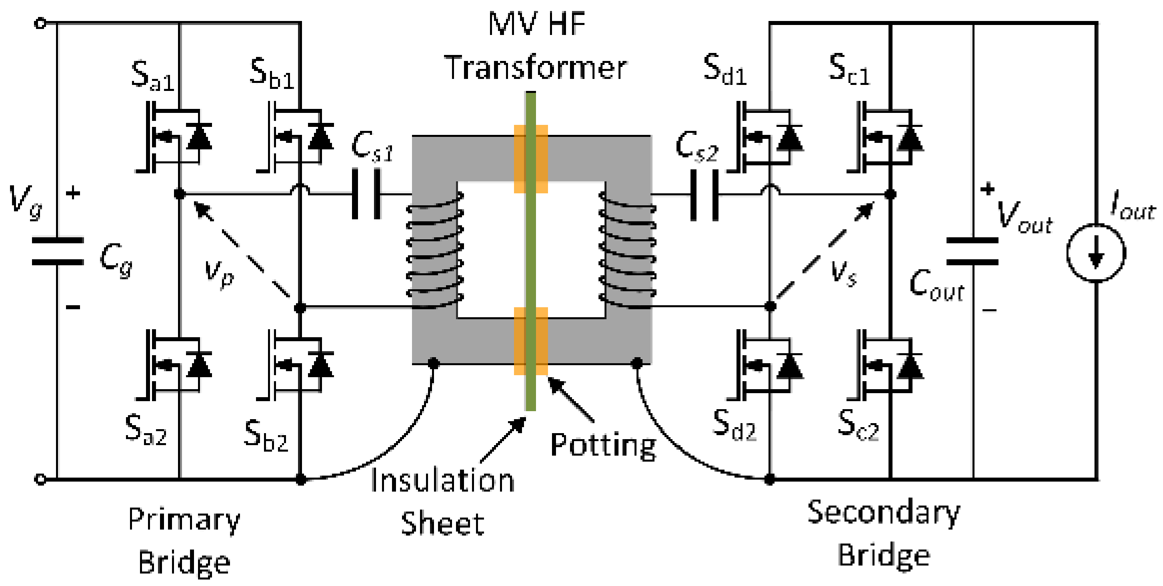
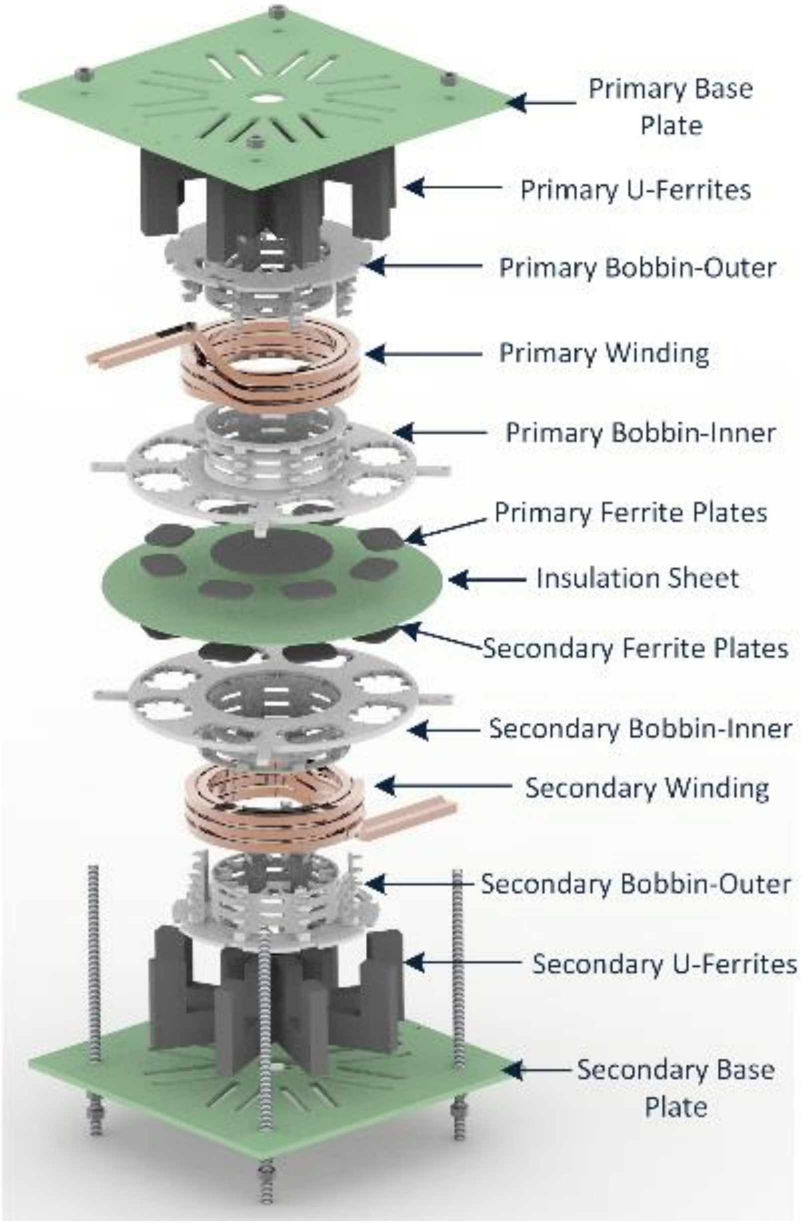




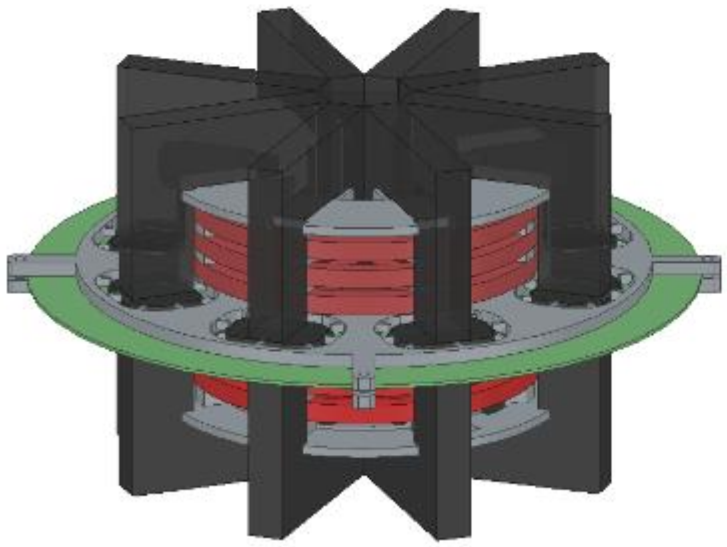
Insulation Concept: Thermal Management

Loss Estimation and Thermal Management:

- **Proper tradeoff between copper and core loss**
- Air cooling-based design
- High current litz wire termination

- Total Transformer Loss at 80 kW: 268 W (25 % of total loss)
  Core: 162.8 W - Copper: 105.2 W
- 99.7 % estimated efficiency for transformer operating at 91.2 kVA stress for 80 kW load

ANSYS Maxwell Model



Insulation Concept: Thermal Management

Thermal Management:

- Proper tradeoff between copper and core loss
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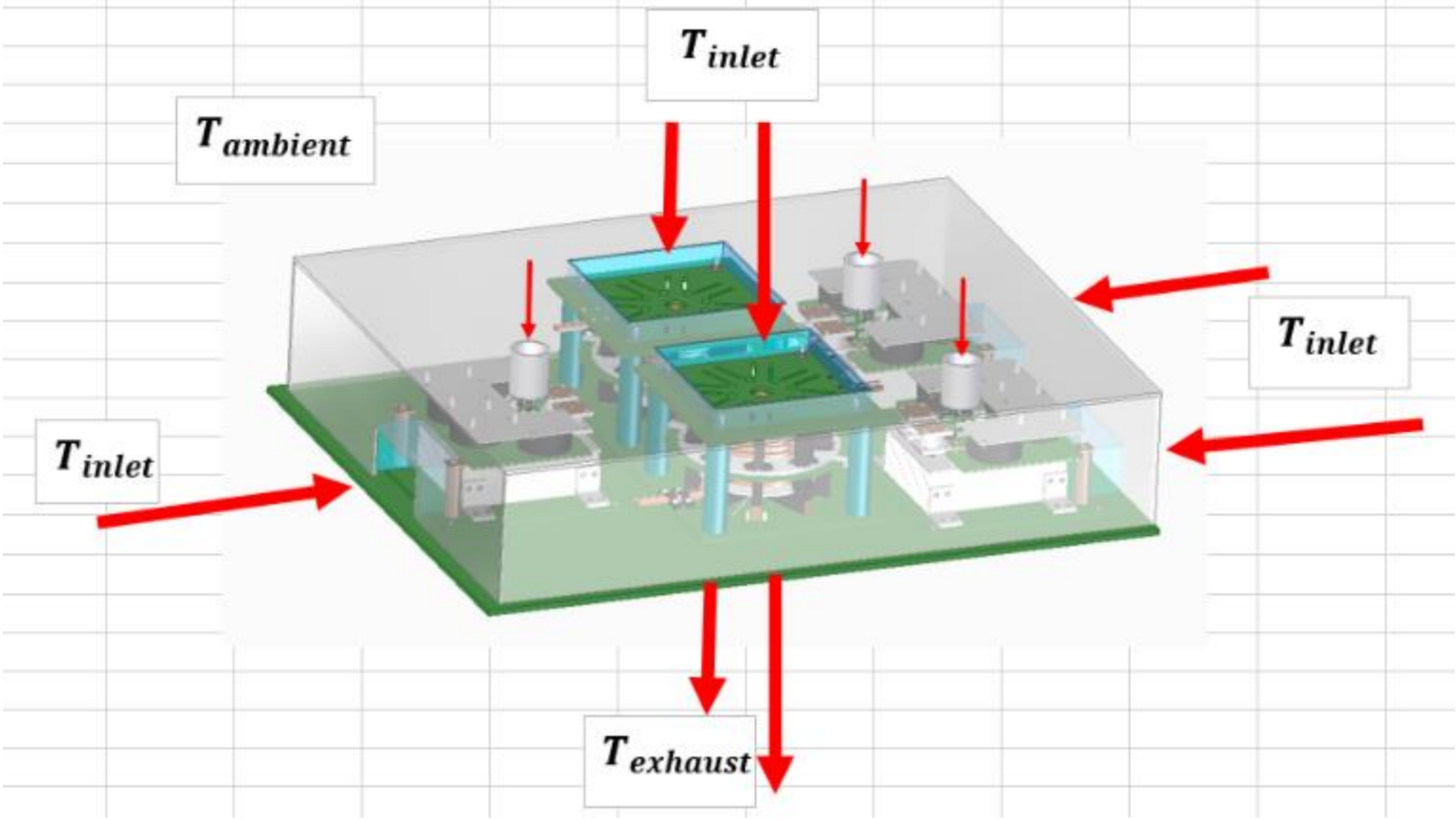

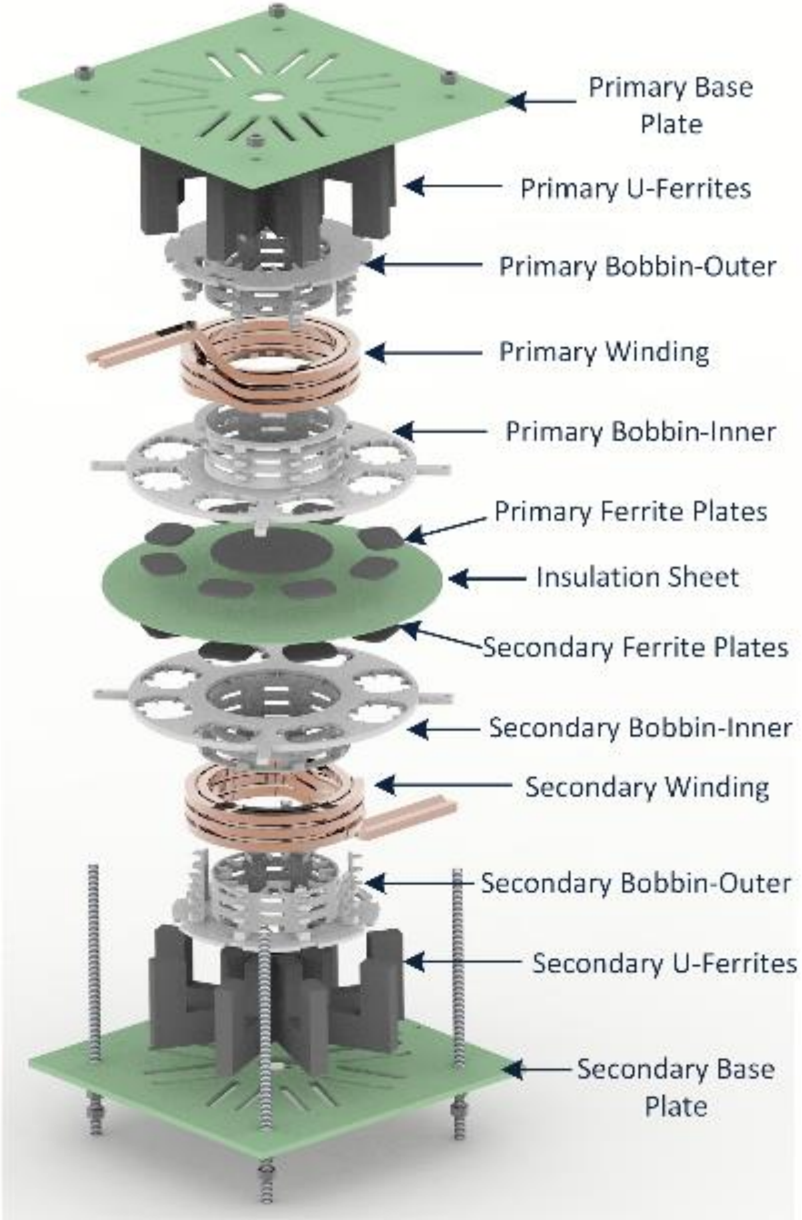

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Thermal Management:

- Air cooling-based design
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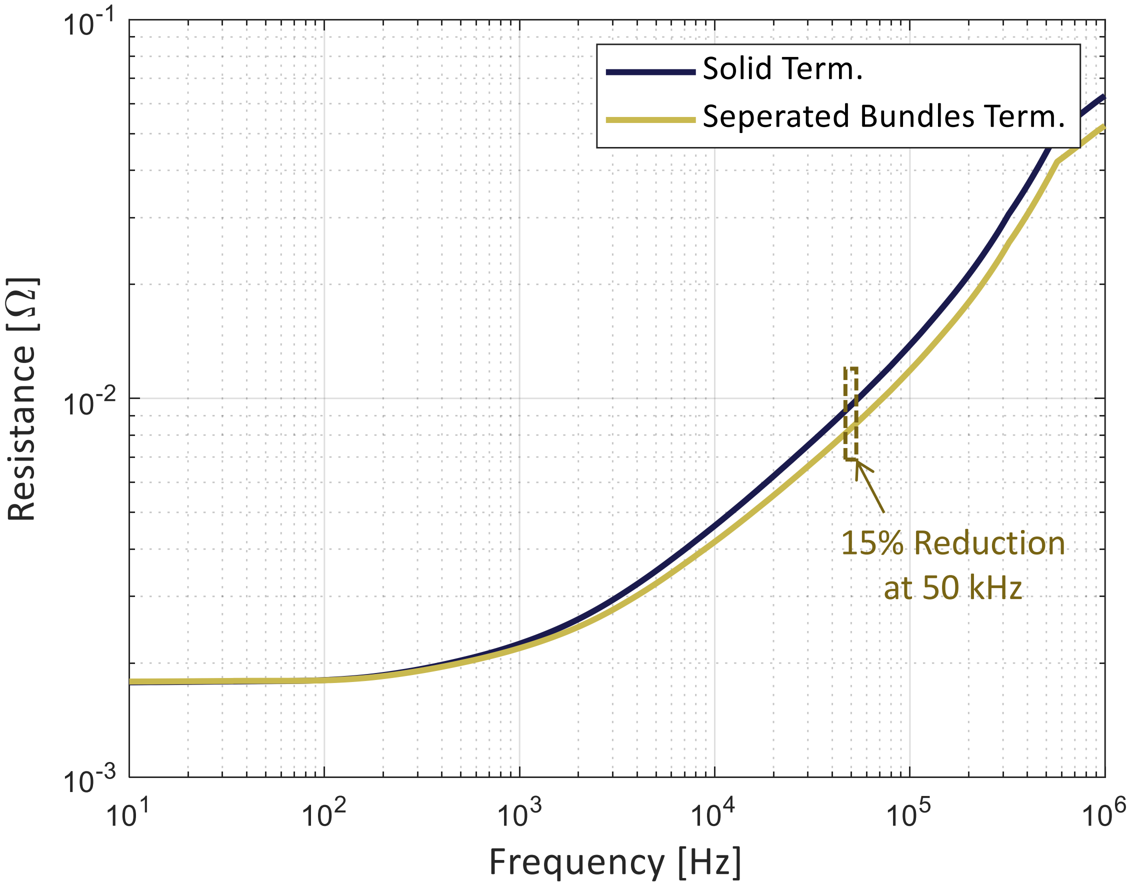
- **High current litz wire termination**

LCR Measurements of a Single Loop

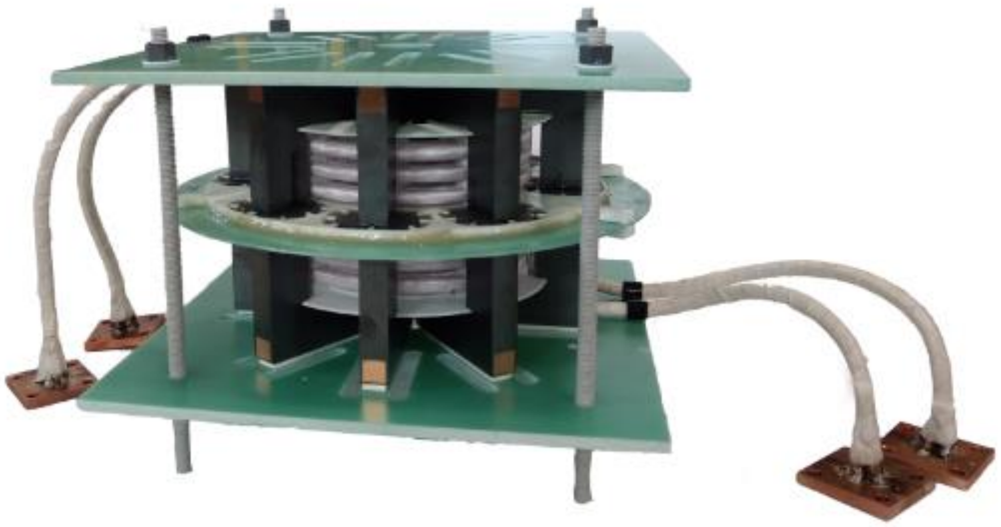


Litz Wire: 9750 Strands of 42 AWG Wire – Length: 9.5 ft

- A. Roßkopf, E. Bär and C. Joffe, "Influence of Inner Skin- and Proximity Effects on Conduction in Litz Wires," in IEEE Transactions on Power Electronics, vol. 29, no. 10, pp. 5454-5461, Oct. 2014.
- D. Barth, T. Leibfried and G. Cortese, "Analytical calculation of the frequency-dependent litz wire resistance considering the wire connectors," 2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe), Genova, Italy, 2019, pp. P.1-P.10, doi: 10.23919/EPE.2019.8915419.

Transformer Fabrication Details

Fabricated Transformer



Key Details:

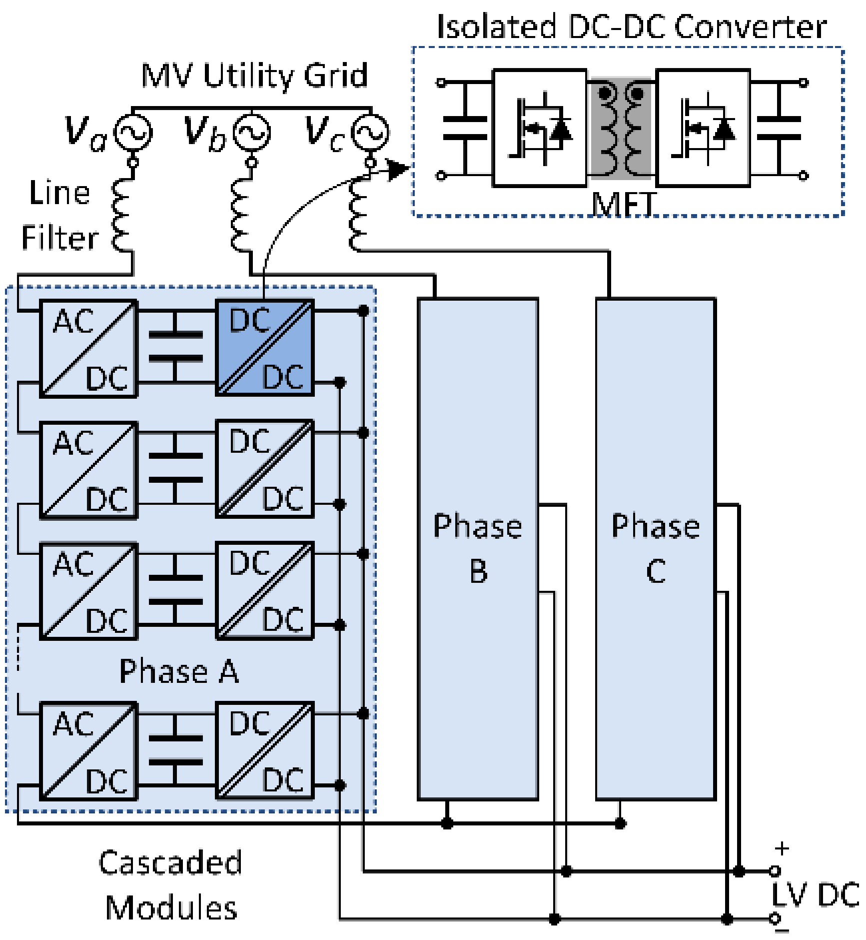
- 12 kV dielectric withstand capability
- 90 mm creepage and 50 mm clearance
- Dimensions W*L*H: 12” X 12” X 12”
  - Height is only 7.2” from primary base-plate to secondary base-plate
  - Height is 12” with the fiber rods used for mounting to converter base-plate
- Weight: 12.56 Kg

Materials Summary

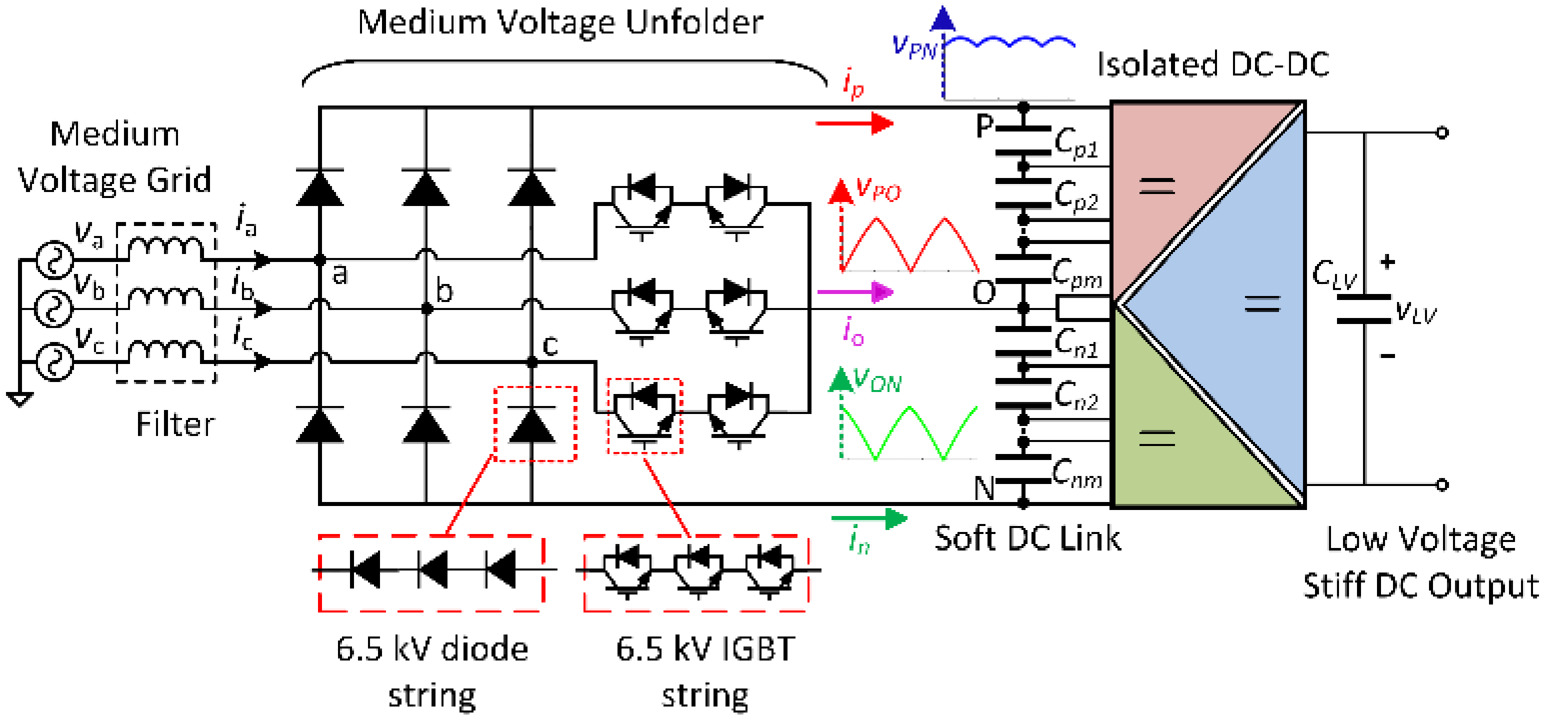
Ferrite U-core	U93/76/16 size, 3C94 material.
Ferrite plates	Custom shape fabricated using PLT64/50/5 plates, 3C94 material
Wire	9750 strands of 42 AWG, single nylon serve. Formed to square-profile.
Insulation disk	FR-4.0/21 material, 1.6 mm thick, electric strength: 40 kV minimum dielectric constant: 5.20
Potting	3M™ Scotchcast™ Electrical Resin 280 material electric strength: 14.8 kV/mm at 3.175 mm thickness dielectric constant: 3.50
Bobbin	3D printed in Nylon material

Application: Unfolding-based DC SST

Two-Stage Approach



Quasi Single-Stage Approach



Potential Benefits:

→ Higher power density by eliminating LF filtering

→ Higher efficiency by eliminating a hard-switched front-end

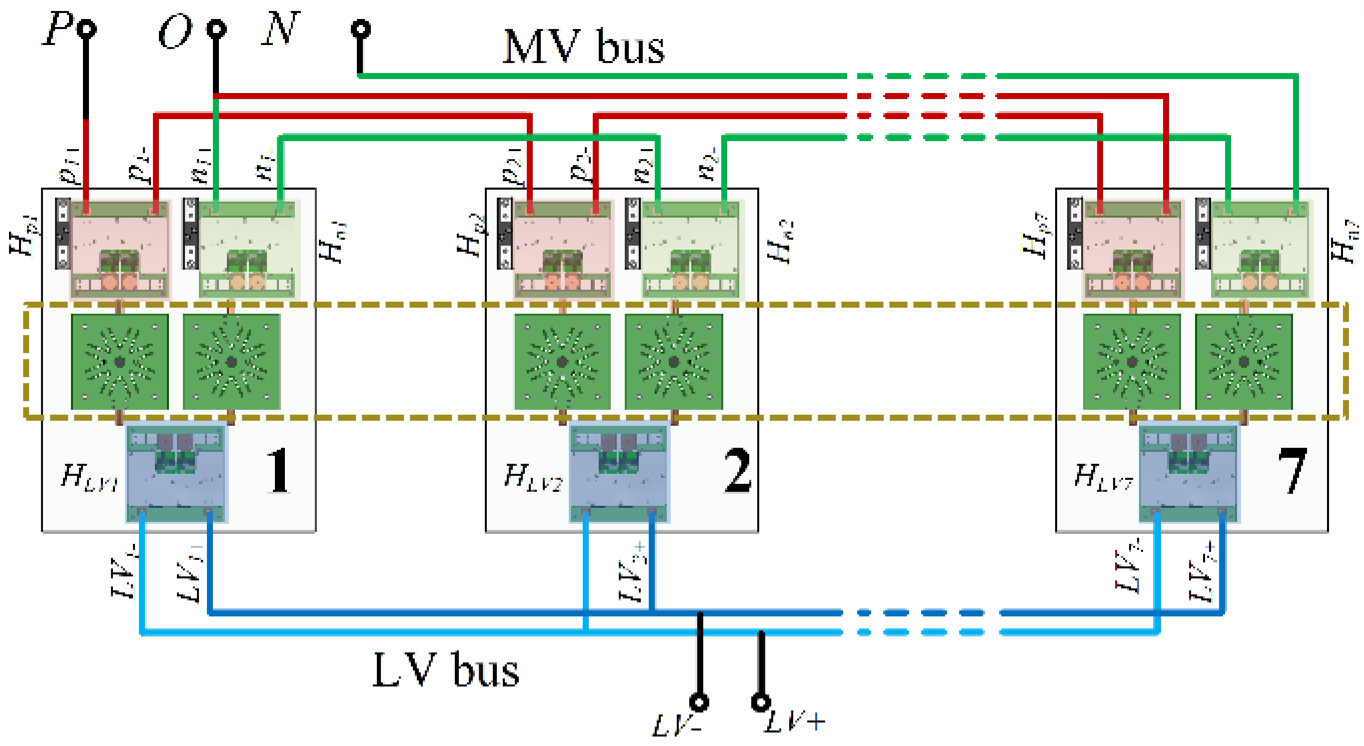
→ More constant power processing

Challenges:

→ Requires new and advanced modulation and control techniques [7,8]

Application: Unfolding-based DC SST

- 4.16 kV three-phase input, 560 kW, 750 V – 900 V DC output
- Soft dc-link front-end with 6.5 kV IGBT implementation
- Seven DC-DC series stacked modules (80 kW each)
- Each module is an isolated three-port converter



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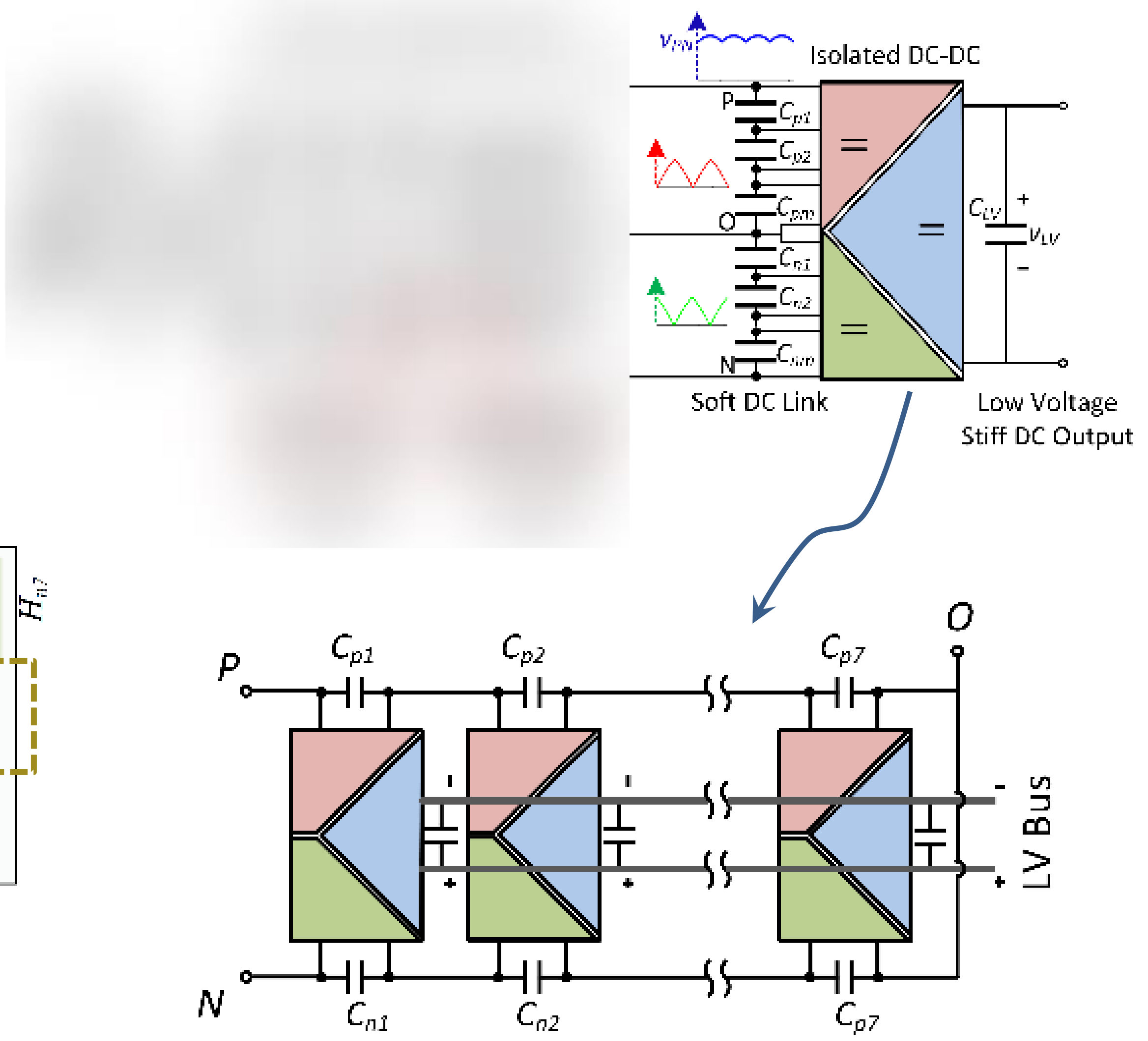
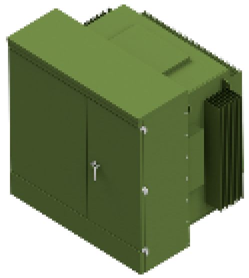


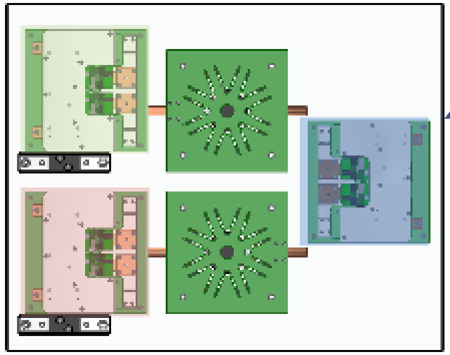
Application: Unfolding-based DC SST

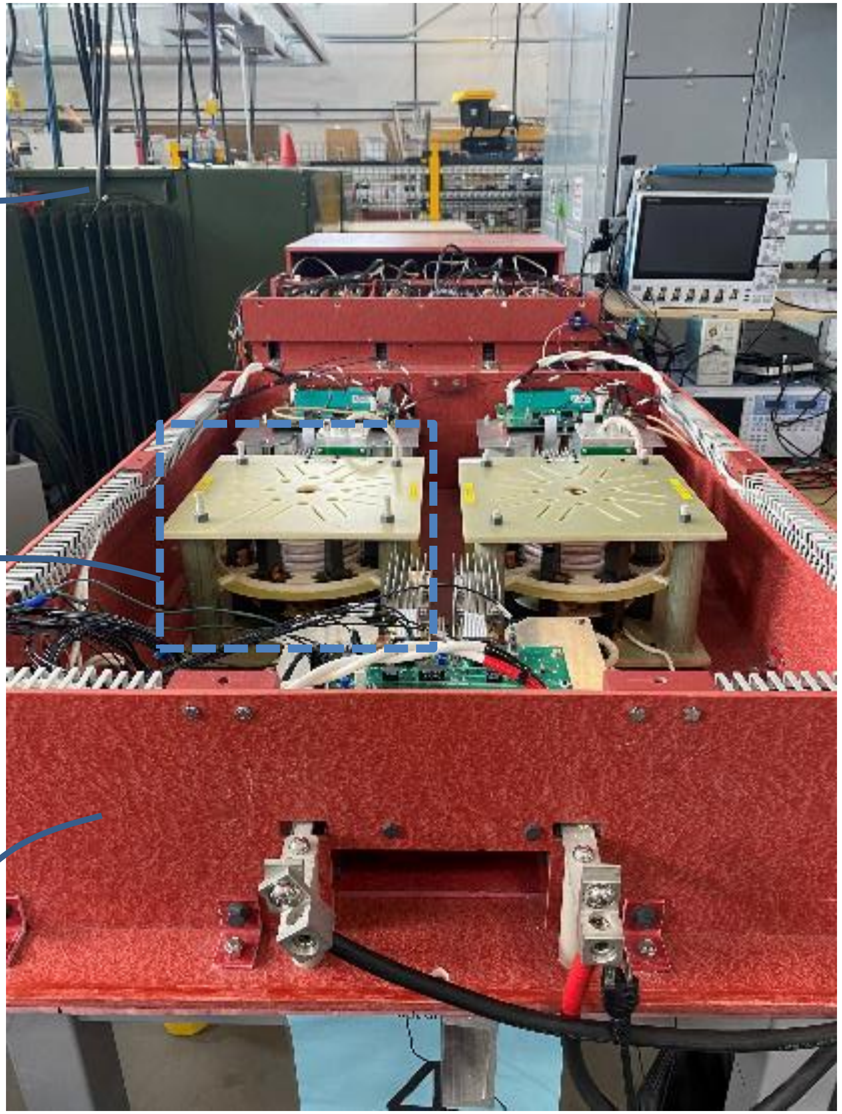
Step-up LF Transformer for In-lab Testing



Fabricated MV/MF Transformer

TABSRC 80 kW Module





External Setup for the MV Unfolder and a Three-port 80 kW DC-DC

The full components for the 560 kW unfolding-based SST

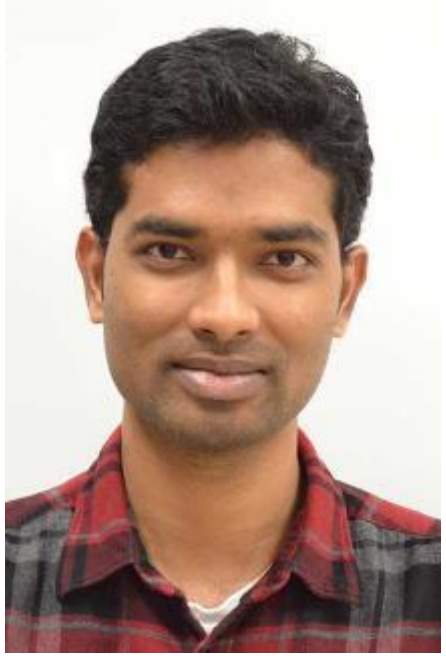
The Research Team

Regan Zane

Director
ASPIRE NSF ERC

Bryce Hesterman

Principal Research Engineer
ASPIRE NSF ERC



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ASPIRE NSF ERC

This material is based upon work supported by the Department of Energy (DOE)
Award Number: DE-EE0008360 – Partners: WAVE and Schneider Electric

Summary

- MV AC to LV DC Solid-State Transformer applications and design challenges
- A simple and cost-effective insulation approach
- Design considerations for the proposed MV/MF transformer
- Experimental results of an 80 kW CLLLC Dual Active Bridge converter
- 99.7% is the estimated transformer efficiency at full load
- Practical consideration for transformer design and fabrication

Thank you!

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References

- [1] L. Heinemann, “An actively cooled high power, high frequency transformer with high insulation capability,” in APEC 2002.
- [2] B. Chen, X. Liang, and N. Wan, “Design methodology for inductor integrated litz-wired high-power medium-frequency transformer with the nanocrystalline core material for isolated dc-link stage of solid-state transformer,” IEEE Transactions on Power Electronics, 2020.
- [3] C. Zhao, D. Dujic, A. Mester, J. K. Steinke, M. Weiss, S. Lewdeni-Schmid, T. Chaudhuri, and P. Stefanutti, “Power electronic traction transformer—medium voltage prototype,” IEEE Transactions on Industrial Electronics, 2014.
- **[4] D. B. Yelaverthi, B. Hesterman, M. Mansour, and R. Zane, "CLLLC Dual Active Bridge with Novel Insulation Approach for SST Applications," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC).**
- **[5] D. Yelaverthi, “Three-Phase Unfolding Based Soft DC-Link Converter Topologies for AC to DC Applications“, All Graduate Theses and Dissertations, May 2021.**
- **[6] Bryce Hesterman, D. Yelaverthi, “Insulation Concept for Medium Voltage Transformer”, patent filed, Aug. 2020.**
- [7] M. Mansour, D. B. Yelaverthi and R. Zane, "Voltage Balancing Control for Input-Series-Output-Parallel Three-Port Series Resonant Converter Modules," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC).
- [8] M. Mansour, "Control Development for a Medium-Voltage Three-Phase Unfolding Input-Series-Output-Parallel AC-DC Converter" (2022). All Graduate Theses and Dissertations. 8475.