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Co-Optimization of Boost Converter Reliability and Volumetric Power Density Using Genetic Algorithm

Lee Gill†, Jason C. Neely, Lee J. Rashkin, Jack D. Flicker, and Robert J. Kaplar

Sandia National Laboratories

†lgill@sandia.gov

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Presentation Outline

- Background Information
  - Mean-Time-Between-Failure (MTBF)
- Multi-Objective Optimization Techniques
  - Genetic Algorithm (GA)
- Co-Optimization of Synchronous Boost Converer
  - Inductor design, capacitors, semiconductor switches, and heasink selections
- Pareto Optimial Solutions and Analysis
  - By cooling type, semiconductor material type, magnetic core types
- Experimental Results and Verification
  - Experimental vs. Simulation comparison
- Conclusion

Background Information on MTBF

- **Mean-Time-Between-Failure (MTBF)**
  - Metric to evaluate or estimate the expected lifetime of repairable items.
  - Defined as the probability of an individual unit of interest, operating with full functionality for a specific length of time under specific tests or stress conditions.
  - MTBF of power electronic systems requires understanding of interaction between components, especially uncertainties with the use of novel materials, causing dynamics in thermal and electrical stress on a system in automotive or aviation industry.

$$MTBF = \frac{\text{Total System Operational time}}{\text{Total Number of Failures}}$$

Can also be represented as

$$MTBF = \frac{1}{\lambda}$$

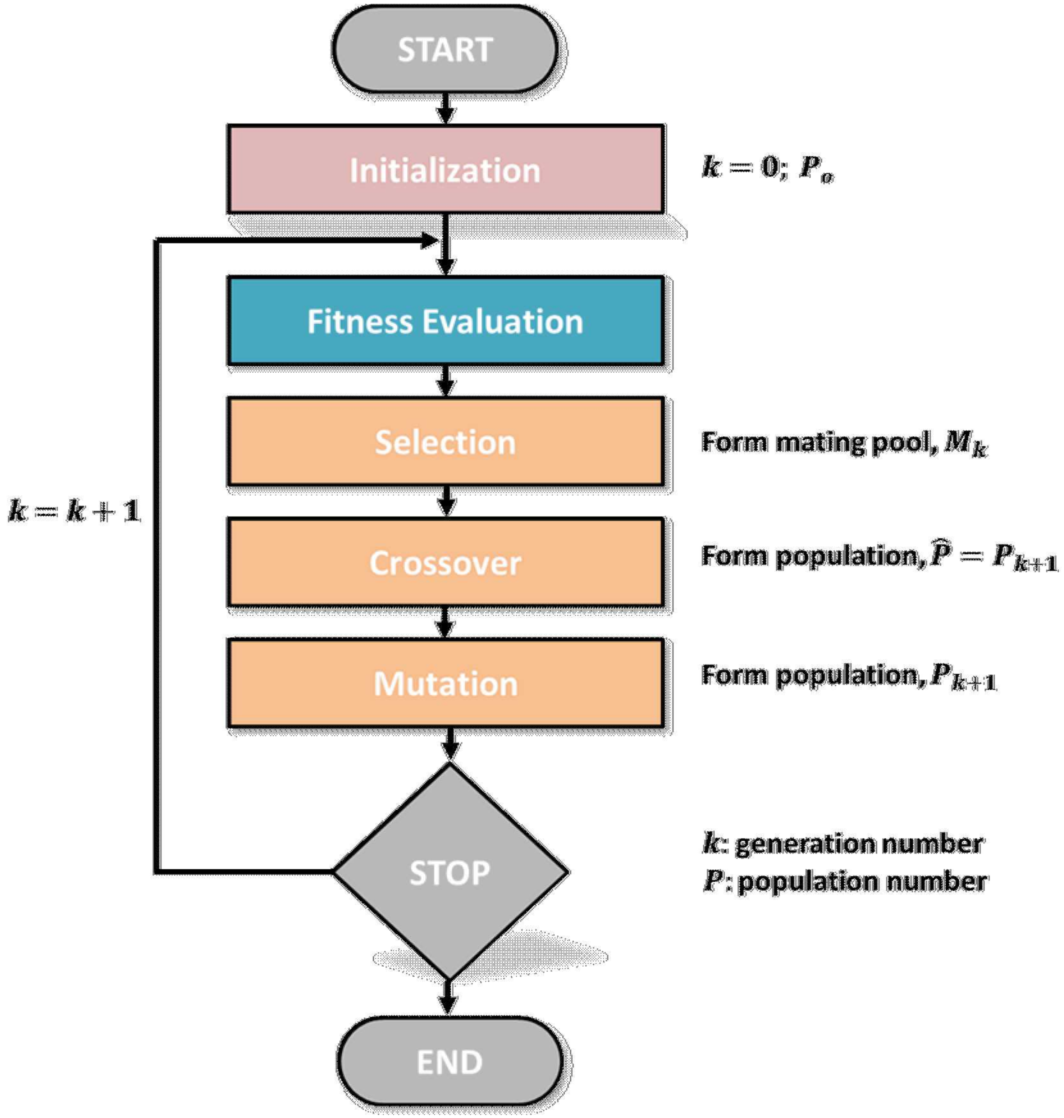
Where

λ: Intrinsic failure rate of a component

For a given system composed of n components,

$$\lambda = \sum_{i=1}^{n} \lambda_i$$

Genetic Algorithm (GA) Optimization Process



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- ***Initialization***

Initial solutions are randomly generated in the predefined representation rule.

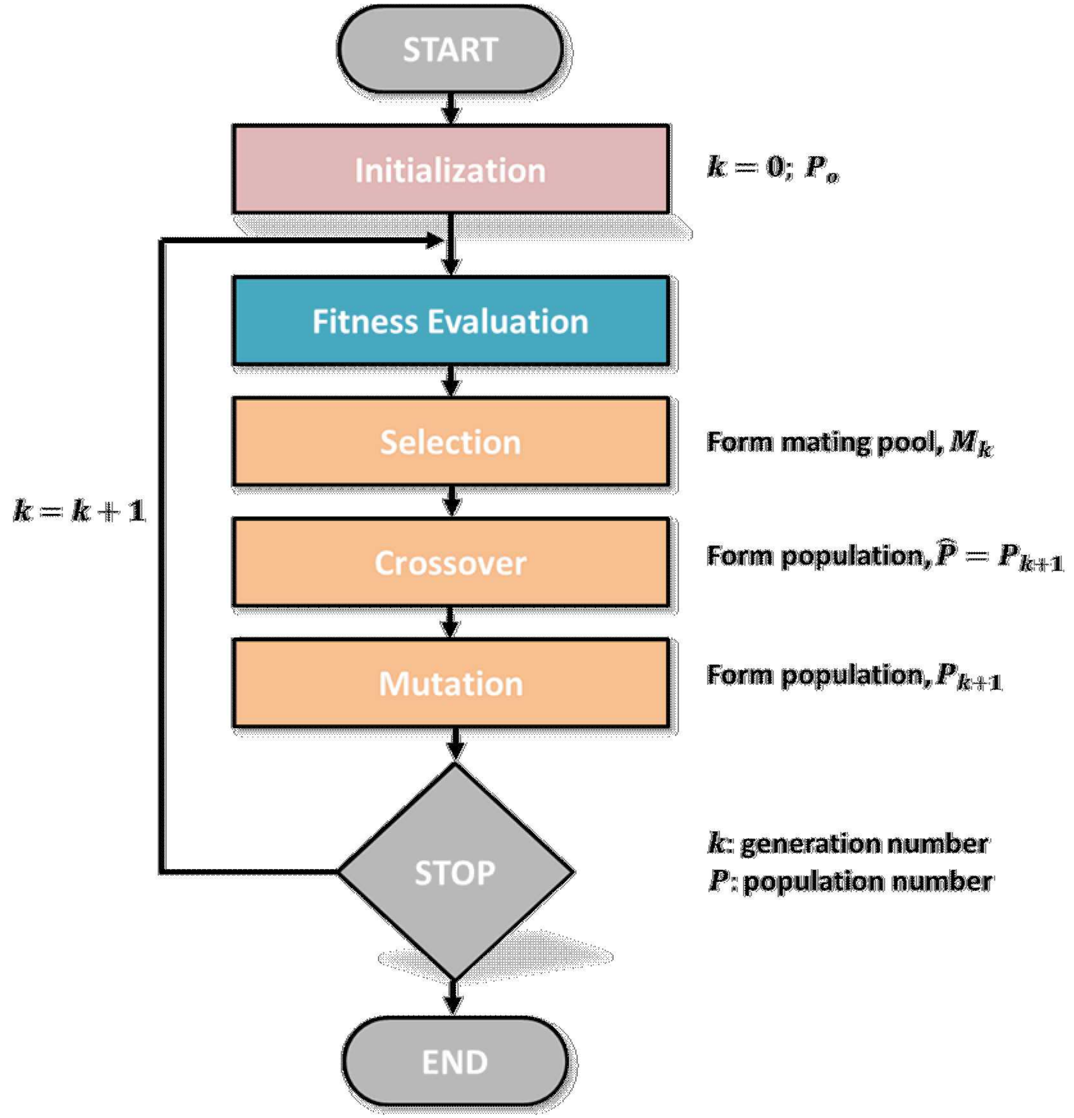
- ***Fitness Function***

Figure of merit for an individual; each individual is assigned with a value, corresponding to a more optimal individual.

- ***Selection***

Ensures that individuals with higher fitness values are more likely to survive. It forms a mating pool, M_k. The roulette wheel and tournament selection algorithms are commonly used techniques.

Genetic Algorithm (GA) Optimization Process



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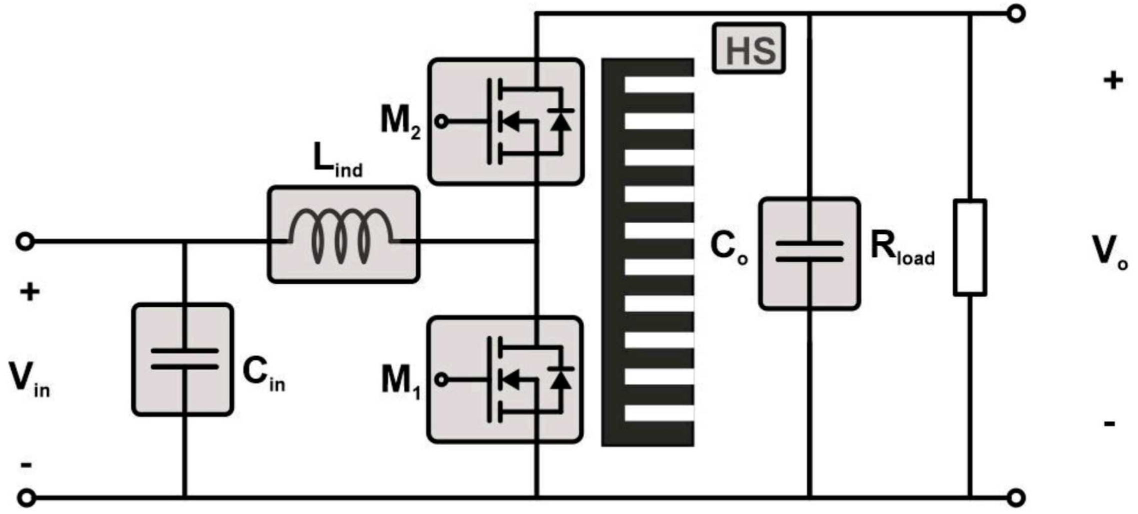
- ***Crossover***

New individuals are generated through crossover and the parental genes are shared. Crossover forms a new population, P_{k+1}There are single-point crossover and the multiple-point crossover operators.

- ***Mutation***

A process of changing genes in chromosomes in a random manner. This maintains the diversity of the population by flipping the selected bit value in a chromosome.

Synchronous Boost Converter Reliability Factors

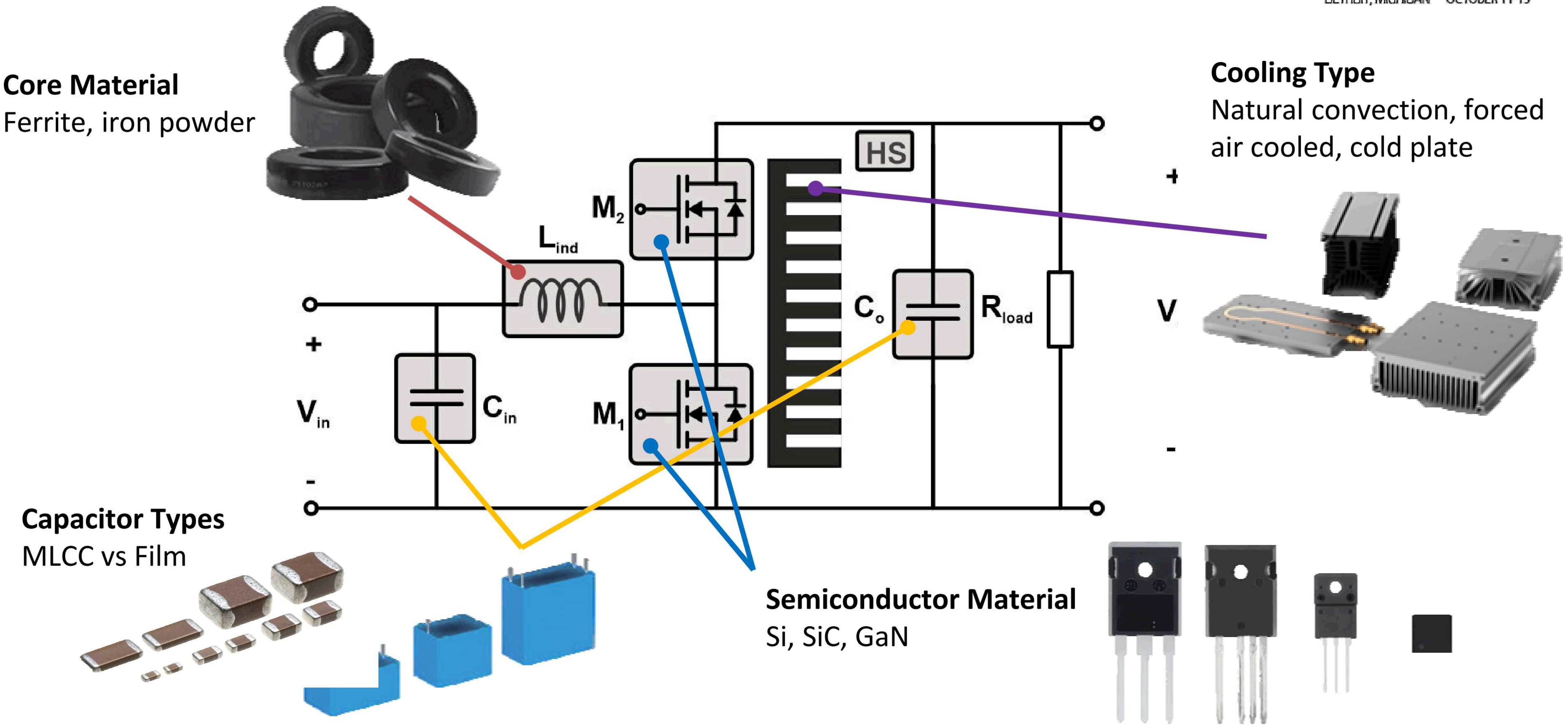


Gene	Description	Data Range [Min…Max]	Data Sweep Type
V_{in}	Input Voltage	[200 V … 400 V]	Logarithmic
V_o	Output Voltage	[500 V … 1000 V]	Logarithmic
f_{sw}	Switching Frequency	[10 kHz … 1 MHz]	Logarithmic
k_L	Inductor Ripple Factor	[5% … 200%]	Linear
k_C	Capacitor Ripple Factor	[5% … 10%]	Linear
η	Target Efficiency	[95% … 99.99%]	Linear

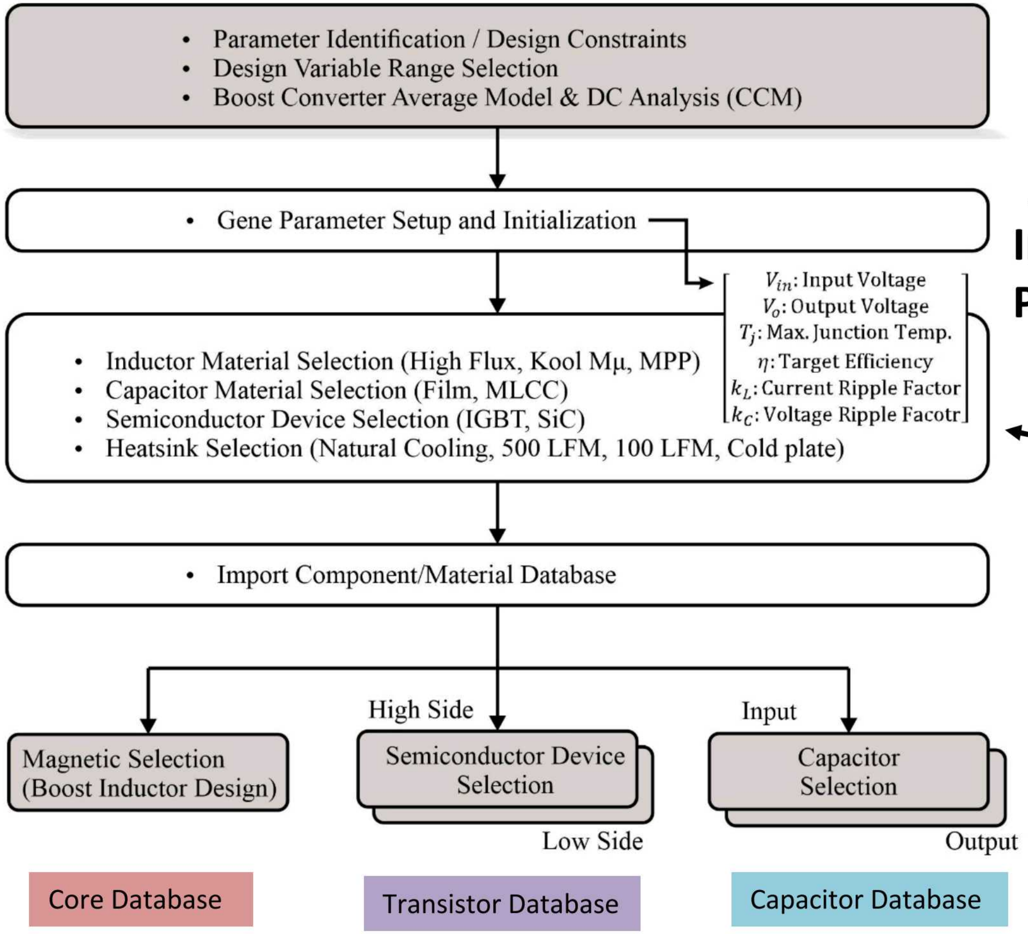
Boost Converter Parameters Affecting Reliability or MTBF and Power Density

- Input & output voltage on the input and output capacitors
- Switching frequency affects transistor switching and conductor losses, and core loss (thermal stress)
- Inductor current ripple factor affects the core size and transistor stress
- Capacitor ripple factor affects the capacitor volume and temperature of operation

Multi-Objective Optimization to Analyze Reliability



Boost Converter Multi-Objective Optimization Flowchart



Boost Converter Multi-Objectives Flowchart

Input Parameters

Gene	Description	Data Range [Min…Max]	Data Sweep Type
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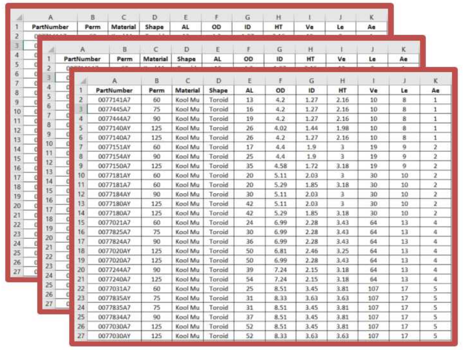
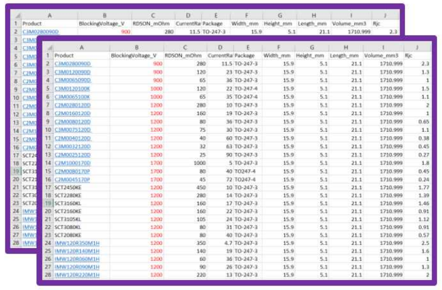
Import database

Core Database



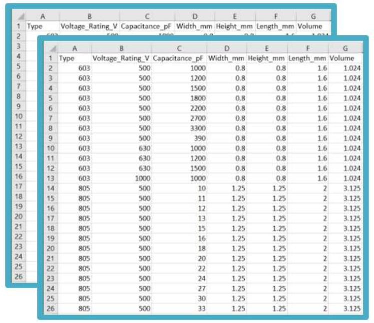
3,551 core sizes

Transistor Database



44 transistors

Capacitor Database



2,532 capacitors

Multi-Objective Optimization: Inductor Design

Gene	Description	Data Range [Min…Max]	Data Sweep Type
V_{in}	Input Voltage	[200 V … 400 V]	Logarithmic
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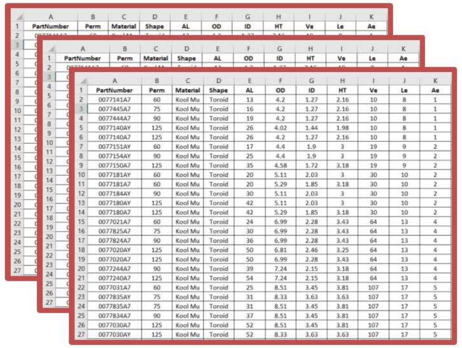
Wire Selection

N1

Wire AWG selected based on frequency

Number of strains needed based on wire resistance, temperature rise, ampacity, RMS current

Core Database



Magnetic Design

N2

$$A_p = \frac{2(Energy)10^4}{B_m \times J \times K_u}$$

Compute every possible inductor design that satisfy the requirement

N3

Select inductor from the minimum cost function

For Kool Mμ, MPP, High Flux

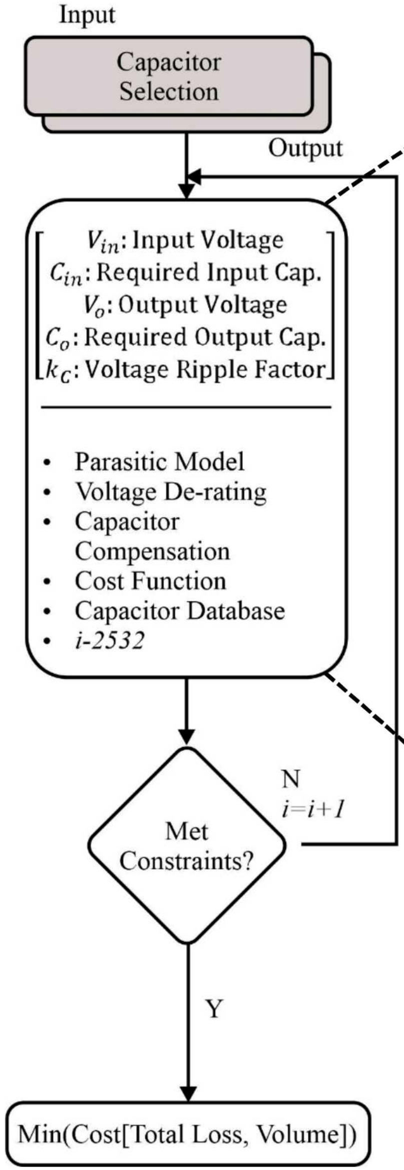
Notes

N1 – Wire selection database included to select appropriate wire gauge and provide dimensions

N2 – Area product used to down-select available cores from the database

N3 – Total of 3,551 core selection list with upto 4 stacked cores

Multi-Objective Optimization: Capacitors



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Required capacitor value calculated based on the ripple requirement

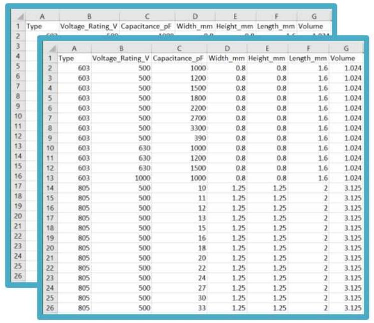
Apply appropriate voltage de-rating and capacitance based on capacitor material type (N1)

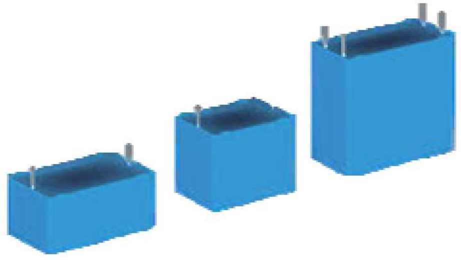
Find all available capacitors that meet the electrical specifications (N2)

Find the capacitor with the minimum cost function

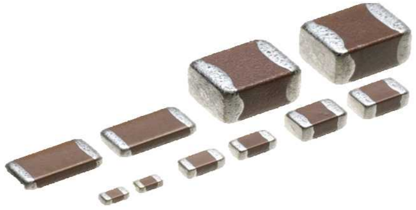
For MLCC and Film

Capacitor Database (N3)





Film type capacitors



MLCC type capacitors

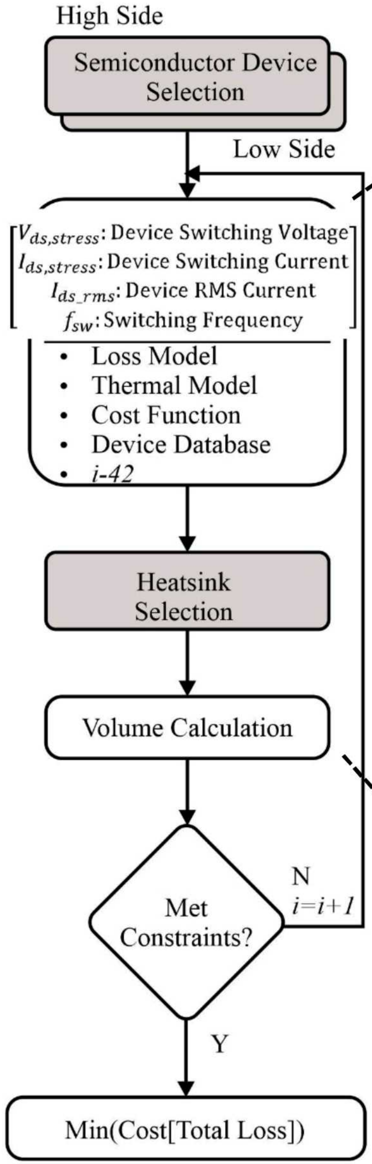
Notes

N1 – voltage de-rating for MLCC is 2 times the rated whereas 1.5 for film

N2 – MLCC capacitor sizes vary from 0402 to 2225 and film capacitor sizes vary largely based on MKP/MFP from TDK

N3 – Total of 2,532 capacitor selection list

Multi-Objective Optimization: Transistors



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For IGBT and SiC MOSFETs

N1 Calculate the minimum voltage and current rating based on the operating conditions

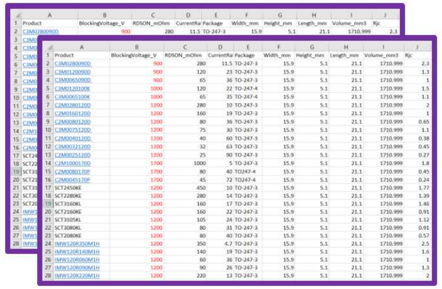
Find datasheet based model for switching and conduction losses

N3 Find the appropriate temperature rise based on the thermal resistance

N4 Find the transistors & heatsink volume with the minimum cost function

Transistor package type

N2 Transistor Database



Notes

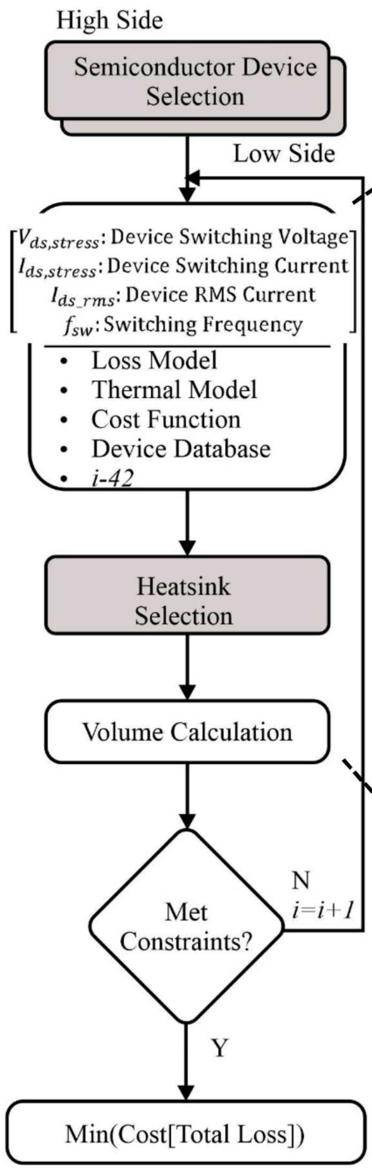
N1 – Peak voltage stress and RMS and peak current stress on both transistors

N2 – Temperature rise calculated based on the datasheet thermal resistance

N3 – Total of 42 transistor selection list

N4 – Cooling type selection explained in the next slide

Multi-Objective Optimization: Cooling System



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Semiconductor Device Selection

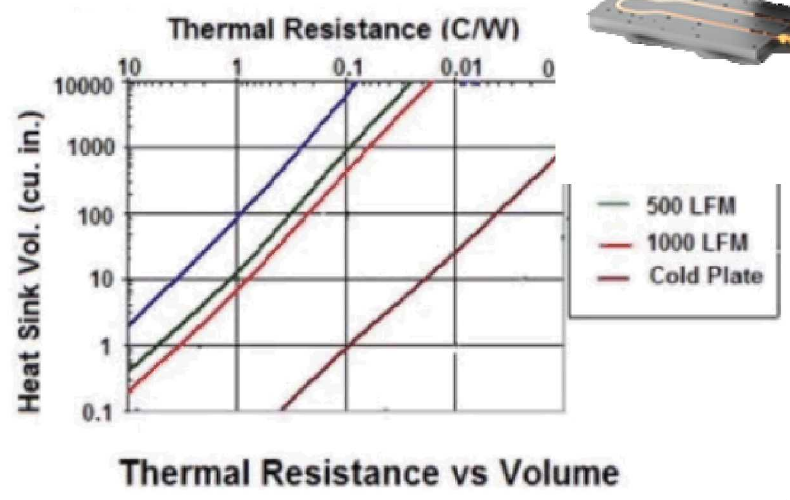
N1 Find required thermal resistance of the cooling system by type

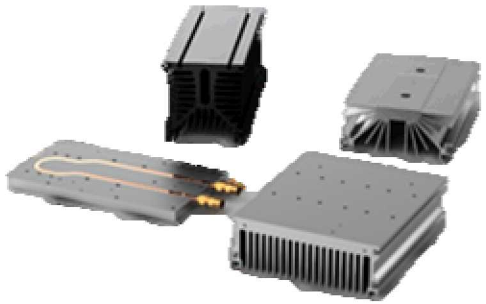
For natural convection, forced air, cold plate

N2 Find the approximated volume by cooling type

Find the transistors & heatsink volume with the minimum cost function

Cooling Type Databa



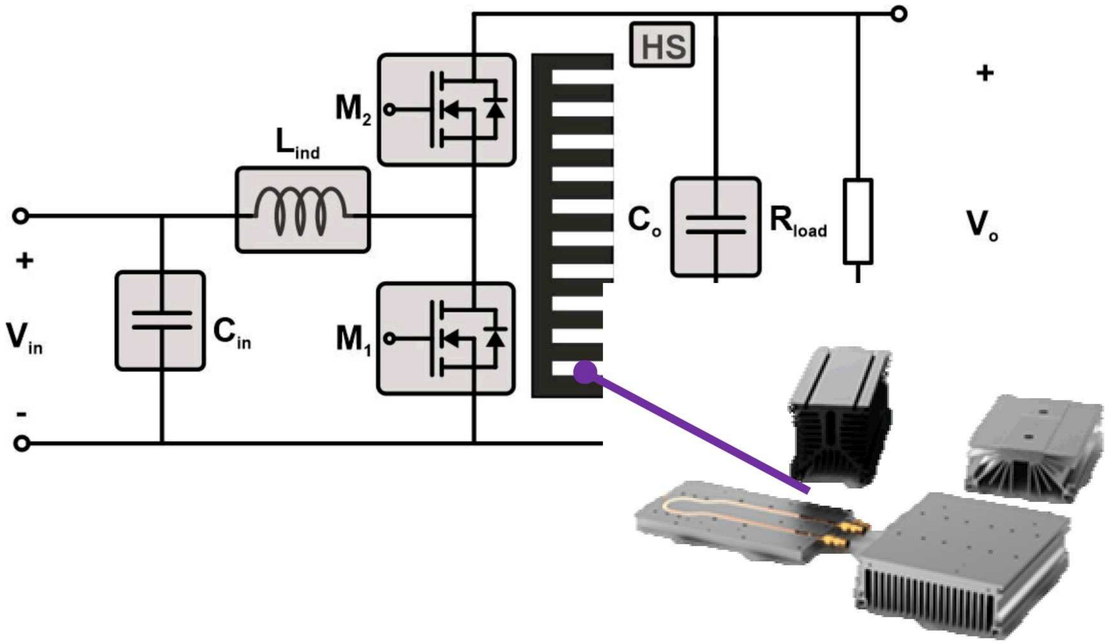


Notes

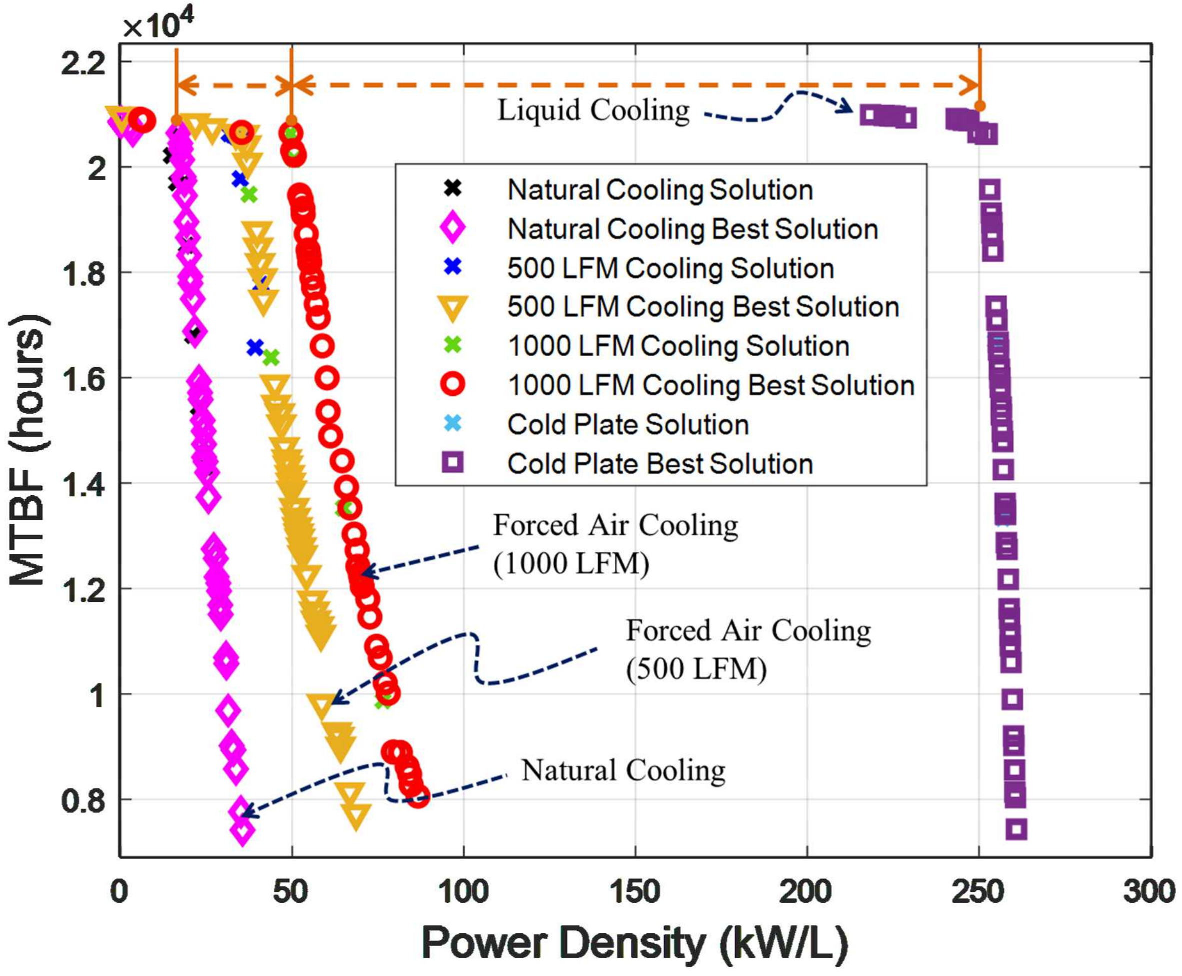
N1 – Total power loss from IGBT or SiC MOSFET model

N2 – Natural Convection, forced air cooling (500 LFM & 1000 LFM) and cold plate

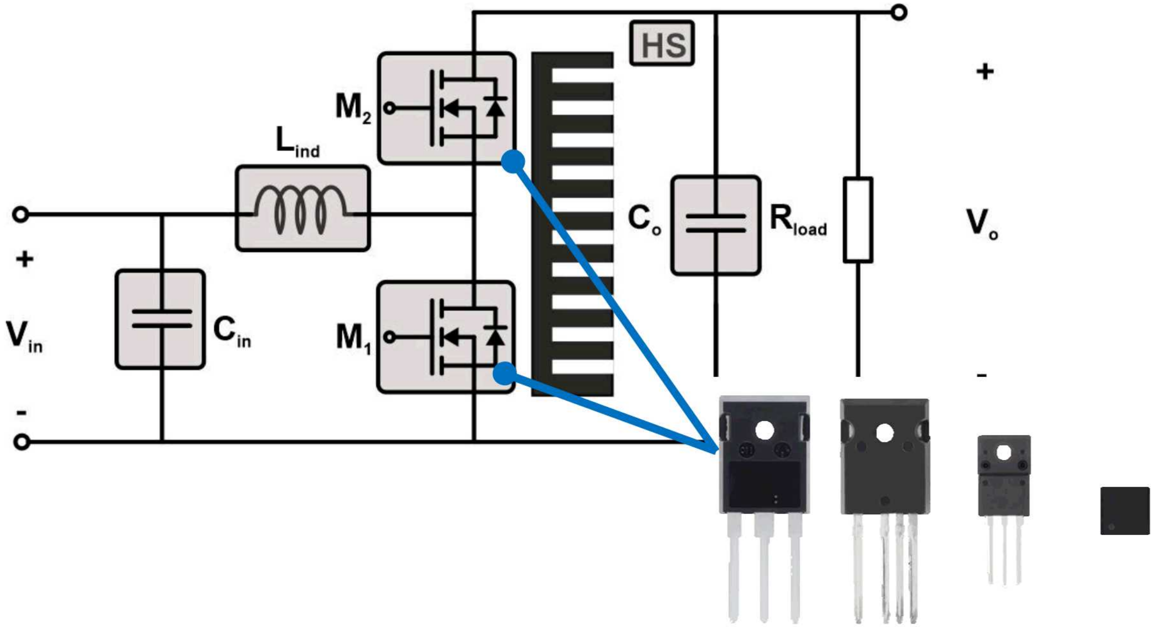
Boost Converter Co-Optimization Analysis #1

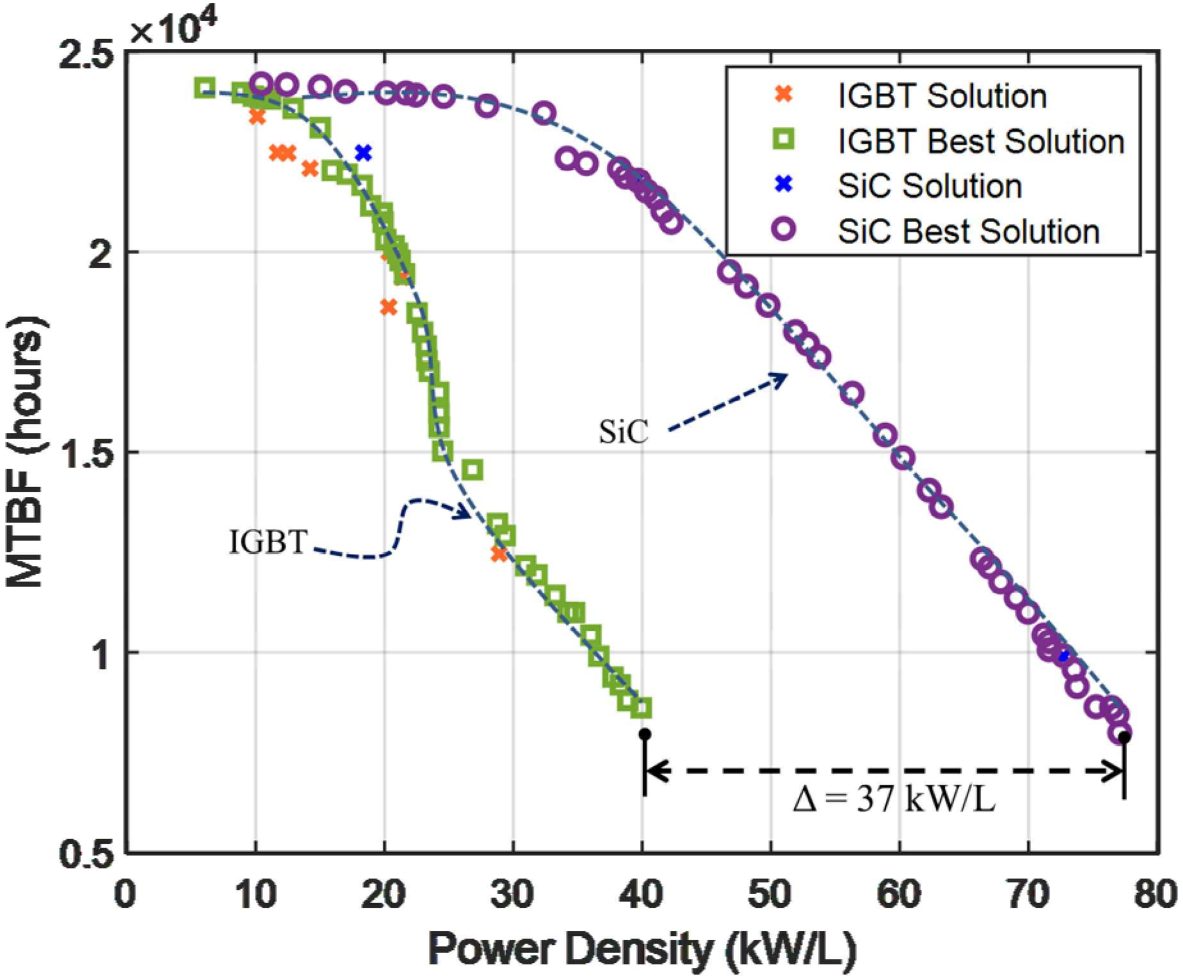


- Capacitor material type fixed to **film**
- Magnetic material type fixed to **High Flux**
- Semiconductor material type fixed to **SiC MOSFETs**
- Cooling varies from **natural cooling**, **forced air cooling**, and **cold plate**



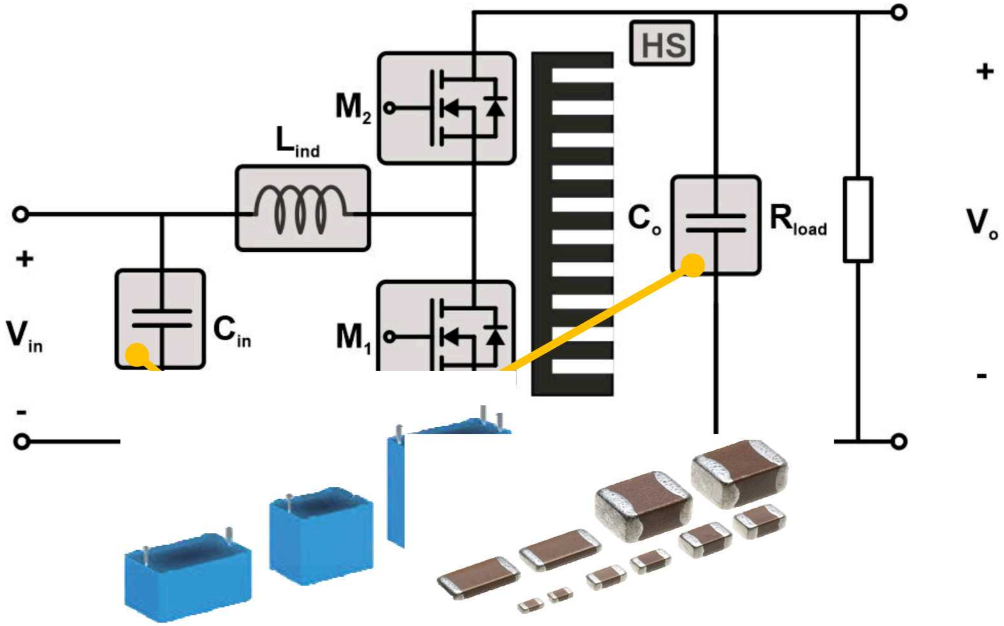
Boost Converter Co-Optimization Analysis #2

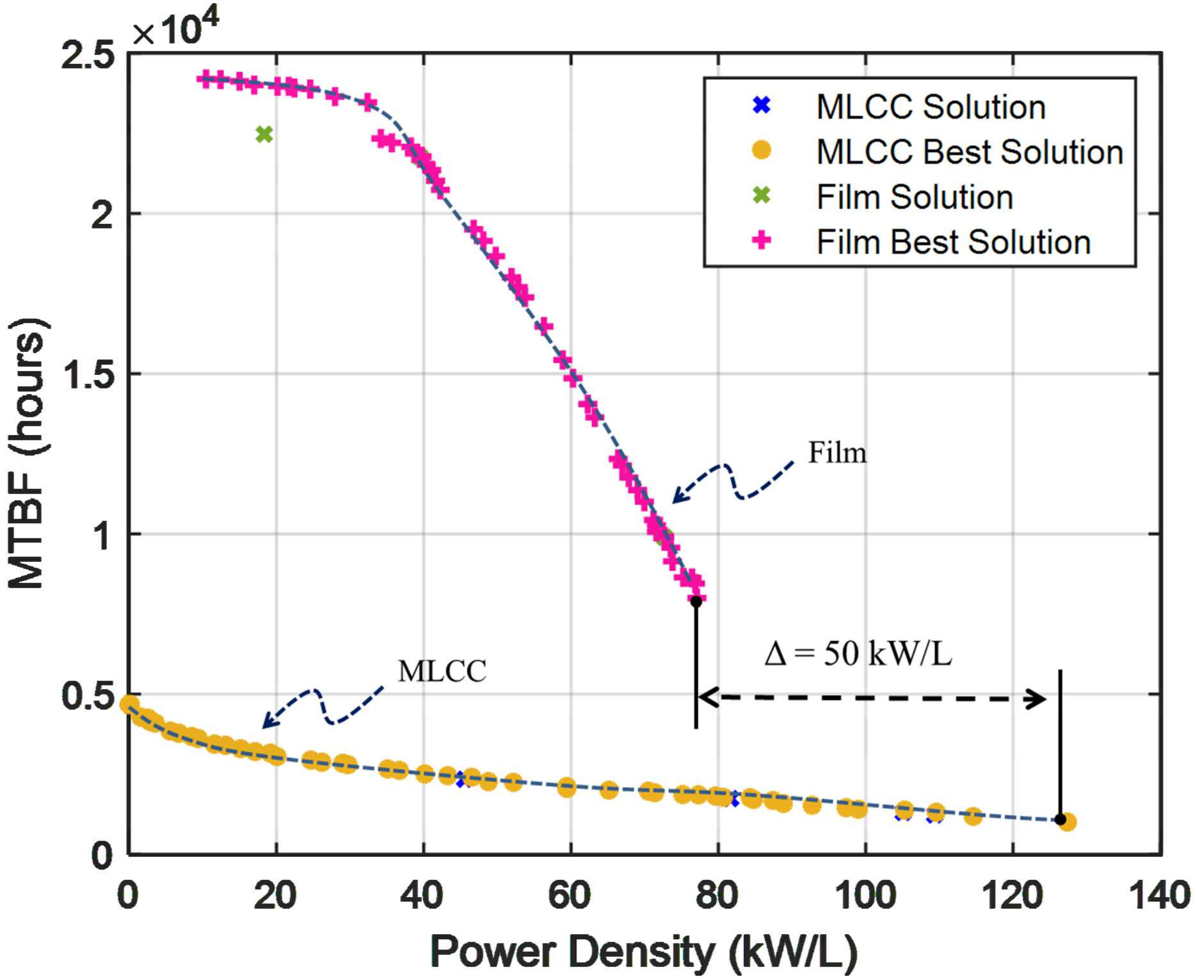




- Capacitor material type fixed to **film**
- Magnetic material type fixed to **High Flux**
- Cooling fixed to **forced air cooling (1000 LFM)**
- Semiconductor material varies from **IGBT** and **SiC**

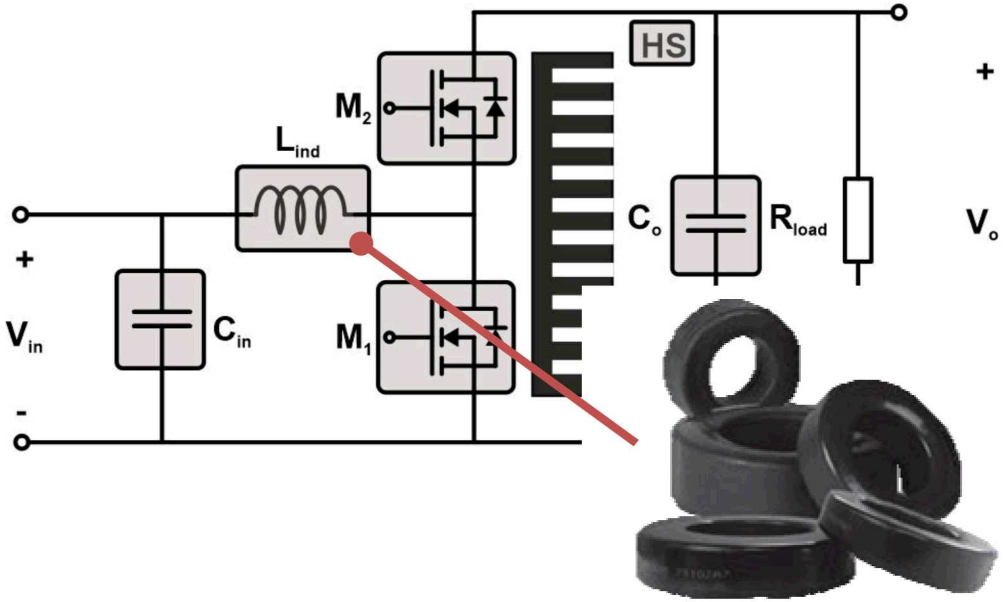
Boost Converter Co-Optimization Analysis #3

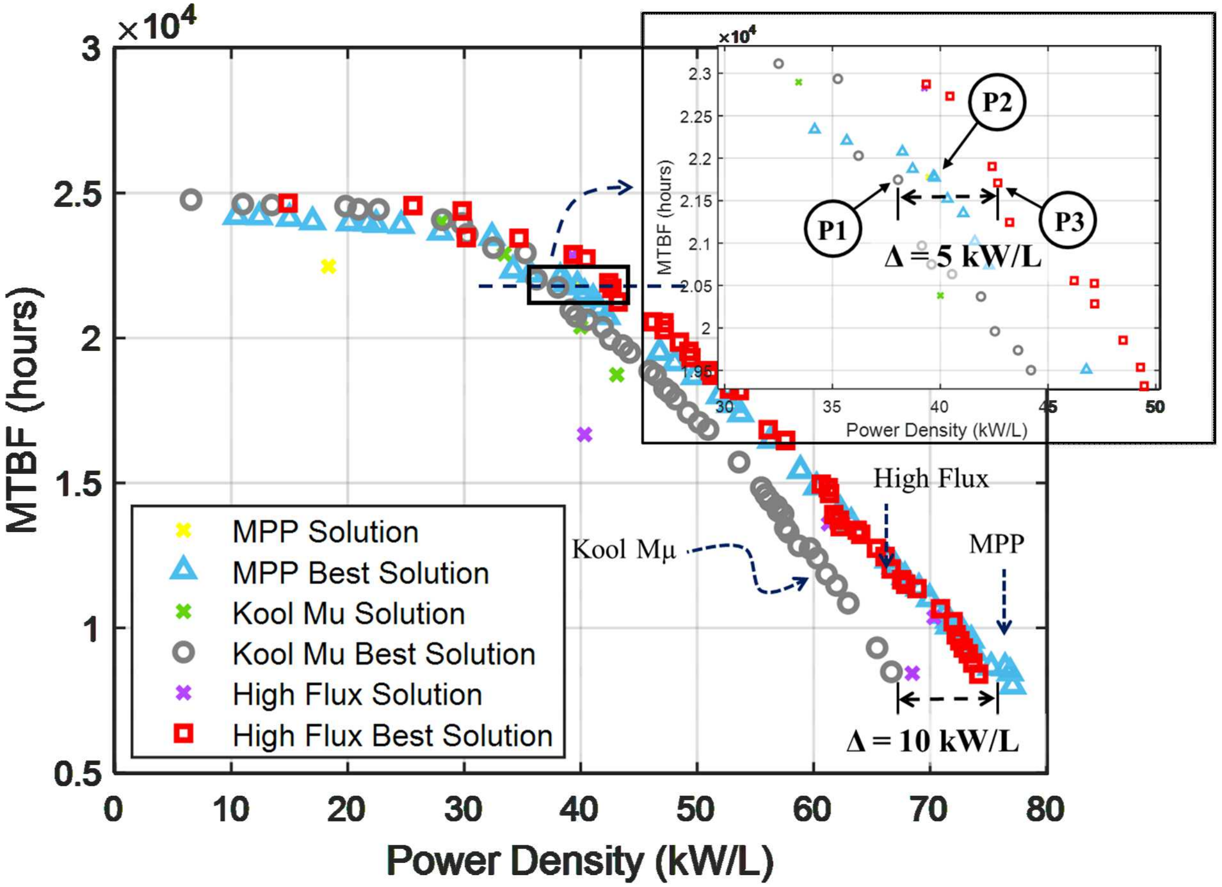




- Cooling fixed to forced air cooling (**1000 LFM**)
- Magnetic material type fixed to **High Flux**
- Semiconductor material type fixed to **SiC MOSFETs**
- Capacitor material type varies between **film** and **MLCC**

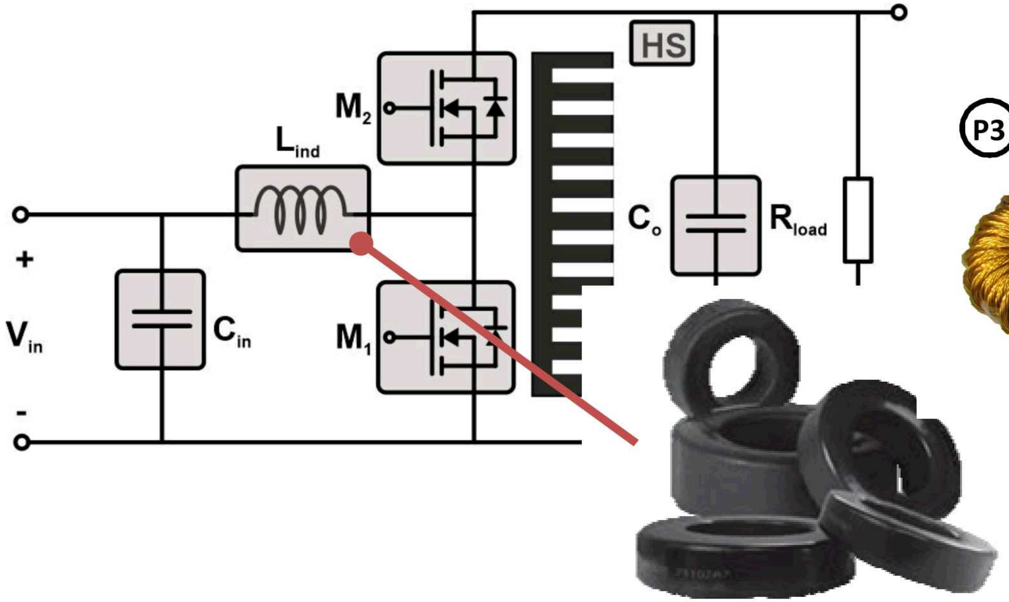
Boost Converter Co-Optimization Analysis #4

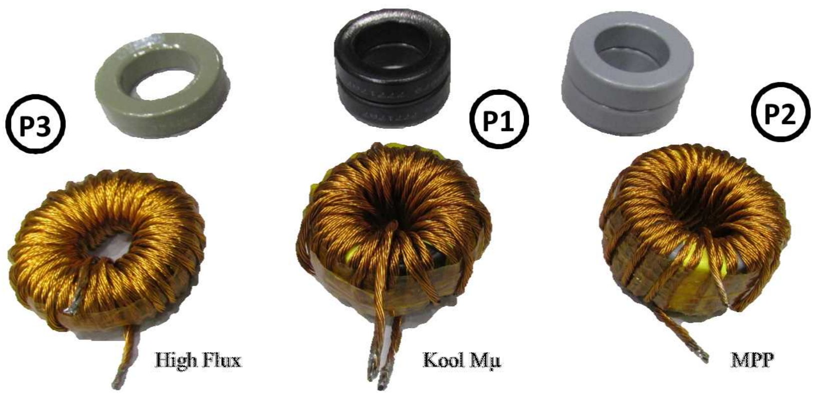


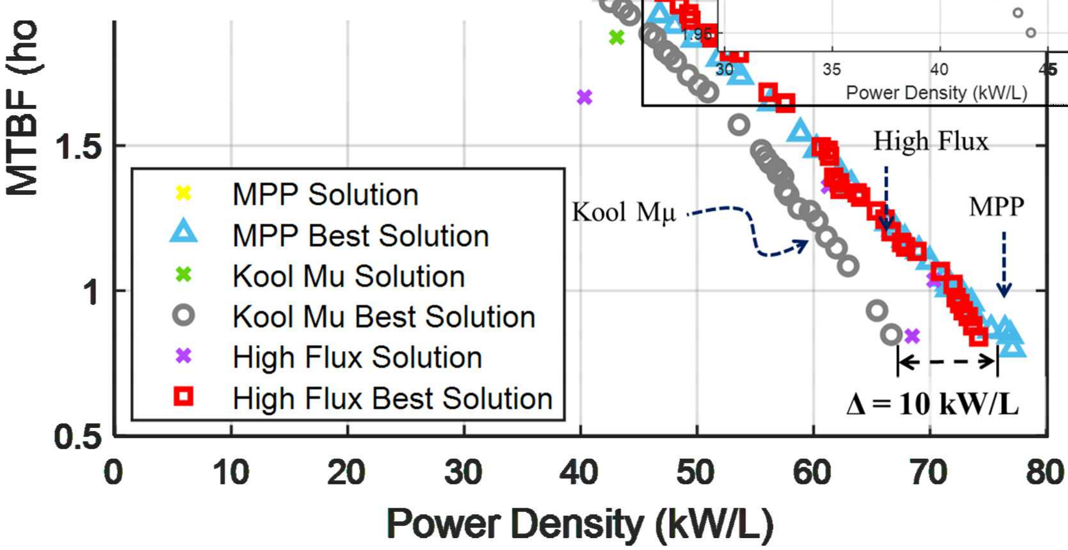


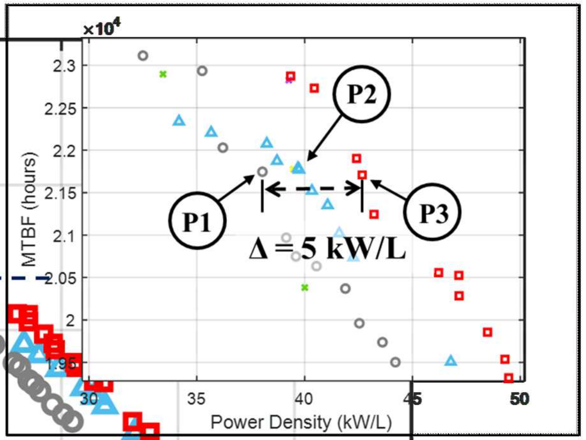
- Capacitor material type fixed to **film**
- Cooling fixed to forced air cooling (**1000 LFM**)
- Semiconductor material type fixed to **SiC MOSFETs**
- Magnetic material varies from **High Flux**, **MPP**, and **Kool Mμ**

Boost Converter Co-Optimization Analysis #4







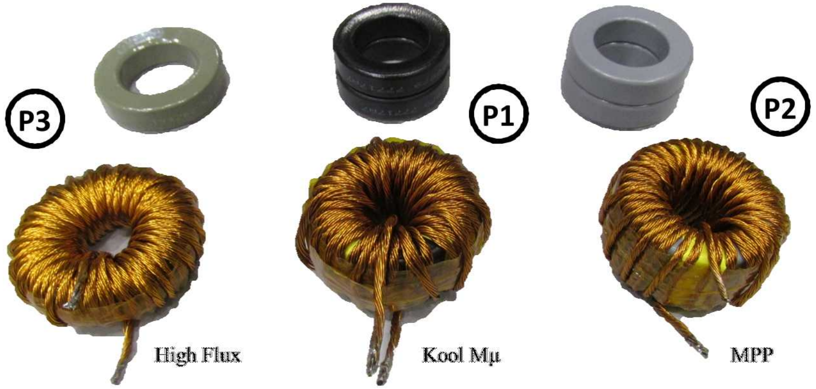


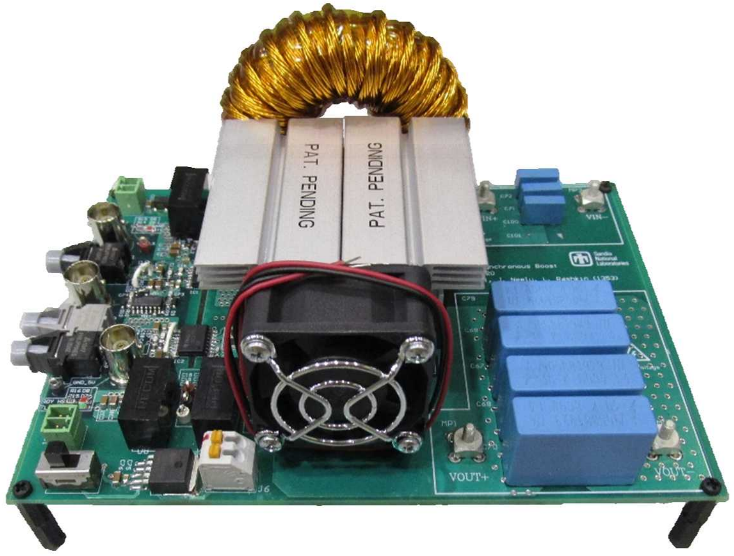
- Capacitor material type fixed to **film**
- Cooling fixed to forced air cooling (**1000 LFM**)
- Semiconductor material type fixed to **SiC MOSFETs**
- Magnetic material varies from **High Flux**, **MPP**, and **Kool Mμ**

Synchronous Boost Converter Candidate Designs

5 kW Synchronous Boost Converter Candidate Design Specifications

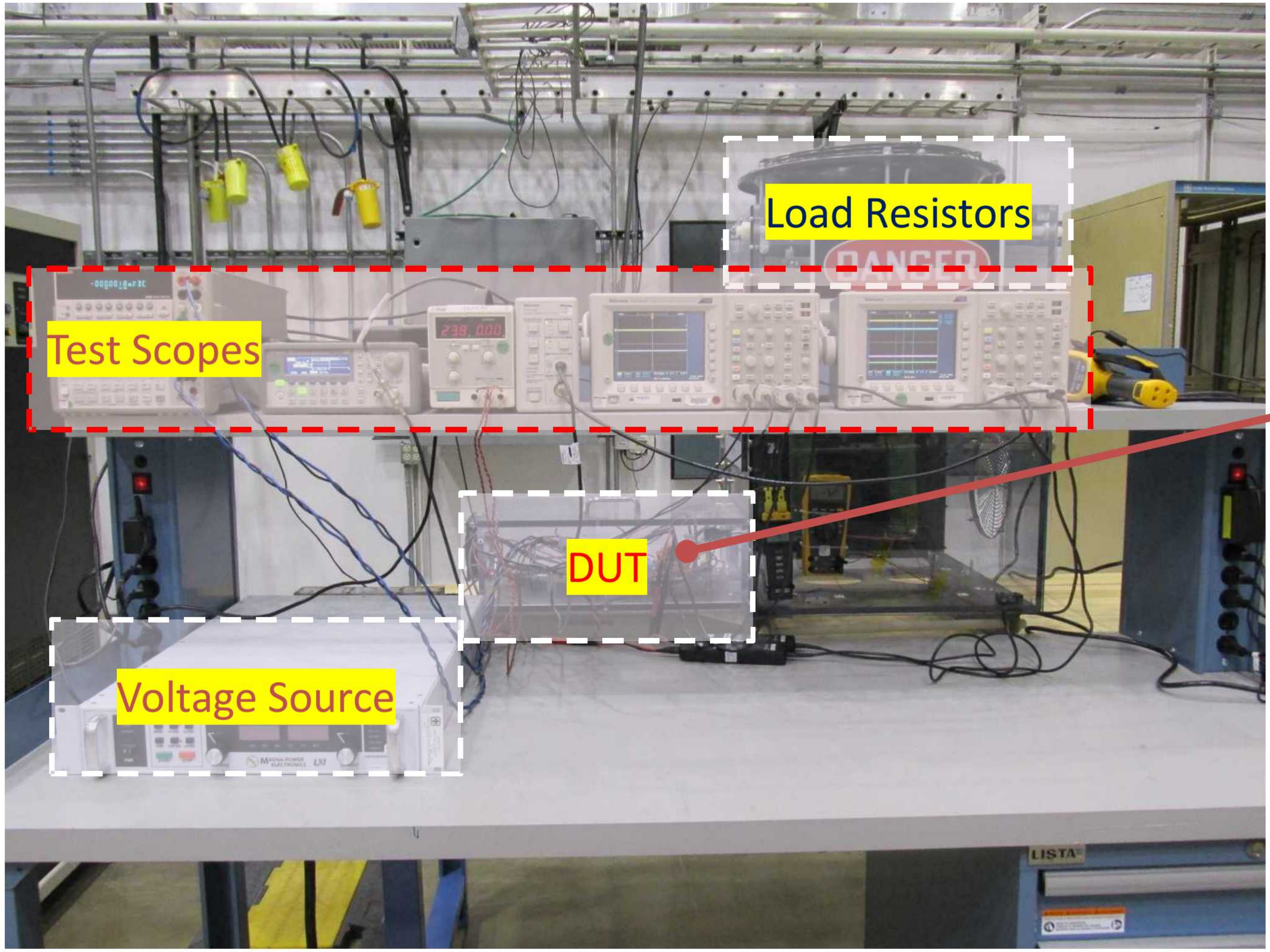
Operating Condition			
Variable	P1 (Kool Mμ)	P2 (MPP)	P3 (High Flux)
Input, Vin	400V	400V	400V
Output, Vo	500V	500V	500V
$I_{in,min} - I_{in,max}$	7.47-17.78A	9.9-15.35A	10.74-14.57A
f_{sw}	47.37 kHz	48.7 kHz	47.87 kHz
Duty Cycle	20.81%	20.8%	21.4 %
T_j	78.8ºC	75.19ºC	75ºC
Inductance	169 μH	310 μH	462 μH
Input Capacitors		**Output Capacitors**	
Model #	B32641B6682J	Model #	B32774X8305
Capacitance	3×6.8 nF	Capacitance	4×3 μF
Boost Inductor			
AWG/Strands	23 AWG/10	23 AWG/10	23 AWG/10
Model #	0077717A7	C055716A2	C058110A2
Fill Factor	20%	17.7%	24%
Turns Number	52	46	78
Loss (W/C)	10.53W/10.8W	10.89W/7.09W	7.84 W/8.8 W
Temp. Rise	48.6 ºC	35 ºC	90 96 ºC
Low Side Semiconductor Device			
Model #	C2M0040120D	C2M0040120D	C2M0040120D
Loss (Ton/Toff/Cond)	2.09W/3.45W/1.33W	2.69W/3.13W/1.33W	2.88 W/2.98 W/1.37W
High Side Semiconductor Device			
Model #	C2M0040120D	C2M0040120D	C2M0040120D
Loss (Ton/Toff/Cond)	5.82W/2.28W/5.05W	4.68W/2.5W/5.05W	2.88 W/2.98 W/1.37 W
Total Efficiency	99.16%	99.2%	99.2 %

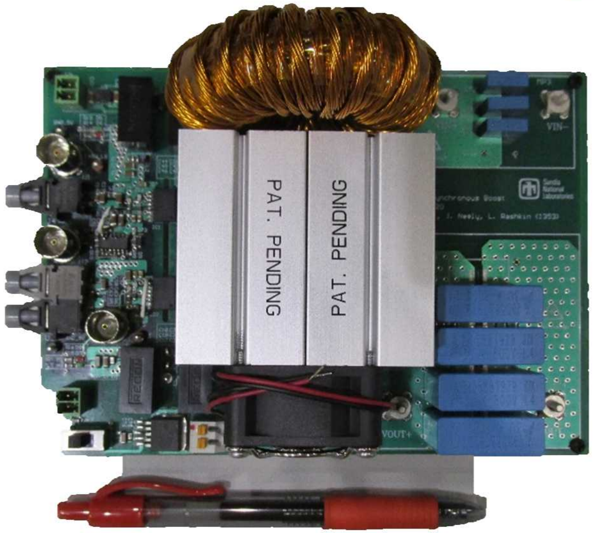


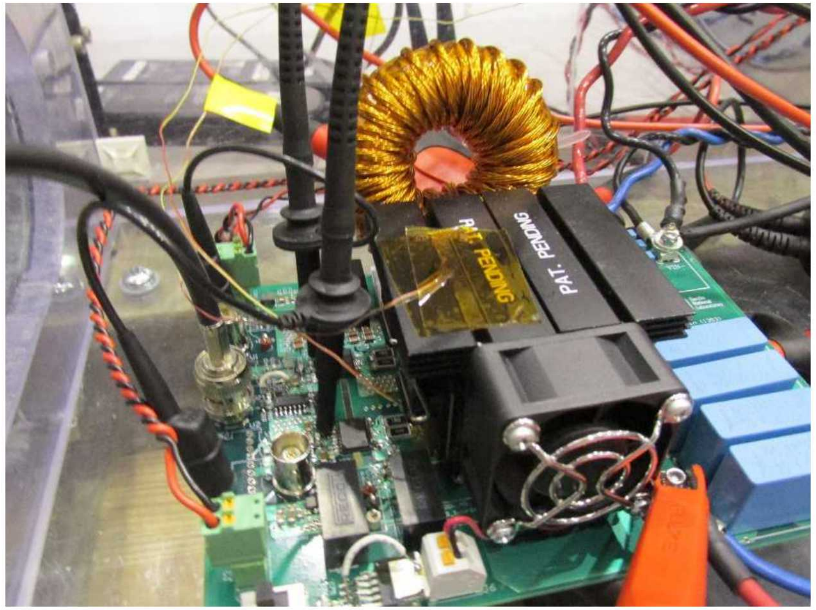


5 kW Synchronous Boost Converter Prototype

Experimental Testbed Setup

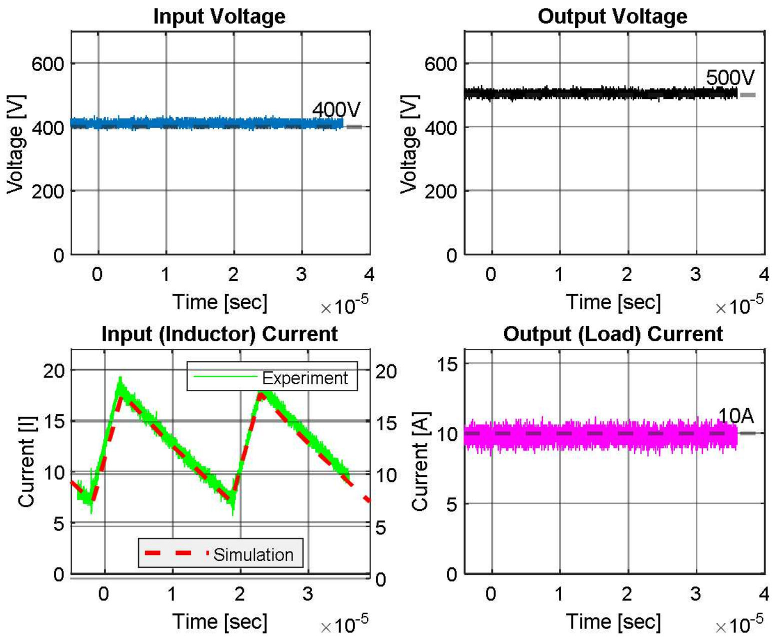




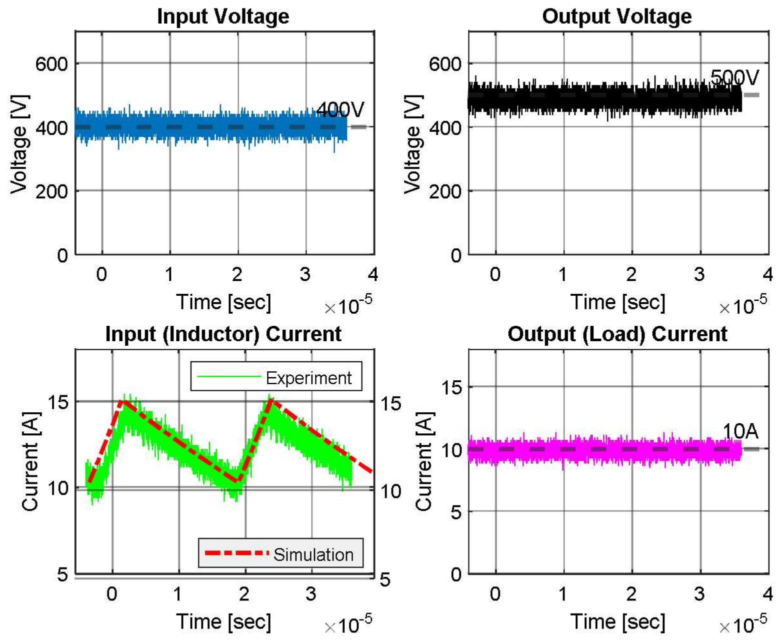


Experimental Results and Simulation Comparison

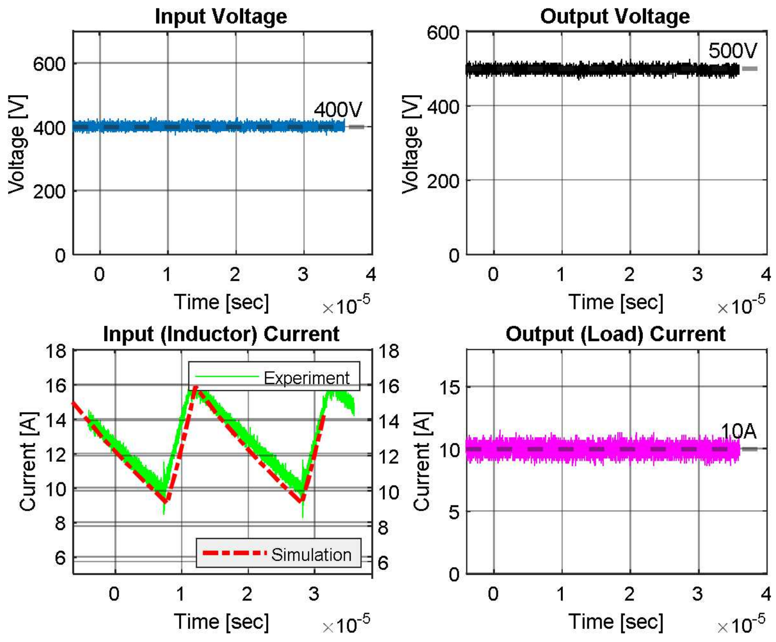
P1 **Kool Mμ**



P2 **MPP**



P3 **High Flux**



Conclusion and Future Work

Conclusion

- Genetic algorithm used to analyze multi-objective (MTBF vs power density) optimization.
- Inductor design, capacitor selection, heatsink selection, semiconductor selection vary depend on the operating point and input genes.
- MTBF and power density analysis based on several combinations.
- Candidate design for each inductor material evaluated and tested in experiment.

Future Work

- Can be applied to different core shapes, e.g. EE, EI, UU, etc.
- Need to consider gate driver and other ancillary ICs into the volumetric calculation.
- More robust cooling system optimization method is required for higher fidelity.

Acknowledgement

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