

HIGH-FREQUENCY, HIGH-VOLTAGE, AND HIGH-INSULATION MAGNETICS FOR MODULAR ENERGY STORAGE SYSTEMS

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Motivation, Objectives and Impact

Modular power electronics topologies for grid-connected battery energy storage systems (BESS) allow each battery to connect to a dedicated DC-DC converter, accommodating varying characteristics, voltages, capacities, and health states (see Fig. 1). This flexible approach enables series connection of DC-DC converter outputs to achieve higher DC link voltages, eliminating the need for large, costly line-frequency transformers (LFTs) for medium-voltage (MV) grid connections.

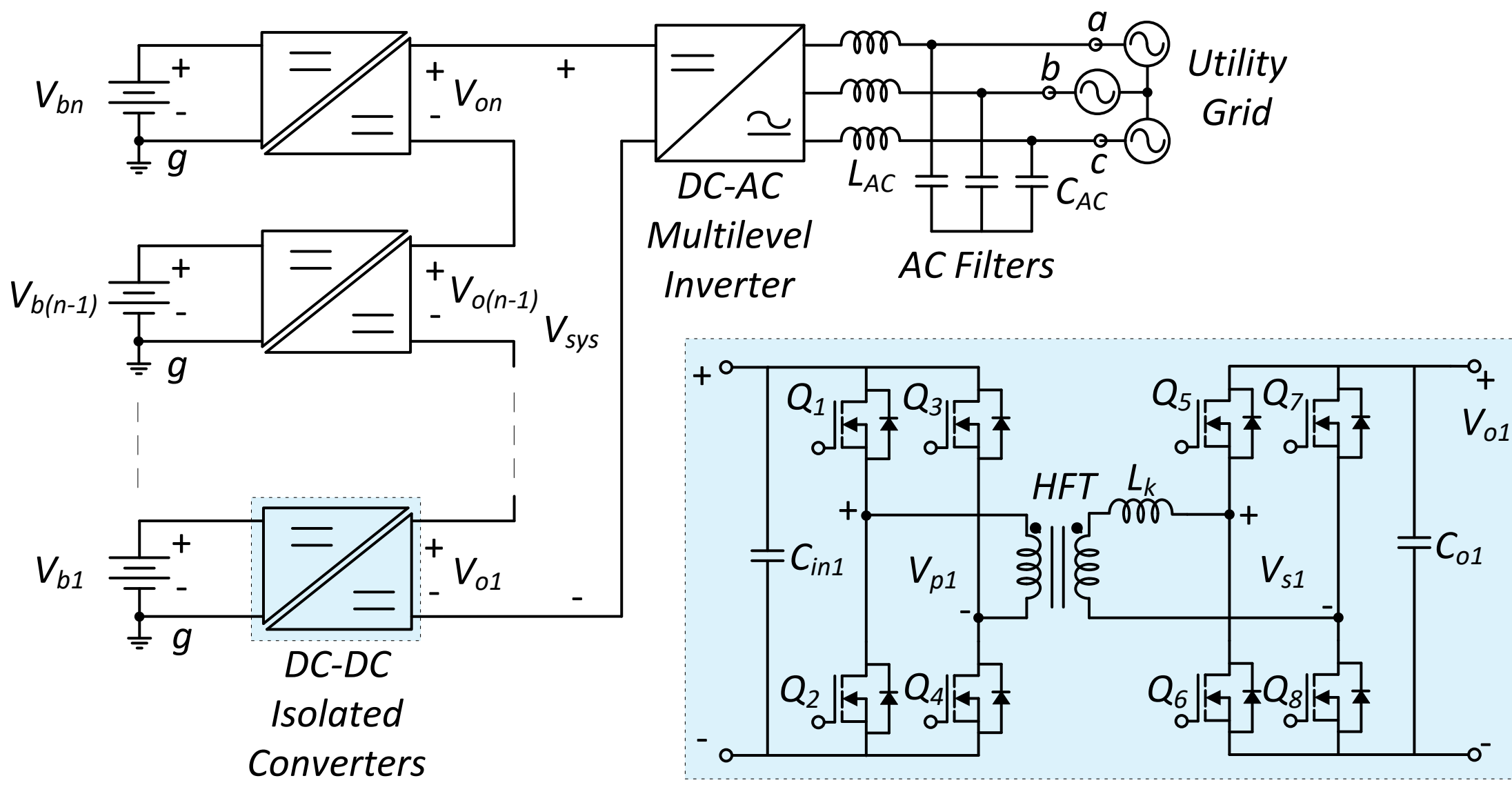


Figure 1. Cascaded DC-DC structure interfacing individual batteries with the medium-voltage (MV) grid. Isolated DC-DC converters are implemented using the dual active bridge (DAB) topology.

Table I. System Specifications	
System Configuration	Indep. In. Out.-Series
DC Link Voltage V_{SYS}	10kV - 12kV
Number of Converters	6
Converter Topology	Dual Active Bridge
Converter Output Voltage V_o	1.5kV - 2kV
Battery Voltage	800V
Converter Switching Freq.	40kHz - 60kHz
System Power Capacity	150kW
Converter Power Capacity	25kW

High-frequency transformers (HFTs) reduce volume and cost compared to LFTs, but their design for cascaded topologies presents challenges due to complex MV stress and electric field distributions across the windings. The smaller size of HFTs also complicates temperature management, requiring careful design considerations.

This project aims to understand the performance requirements for magnetic components in MV BESS. We will conduct electromagnetic field simulations that incorporate electrical excitation conditions, magnetic properties, and transformer geometries to identify designs that meet isolation requirements for modular storage.

Methodology

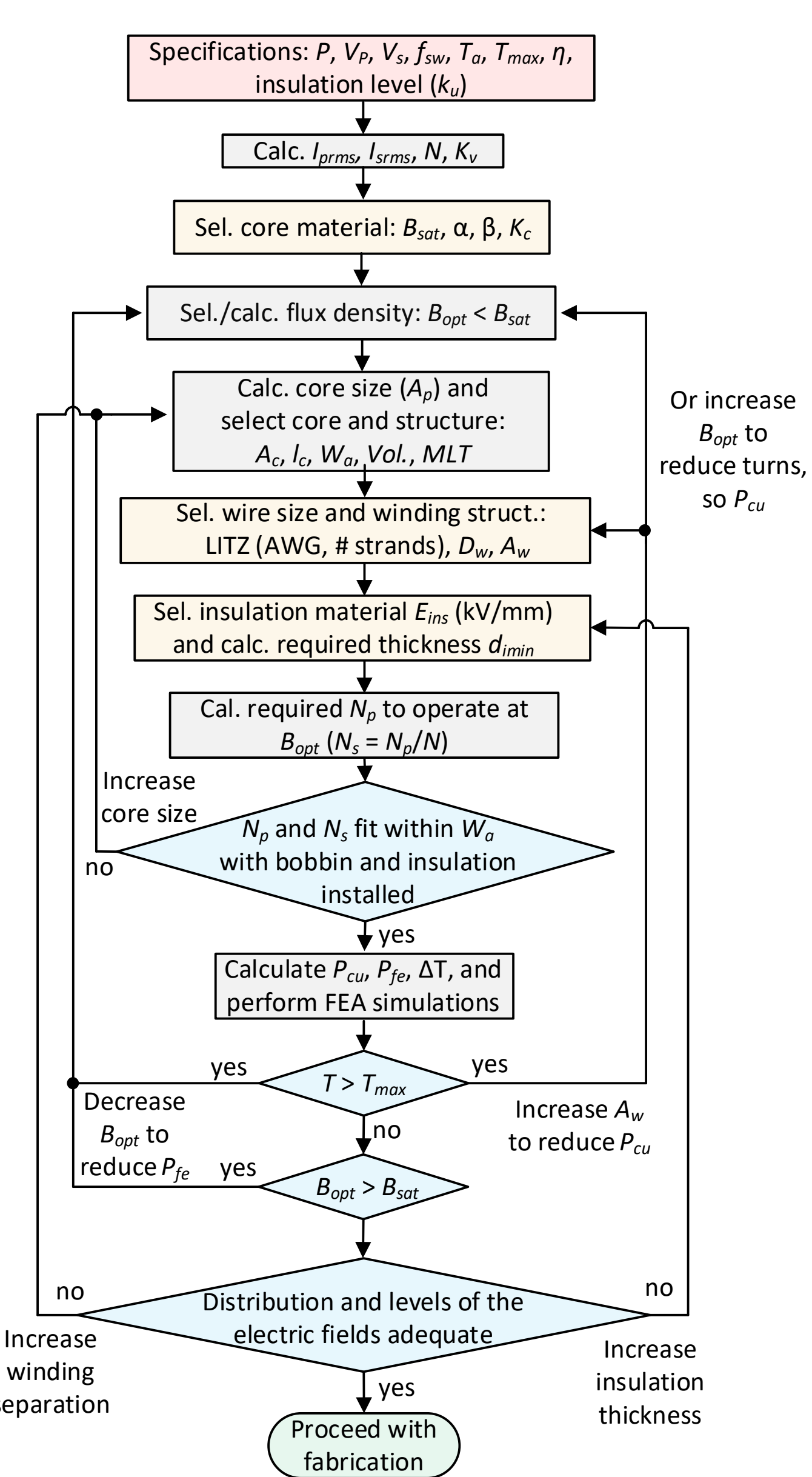


Table II. Transformer Specifications	
V_p	800 V
V_s	2 kV
P_{max}	25 kW
Switching frequency f_{sw}	50 kHz
$I_{p,RMS}$	36.12 A
$I_{s,RMS}$	14.47 A
Turns Ratio, N	2/5
Ambient Temp.	25 °C
Temperature Rise (after cooling)	75 °C
Primary wire 6AWG	38 AWG/1650
Secondary wire 10AWG	40 AWG/1200
Primary current density	270 A/cm ²
Secondary current density	247 A/cm ²
Core Material	Nanocrystalline
Core Model	F1AH0803
Minimum working insulation level	12 kV

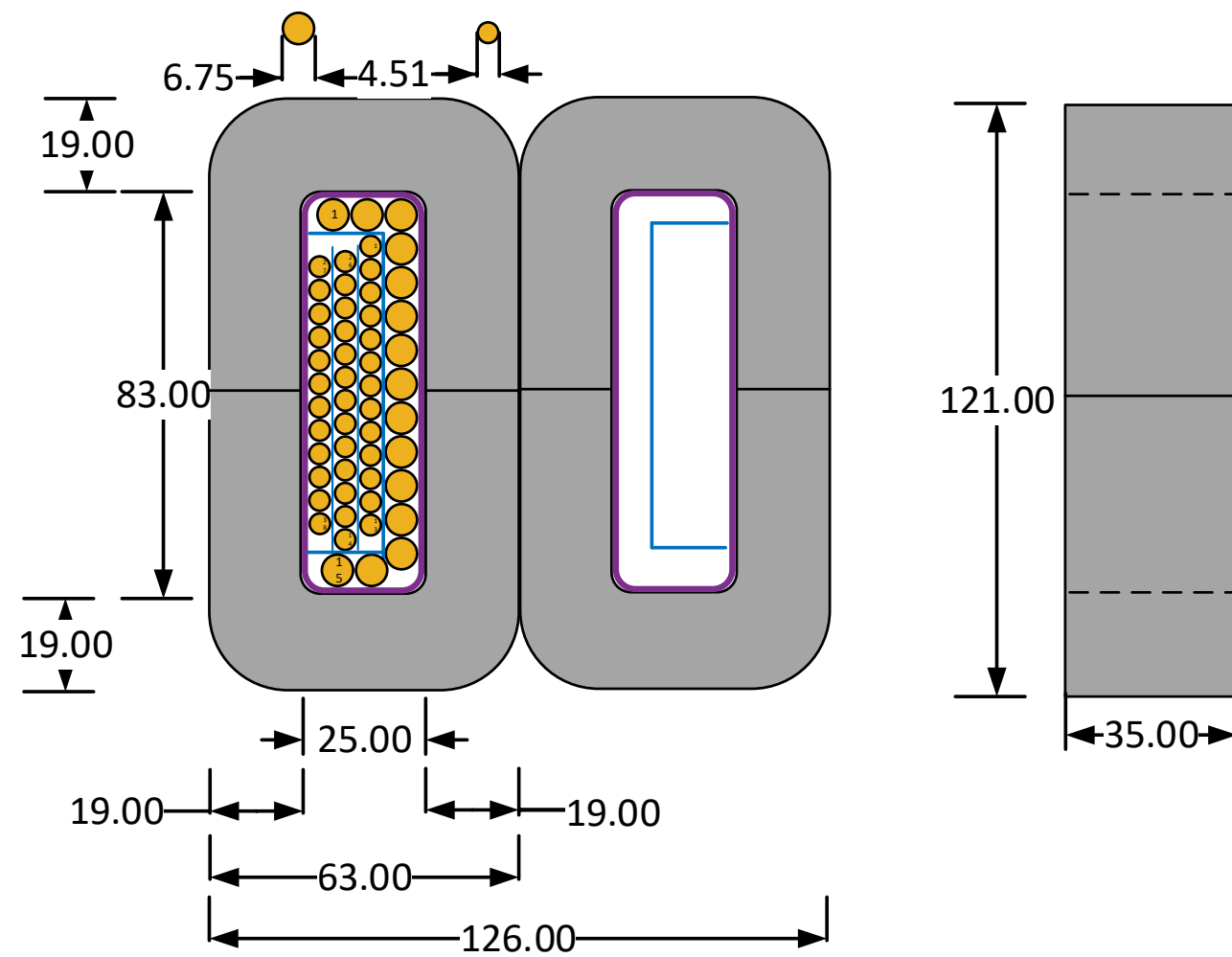


Figure 3. Transformer proposed shelf-type structure with units given in mm.

Constructed Prototype



Figure 6. Baseline prototype with maximization window area utilization for reduced material utilization and cost.

Prototype Development and Simulations

- The bobbin is constructed from Acrylonitrile Styrene Acrylate (ASA), offering a dielectric strength (E_{ins}) of up to 35 kV/mm, depending on the operating frequency.
- The primary winding ($N_p = 15$) is positioned close to the core to minimize insulation requirements.
- An ASA winding insulator is used to separate the primary and secondary windings, with additional reinforcement at the joints provided by Nomex paper ($E_{ins} = 33$ kV/mm).
- Once the secondary winding ($N_s = 38$) is completed, it is covered by Nomex paper to insulate it from the core.

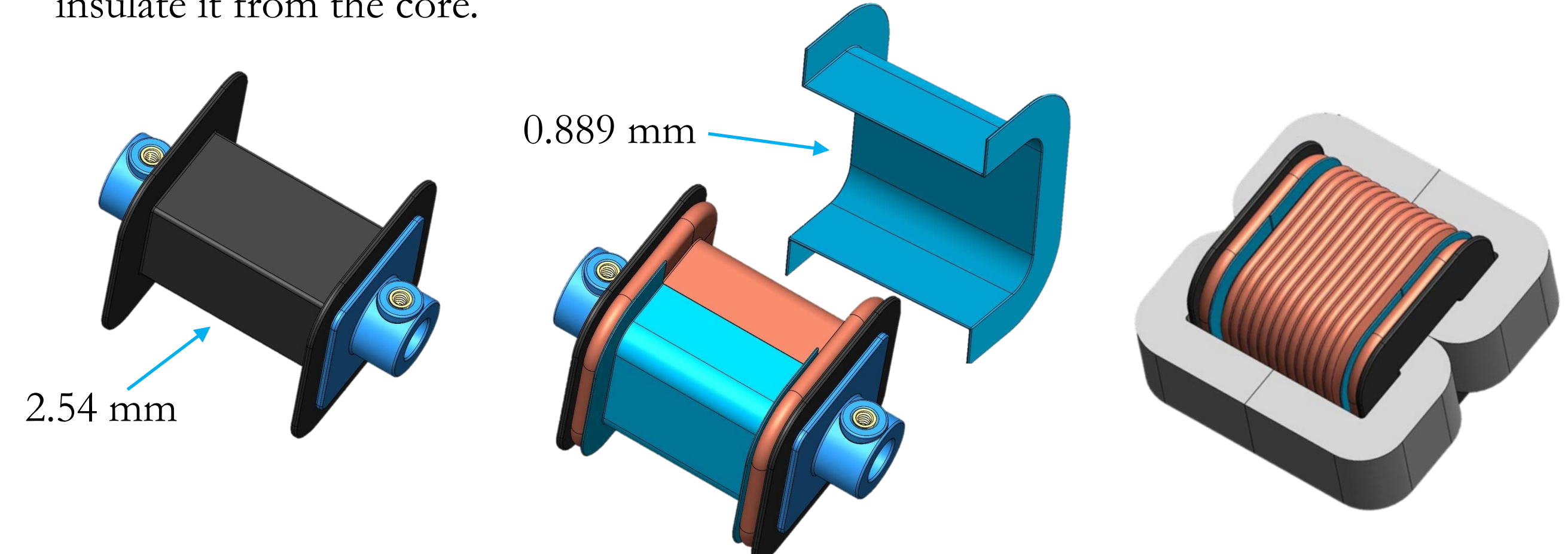


Figure 4. Transformer assembly featuring a bobbin that provides structural support and insulation.

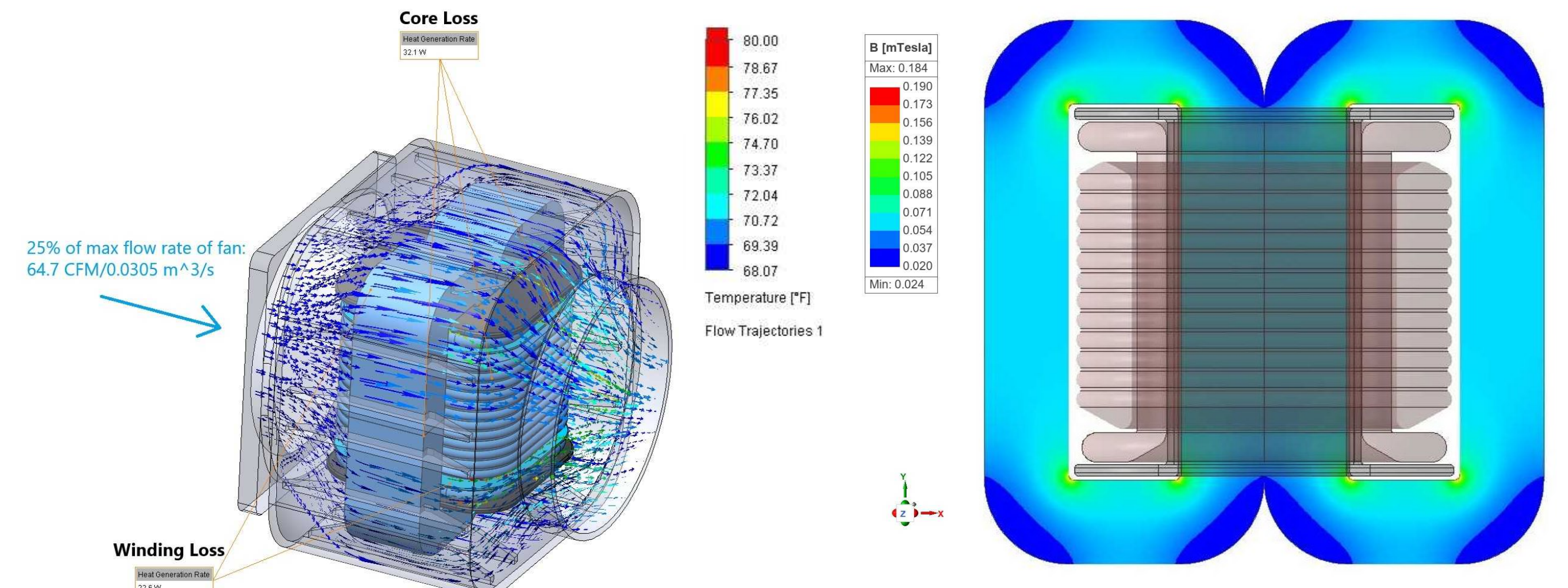


Figure 5. Left: Simulated thermal performance with a fan, showing core losses of 32.1 W and winding losses of 22.6 W. Right: Magnetostatic simulation illustrating the core flux density within the desired range for optimal performance.

Current and Future Work

- The constructed prototype will be characterized and evaluated at rated conditions.
- Thermal, conversion and insulation performance will be evaluated and simulation models will be updated to match experimental results.
- Additionally, we will investigate the relationship between isolation levels and power conversion performance, which may limit scalability in modular power conversion architectures.