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Automated Layout Optimization Methods of a Bidirectional DC-DC ZVS Converter Using PowerSynth

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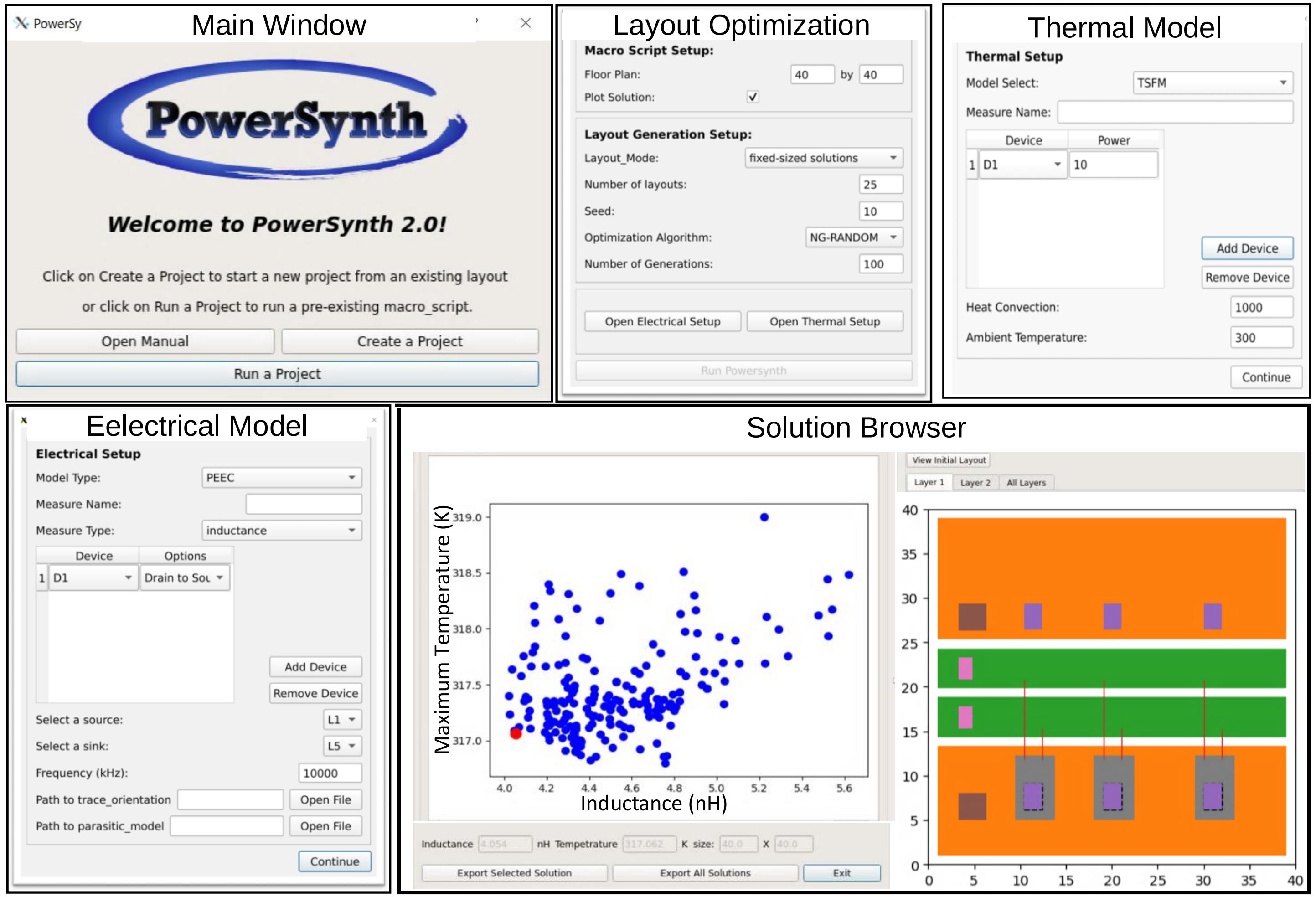
Presentation Overview

- ✓ **Introduction for PowerSynth tool running proses**
- ✓ **Applications of ZVS DC-DC bidirectional converters**
- ✓ **Advanced methodology for design optimization of a bidirectional DC-DC converter**
  - ✓ **Optimization of SWaP-C Parameters for selecting components**
  - ✓ **Tradeoff between achieving low volume and high-power for the modular structure**
- ✓ **Automated physical layout optimization of DC-DC converter utilizing PowerSynth 2**
  - ✓ **Achieving high power density converter design**
  - ✓ **Tradeoff between low loop inductance value and maximum junction temperature**
  - ✓ **Aiding in selecting the optimum layout arrangement among different layouts**
  - ✓ **Reliability analysis**
- ✓ **Experimental results**
- ✓ **Conclusions**

Introduction of PowerSynth 2 for Physical Layout Optimization

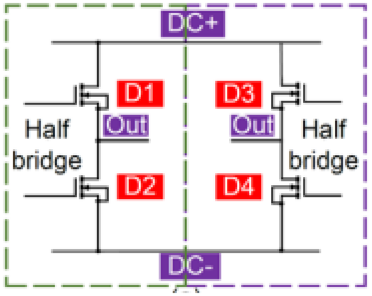
- **Command Line Interface (CLI)**
  - **Linux compatibility**
  - **User input through terminal**
  - **Modes: Script-based or Step-by-step**

- **Graphical User Interface (GUI)**
  - **Developed by REU student**
  - **Two flows:**
  - **Creating new project**
  - **Run existing project through ‘Macro script’**
  - **MDK editor**
  - **Optimization setup**
  - **Performance evaluation model setup**
  - **Interactive solution browser**

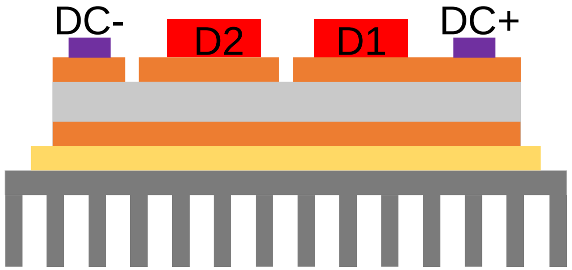


PowerSynth 2 Interfaces

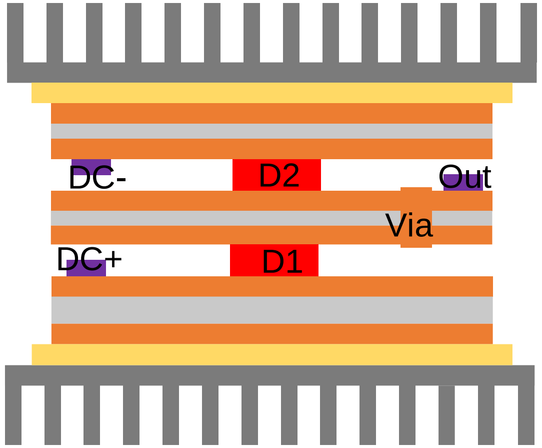
- 2D layout: One device layer with routing layers on the same substrate
- 2.5D layout: Multiple 2D designs connected on a supporting 2D plane
- 3D layout: Multiple device layers stacked vertically on a substrate

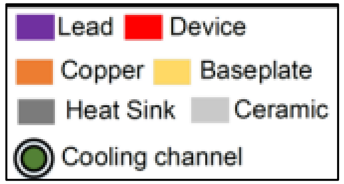


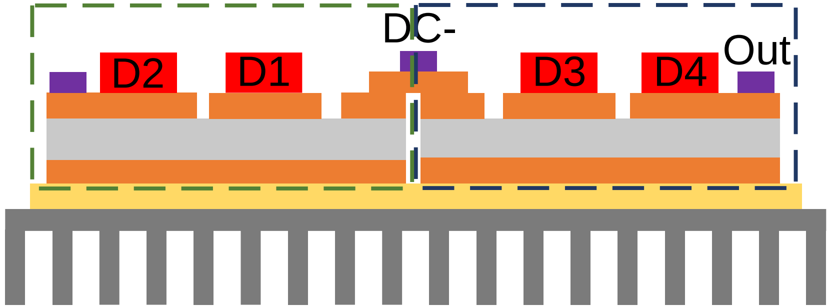
(a) Circuit of Power Module



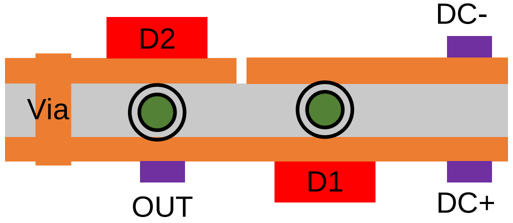
(b)2D Half-Bridge Power Module





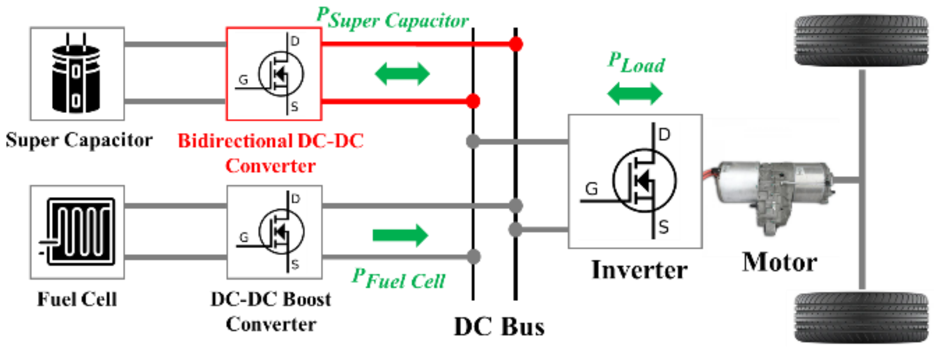


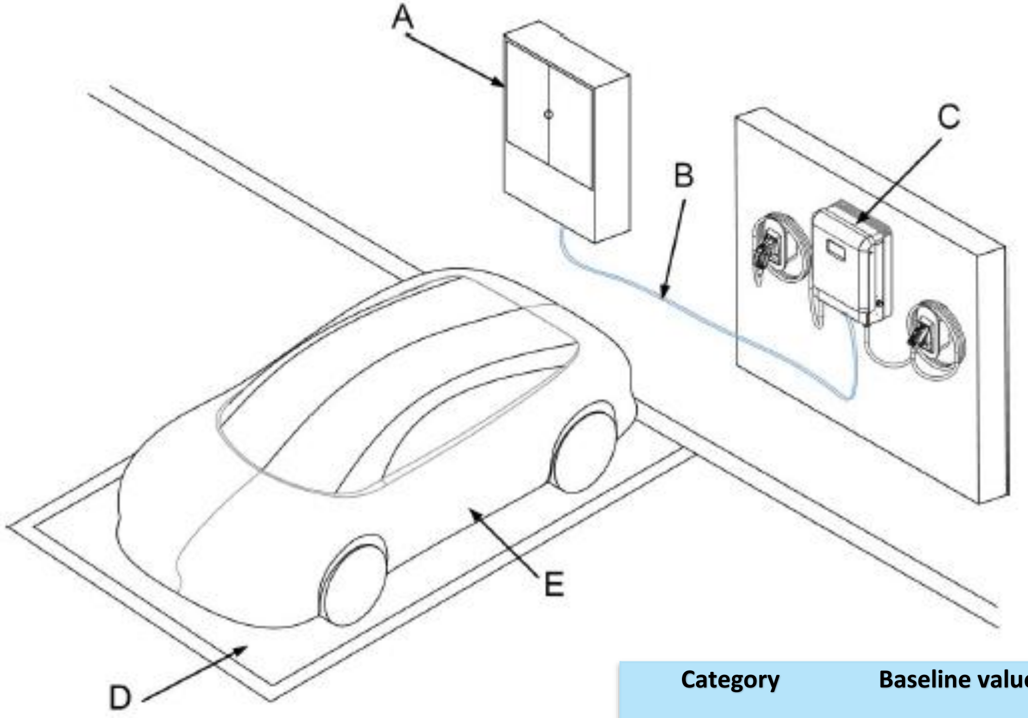
2.5D Full-Bridge Power Module



3D Half-Bridge Power Module

1) Electric Vehicle (EV)





Example of a complete installation

A	Power distribution board of the owner
B	Cables in conduit
C	Terra DC Wallbox
D	Parking space for charging
E	Electric vehicle

2) Terra DC Wallbox for EV application

Temperature: -40Cto70C/-40F to 160 F

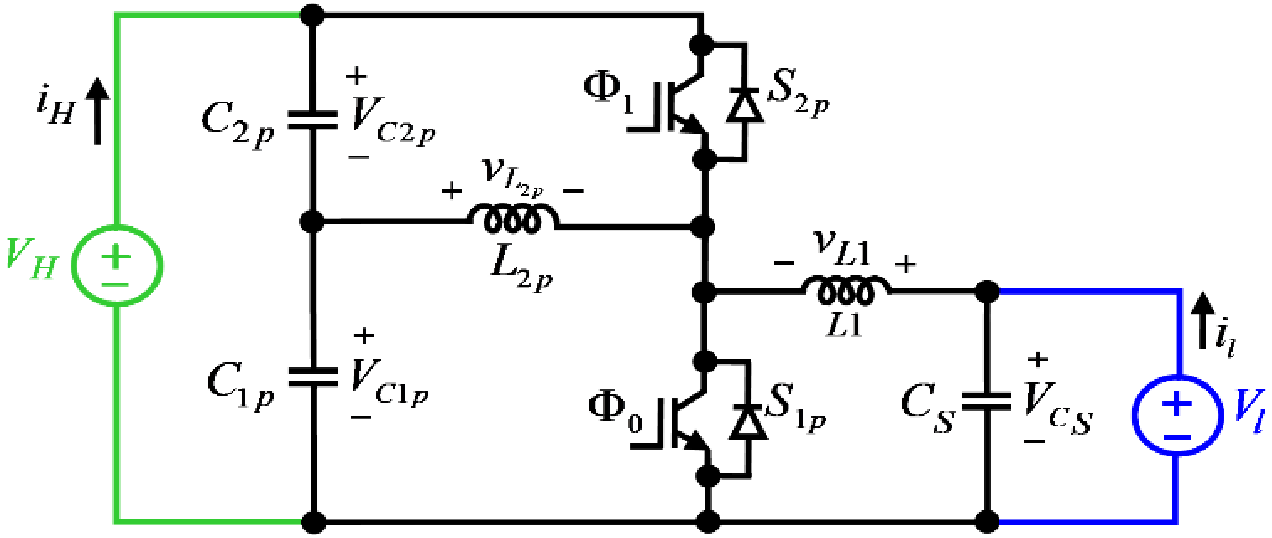
Category	Baseline value
Vin min	380
Vin max	460
Vout min	900
Vout max	920
Maximum output current	60 A

Bidirectional ZVS DC/DC Converter

- ✓ **Bidirectional ZVS dc-dc converter structure utilized for automated design optimization**
- ✓ **Advantages;**

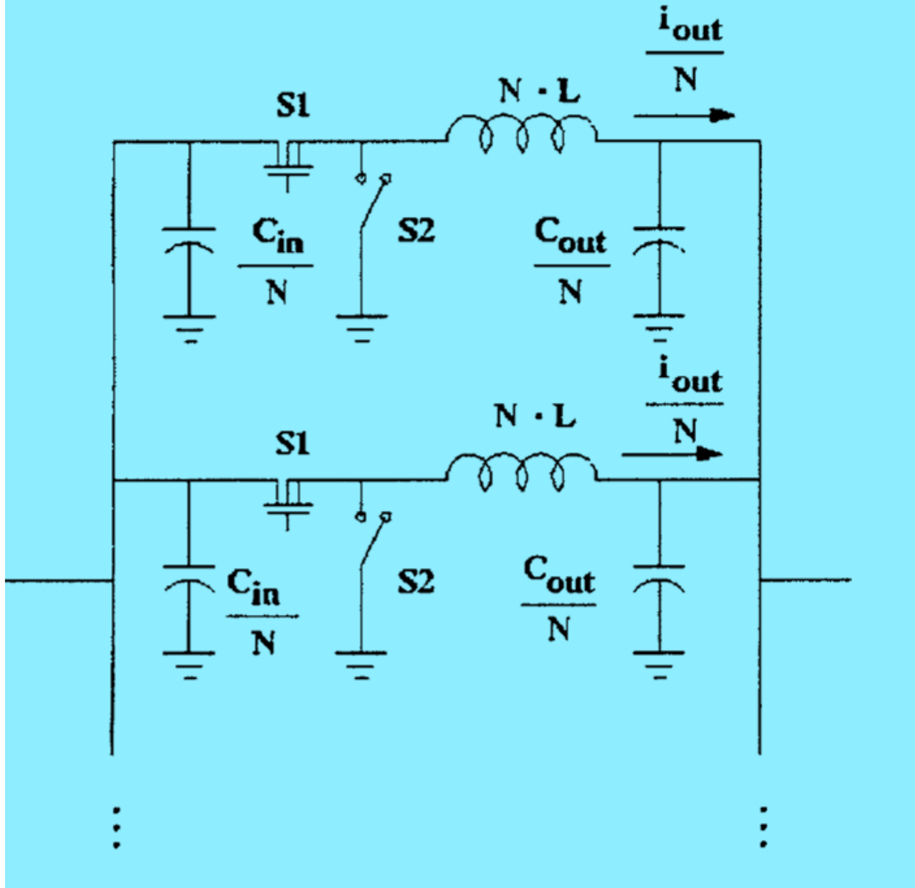
1. **Bidirectional power flow**
2. **ZVS-operated switches to avoid switching loss**
3. **Simple switching pattern to avoid concurrent turning on both switches**
4. **Applicable for automotive wall chargers**

The low voltage side (Vl) : 380V-460V and high voltage side (VH) : 900V-920V



DESIGN CONSIDERATIONS

- ✓ The nominal power for the low-voltage bus is estimated to be 22.5kW (peak power = 24kW)
- ✓ To achieve this power level, multiple modules can be used in an input/output parallel connection.
- ✓ The optimized number of cells is determined through the proposed automation process.
- ✓ Modular converter improves flexibility and scalability due to the use of multiple paralleled converter cells

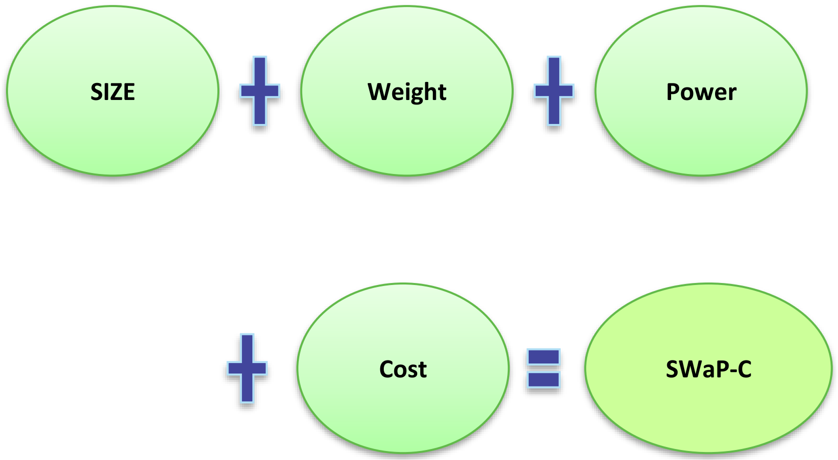


Optimization Process

- ✓ The optimization process involves exploring the design space of the DC-DC converter to identify the designs that minimize a cost function. Cost function is a weighted sum of converter price, weight, and volume.
- ✓ Various design variables for generating codes;

1. The number of cells (for high-power applications),
2. Cell switching frequency
3. Ripple ratio
4. Component types

- ✓ Applying Monte Carlo approach by starting from random points in the design space that meet user-defined specifications
- ✓ The final version of the code will be open-sourced later on GitHub.



SWaP-C solutions in the design of the dc-dc converter

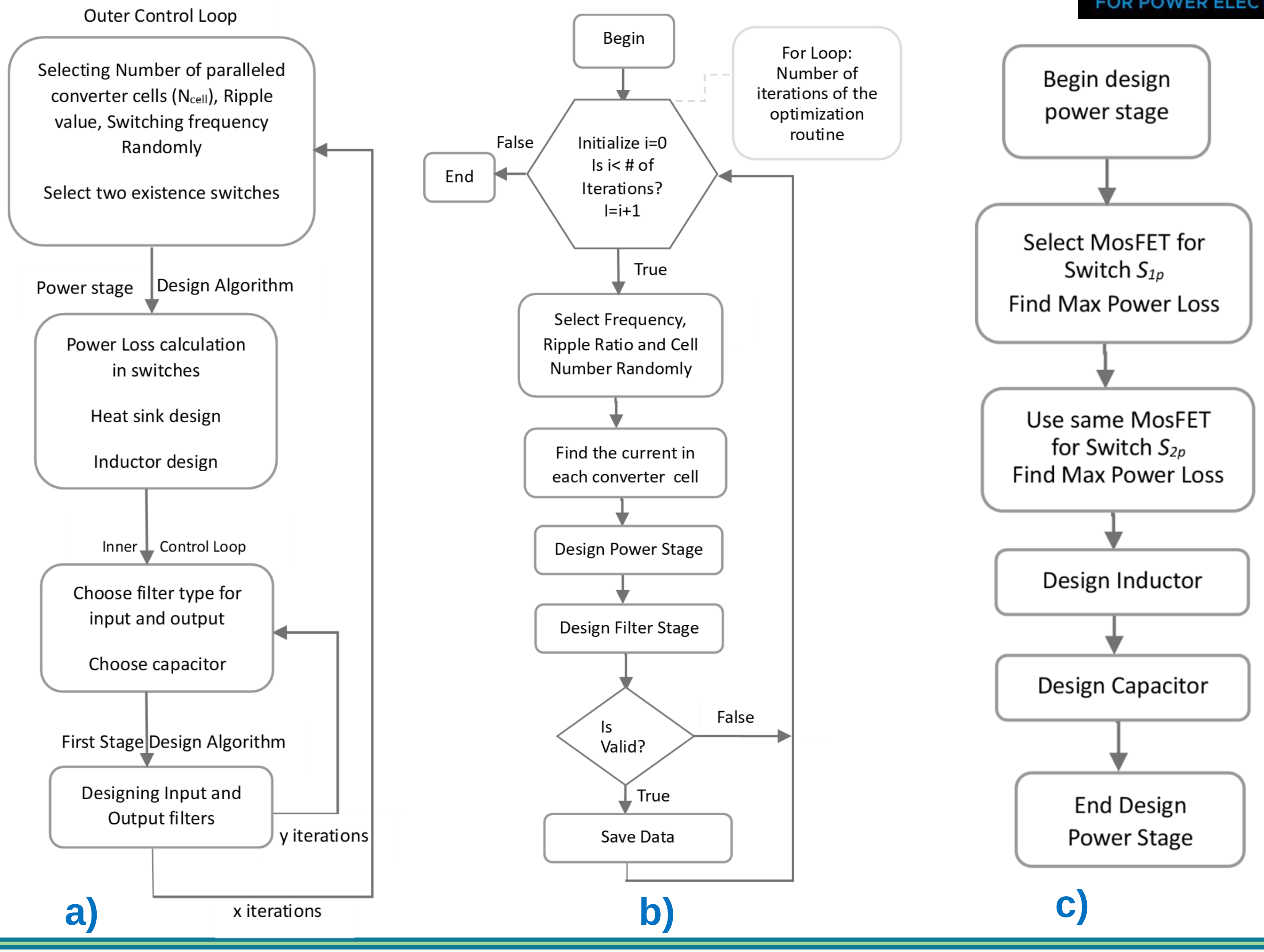
OPTIMIZATION PROCESS

Optimization Flowcharts;

(a) parameter optimization process

(b) optimization algorithm

(c) power stage design



POWER LOSS ANALYSIS AND EFFICIENCY MODELING

DESIGN METHODOLOGIES FOR POWER ELECTRONICS

✓ **Conduction and switching losses, efficiency, power loss, and power density.**

- **Voltage stress on switches;** $V_{S1p} = V_{S2p} = V_H$

- **Average current stress on switches during conducting;** $I_{S2p}\big|_{S2p:ON} = I_H / (1-D) = -I_{L1}$

- **The voltage conversion ratio between low and high voltage ports;** $G = V_H / V_l = 1/(1-D)$

- **The Conduction losses of the switches;**

$$P_{Cond,S1} = \frac{1}{T_s}\int_0^{DT_s} (V_{FS1} i_{S1p} + r_{S1} i_{S1p}{}^2)dt = (V_{FS1} + r_{S1} I_l) I_l D,$$

$$I_l = -I_H / (1-D) \;\; , I_H = V_H / R_H$$

$$P_{Cond,S2} = \frac{1}{T_s}\int_{DT_s}^{T_s} (V_{FS2} i_{S2} + r_{S2} i_{S2}{}^2)dt = \left[V_{FS2} + r_{S2}\frac{I_H}{1-D} \right] I_H$$

Power Loss Analysis And Efficiency Modeling

- **The switching losses of the switches;**

$$P_{sw,S2}=\frac{1}{T_s}\int_0^{t_{on}} v_{S2}i_{S2}dt+\frac{1}{T_s}\int_0^{t_{off}} v_{S2}i_{S2}dt=\frac{1}{6}f_S V_{S2}i_{S2}\Big|_{t=toff}t_{off}$$
$$=-\frac{1}{6}f_S V_H\left[\frac{-I_H}{1-D}+\frac{-V_l DT_s}{2}\left(\frac{1}{L_1}+\frac{1}{L_{2p}}\right)\right]t_{off}$$

$$P_{sw,S1}=\frac{1}{T_s}\int_0^{t_{on}} v_{S1}i_{S1}dt+\frac{1}{T_s}\int_0^{t_{off}} v_{S1}i_{S1}dt=\frac{1}{6}f_S V_{S1}i_{S1}\Big|_{t=toff}t_{off}$$
$$=\frac{1}{6}f_S V_H\left[\frac{-1}{1-D}I_H+\frac{V_l DT_s}{2}\left(\frac{1}{L_1}+\frac{1}{L_{p2}}\right)\right]t_{off}$$

- **Total power loss of the switches;**

$$P_{S,Tot}=P_{Cond,S2}+P_{sw,S2}+P_{Cond,S1}+P_{sw,S1}$$

- **The efficiency of the proposed converter**

$$\eta_{boost}=\frac{P_H}{P_H+P_{Loss\_boost}}$$

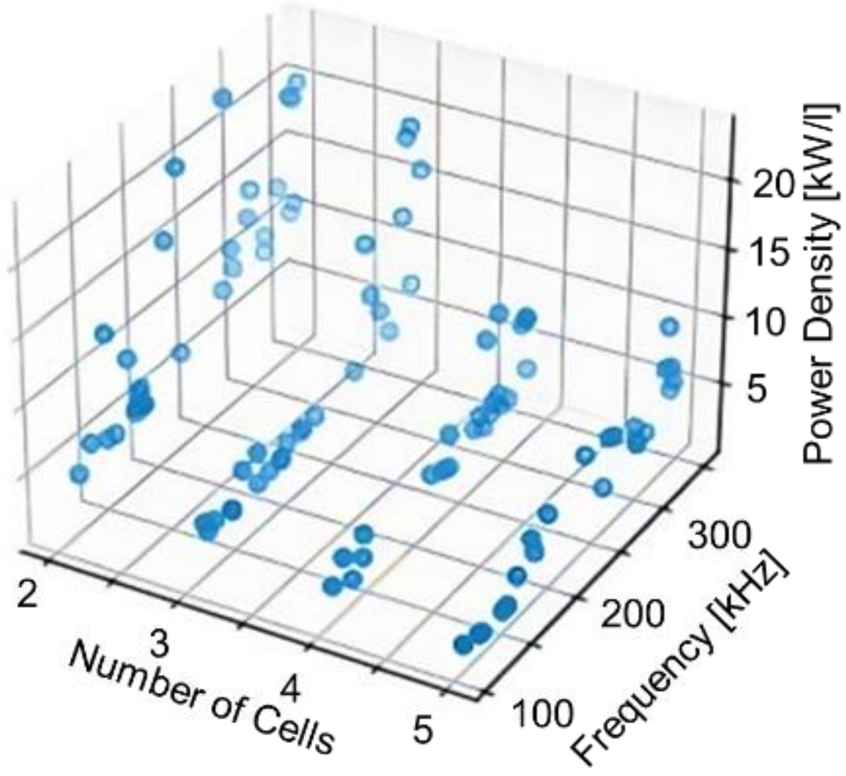
- **Power Density**

Power Density=(P_l-P_{Loss})/Volume

Where, duty cycle of switches: D

Design Tradeoff and Methodology

- ✓ **Required number of modules**
  - ✓ **Tradeoffs between constructing a single, large converter or dividing it into multiple paralleled cells**
  - ✓ **The number of cells significantly impacts the current ripple in input and output buses**
  - ✓ **Moreover, the number of cells influences the required heatsink size and power losses with potential gains in efficiency offset by increased complexity.**
  - ✓ **In this regard, the optimized number of modules is obtained to be 5, which meets the power density of 5kW/l in the frequency range of 100kHz-300kHz.**



The selection process on module numbers

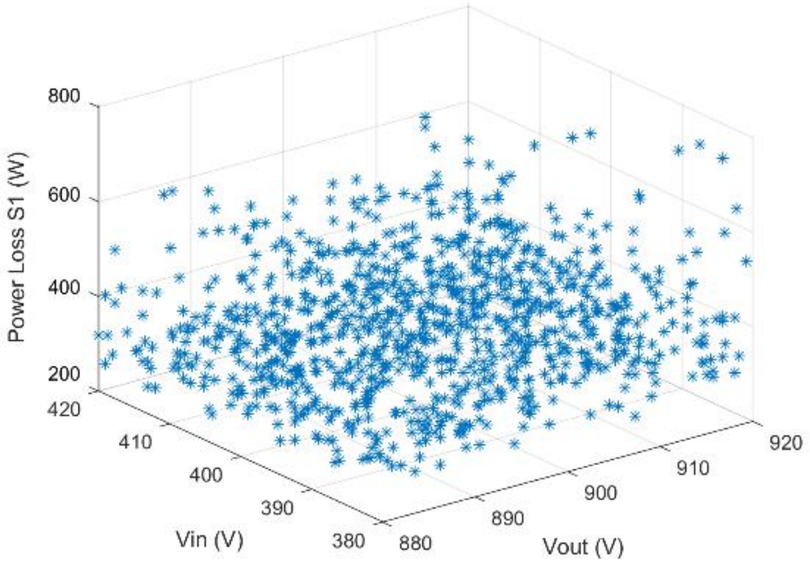
DESIGN TRADEOFF AND METHODOLOGY

✓ **System Specifications**

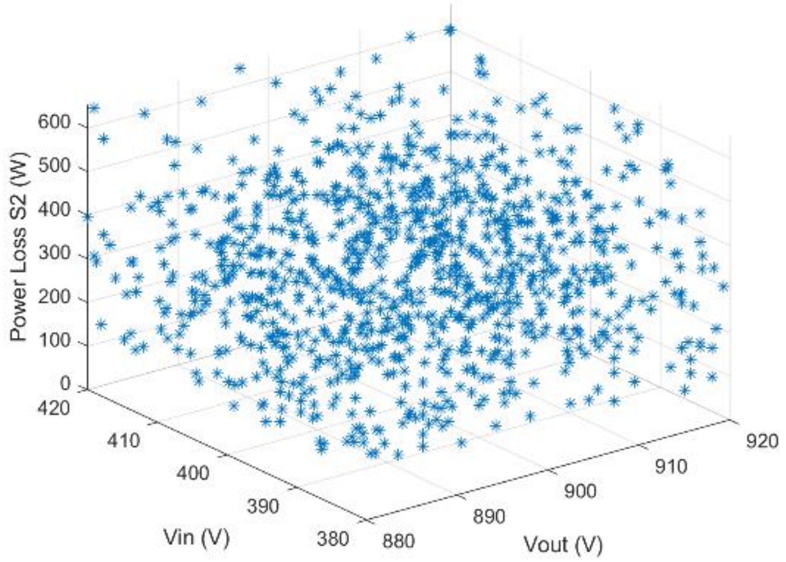
Category	Baseline value
V_I (Input voltage range)	380-460 V
V_H (Output voltage)	900-920V
Maximum output current	60 A
P_I (Input power)	22.5 kW-24 kW
Duty Cycle (D)	(1-VH/VI)
N_{cell} (Number of converter cells)	2-5
Ambient temperature	100°C
Maximum junction temperature	140°C

Design Tradeoff and Methodology

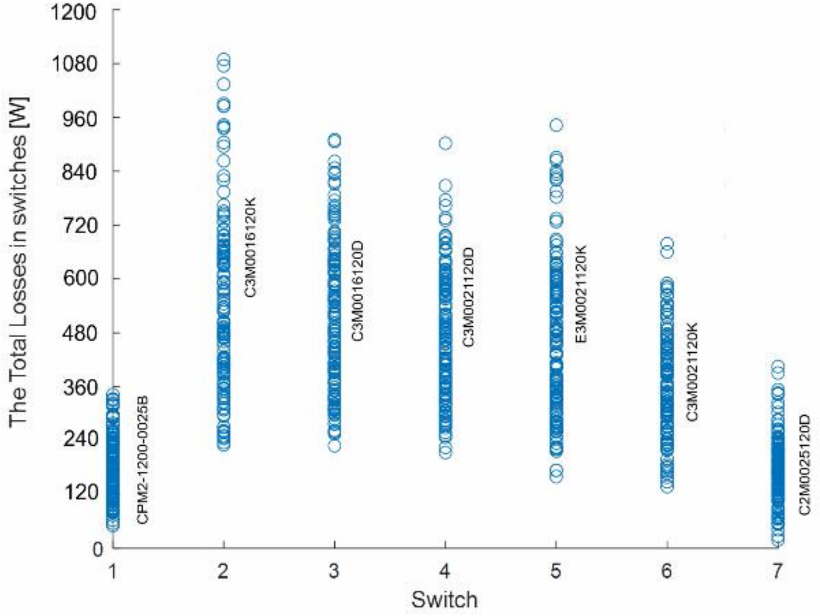
- ✓ **Switching Device Selection**
  - ✓ **The power losses of the switches within the chosen input and output voltage ranges are displayed in the following Figures;**
  - ✓ **Highest power density and the lowest power loss are achieved with Switch number 1 (CPM2-1200-0025B) when each module is operated at a 5kW output power level and the target power level of 24kW. Therefore, Switch number 1 is selected for designing the physical layout in Power Synth 2.**



(a) High-side switch (S2)



(b) Low-side switch (S1)

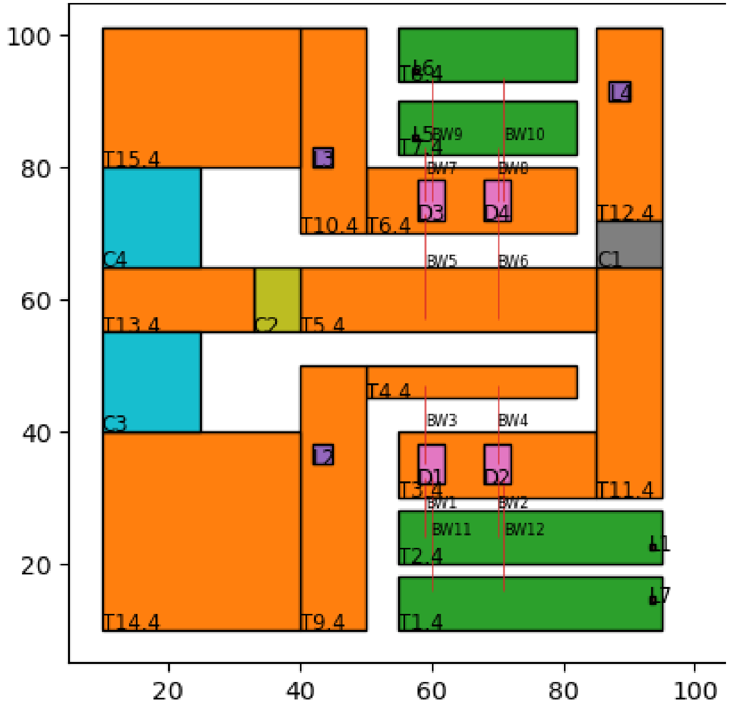


(c) Total Losses

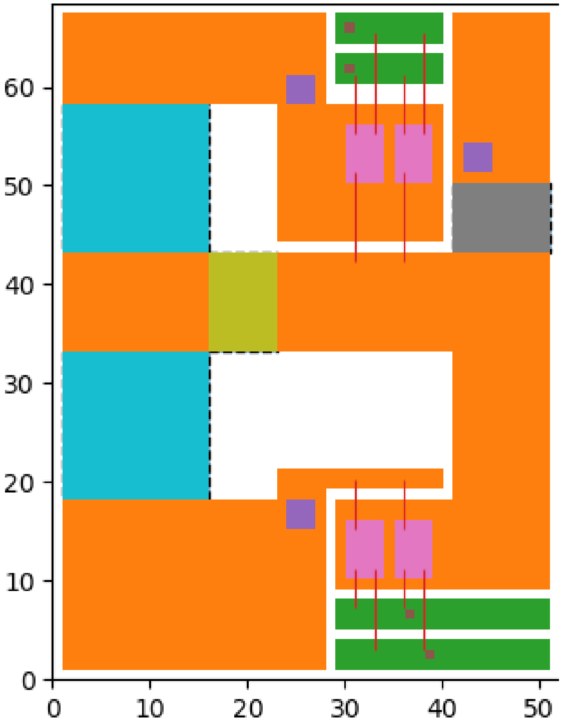
Initial Results with an Optimized Layout

- ✓ **Bidirectional dc-dc converter layout Design in PowerSynth2**
  - **(a) Initial layout geometry of the converter,**
  - **(b) Layout geometry for Layout Mode=1,**
  - **(c) Solution space for 2D layout optimization Layout Mode=1 (Fixed size solution).**

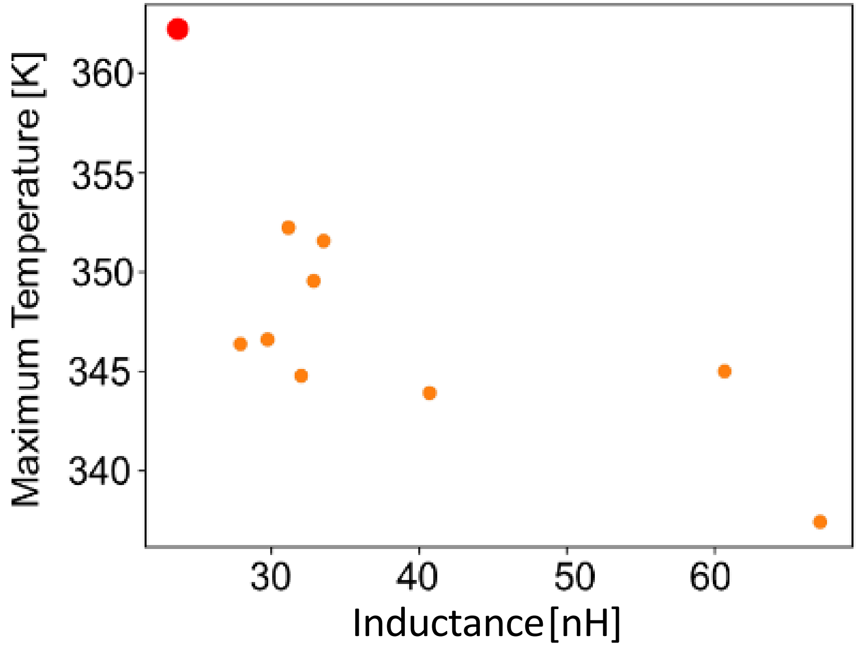
Algorithm: NG-RANDOM



a)



b)

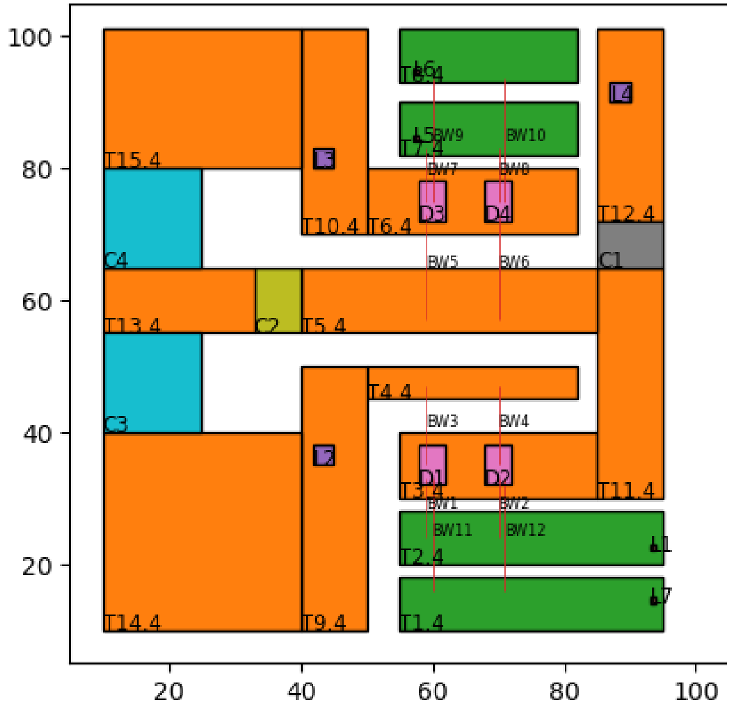


c)

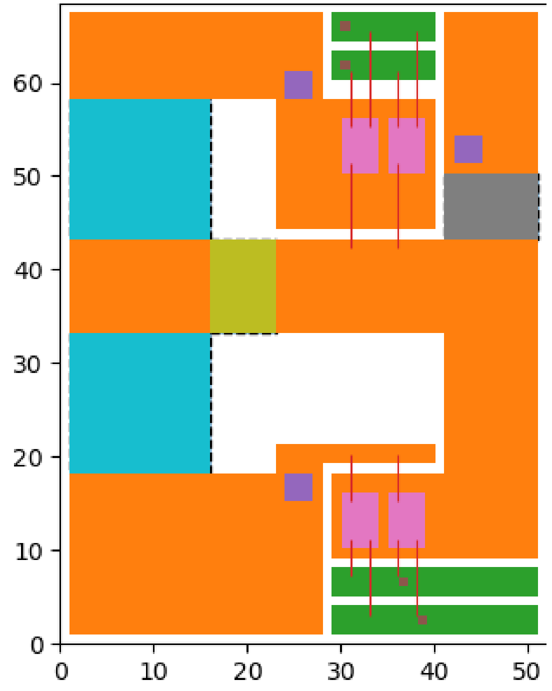
Initial Results with an Optimized Layout

✓ **Bidirectional dc-dc converter layout Design in PowerSynth2**

(a) Initial layout geometry of the converter
(b) Layout geometry for Layout Mode=0
(c) Solution space for 2D layout optimization Layout Mode=0 (Minimum sized solution).



a)



b)

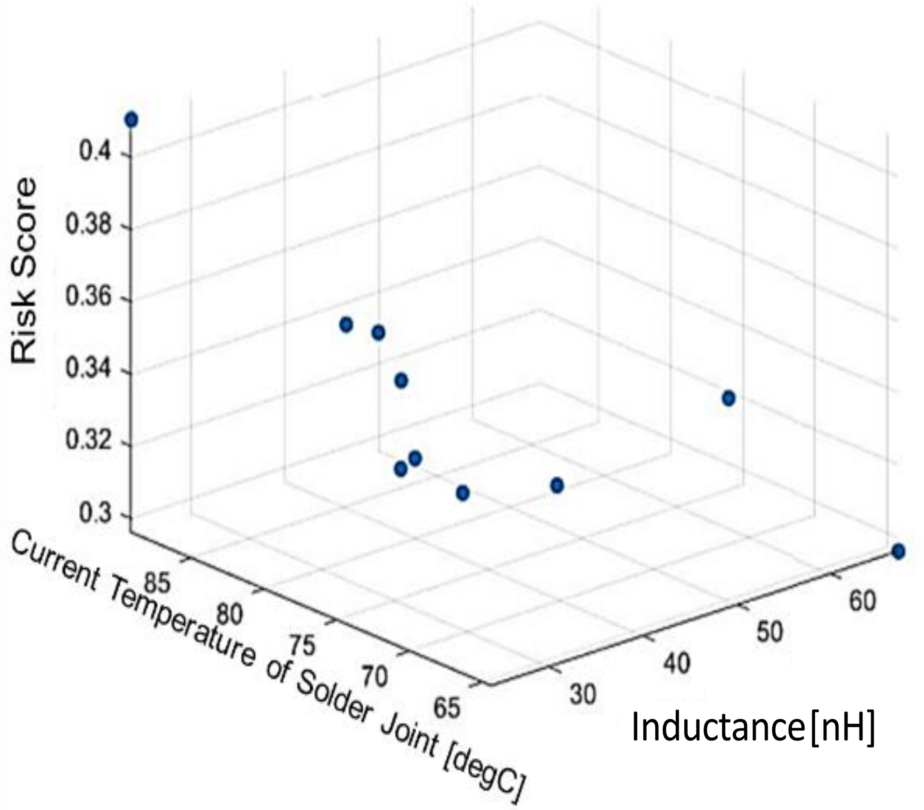
Algorithm: NG-RANDOM
Number of layouts :10

Size	Inductance [nH]	Max_Temperature
[52.1, 68.5]	20.20033902	366.2995648

c)

Initial Results with an Optimized Layout

- ✓ **Reliability and Risk Analysis**
  - ✓ Automated optimization of component selection and physical layout design for reliable bidirectional DC-DC converters is achieved through the **integration of the ParaPower Tool with PowerSynth.**
  - ✓ This process extracts maximum temperature data, with a focus on solder joints, and compares current temperatures to the designated melting point (set at 217°C for SAC 405 solder joints) to assess layout design risks.
  - ✓ Guiding the selection of the most dependable converter design, with homologous temperature (current temperature divided by melting temperature) serving as a key metric for evaluating solder joint thermal performance and **severity risk scores**;



Risk Score versus Inductance and Solder joint temperature for different layout models.

Summary of Design flow of a Power Converter

DMC
DESIGN METHODOLOGIES FOR POWER ELECTRONICS

Convertor Data

- Converter Structure
- Defining the Baseline System based on the Application (Voltage and Power Standard level ranges)
- Number of Paralleled Modules of structure
- Switching frequency
- Control algorithm

Data Base of Components

- Components Selection based on the application for the Switches, Capacitors, Inductors, Filter, Heatsink, Gate Driver

Components Selection Optimization

- Power density optimization by using Power Loss equations and available loss data for switches, inductors, capacitors, etc applying Monte-Carlo simulation

Extract Result of SWaP-C Optimization

- Creating Baseline system for PowerSynth tool distribution by using selected components from SWaP-C Optimization

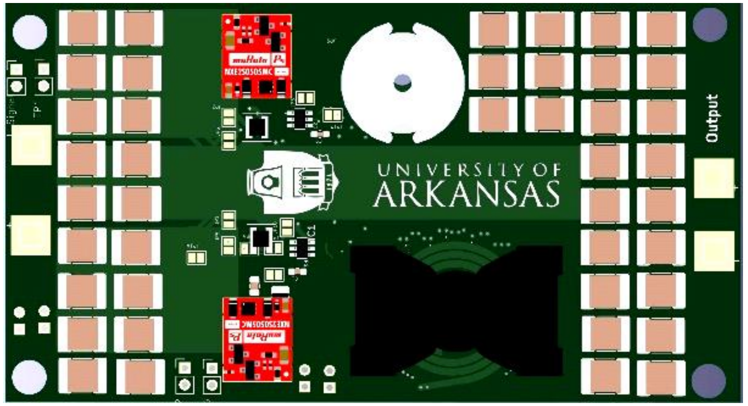
Physical Layout Optimization Utilizing PowerSynth

- Utilize the components from previous stage
- Running PowerSynth 2
- Minimize Inductance power loop
- Integration of PowerSynth 2 and ParaPower for Reliability analysis

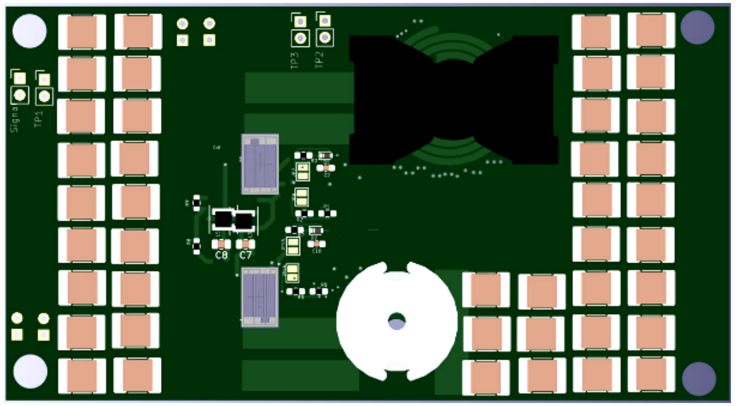
Initial Results with an Optimized Layout

✓ **Bidirectional dc-dc converter layout Design**

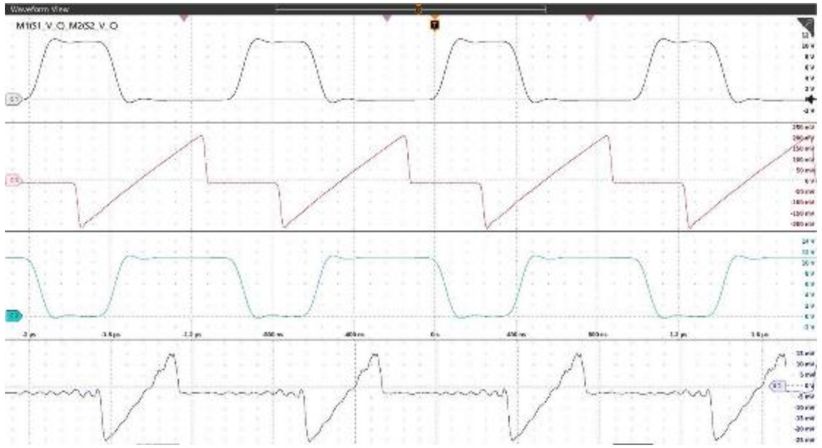
(a) Top view of the extracted layout
(b) Bottom view of the extracted layout
(c) The primary experimental results



a)



b)



c)

CONCLUSION

- ✓ Presenting a methodology for optimizing bidirectional ZVS DC-DC converter design automation.
- ✓ It employs PowerSynth 2 for layout optimization and utilizes Monte Carlo optimization for tradeoff analysis.
- ✓ The study emphasizes the importance of component selection, particularly switches,
- ✓ Demonstrates the significance of temperature and inductance values in thermal analysis.
- ✓ By integrating mathematical design analysis with PowerSynth 2 and ParaPower tools, this research contributes to the automation and optimization of ZVS bidirectional DC-DC converter design with more reliable layout
- ✓ Comparing to previously presented optimization methods, the proposed approach not only include 1) components selection optimization, but also 2) the physical layout optimization for layout arrangement selection utilizing PowerSynth tool .

Thank You!

PowerSynth Release Website:
https://e3da.csce.uark.edu/release/PowerSynth/
PowerSynth Source Code Repository: **https://github.com/e3da**