The views expressed are those of the authors and do not reflect the official policy or position of the U.S. Department of Defense or the U.S. Government.

MIT ESRDC Mini-Symposium

MIT Sea Grant College Program

Electric Ship Research and Development Consortium

May 21, 2025

Agenda

1200	Welcome, Opening Remarks	Dr. Julie Chalfant CAPT L.J. Petersen, USN, Ret (ONR)
1210	Navy Integrated Power and Energy Corridor (NiPEC) Overview	Dr. Julie Chalfant
1230	A Multi-Objective Design for PEBB-Based Power Corridors in Shipboard Applications	Marco Gallo, University of Genova, IT
1250	Metaheuristic Optimization for Automatic Arrangement of Power Electronics Components in a Shipboard Electrical Distribution System	Sebastien Lohier
1310	Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks	Dr. Aniruddha Bora, Brown University
1330	NiPEC-PEBB Latching Mechanism	MIDN 1/C Jack Dirig, USN
1350	NiPEC PEBB Latching: A Clamping Paradigm Shift	Jacob Film
1420	BREAK	
1440	Shipboard Power Systems	Prof. Steve Leeb
1545	Wrap-up, Closing Remarks/Discussion	ALL

Team (to date)

UNIVERSITY of WISCONSIN
UWMILWAUKEE

UNIVERSITY OF
TEXAS
ARLINGTON

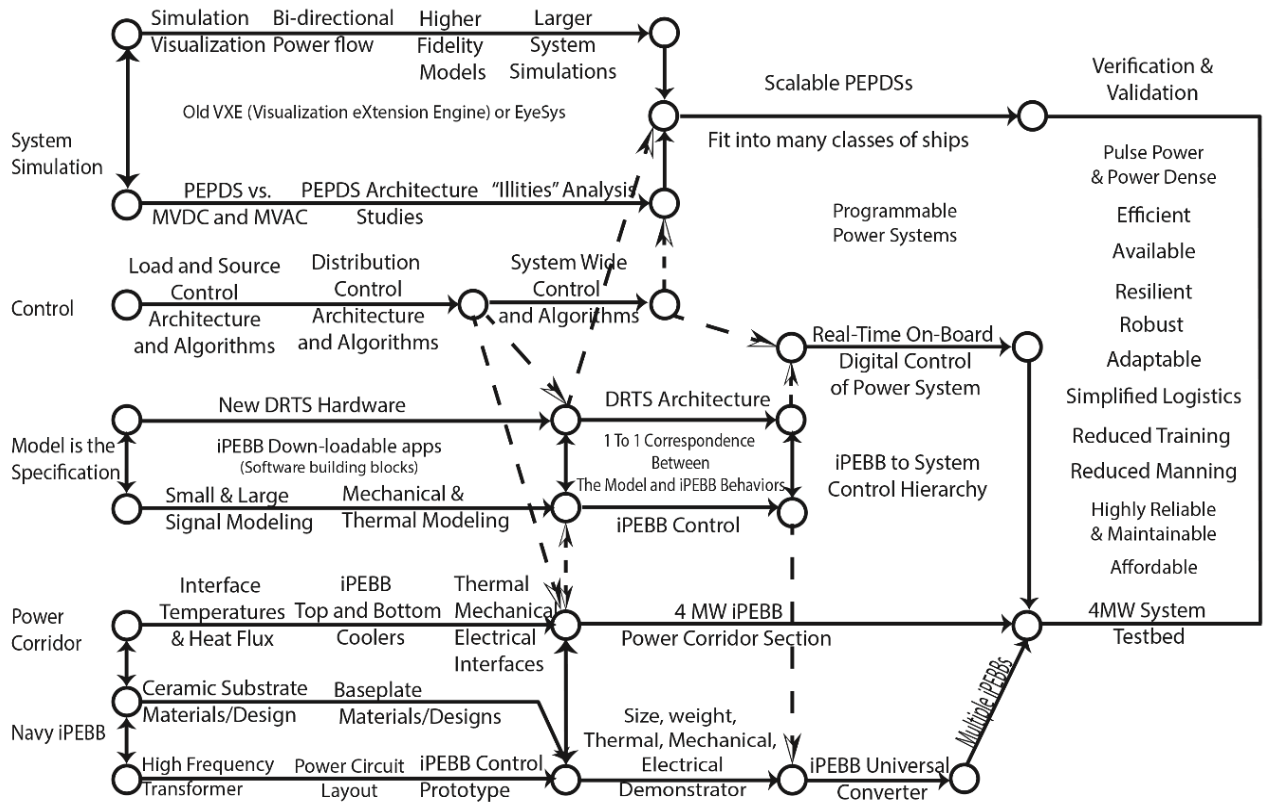
Office of Naval Research
ONR
Science & Technology

VIRGINIA TECH

NAVSEA
WARFARE CENTERS
PHILADELPHIA

UNIVERSITY OF
South Carolina

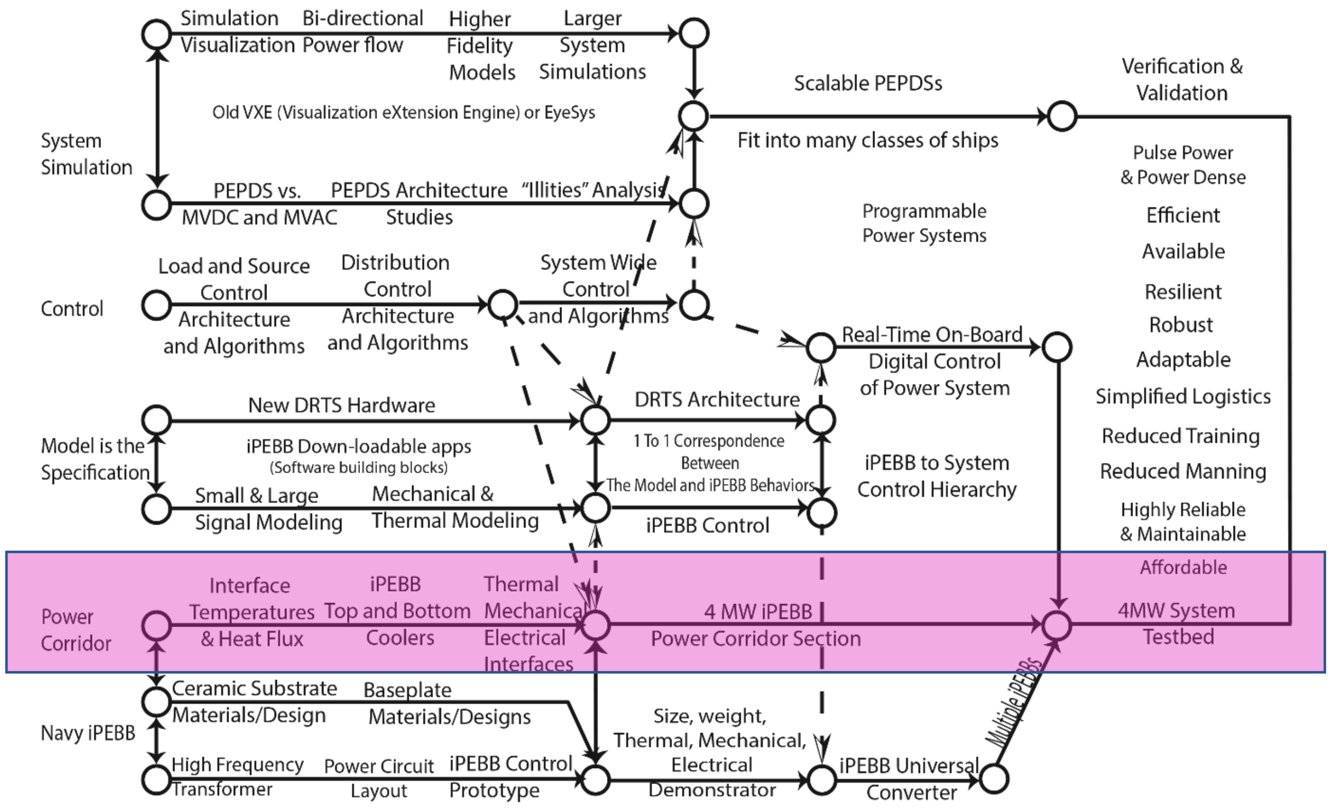
Multi-year Multi-university Research Program



Areas of study:

- Controls
- Energy Storage
- Dielectrics/EMI
- Thermal Management
- PEBB
- Electrical/Thermal/ Mechanical Interfaces
- Health Monitoring
- Ship Integration

Multi-year Multi-university Research Program



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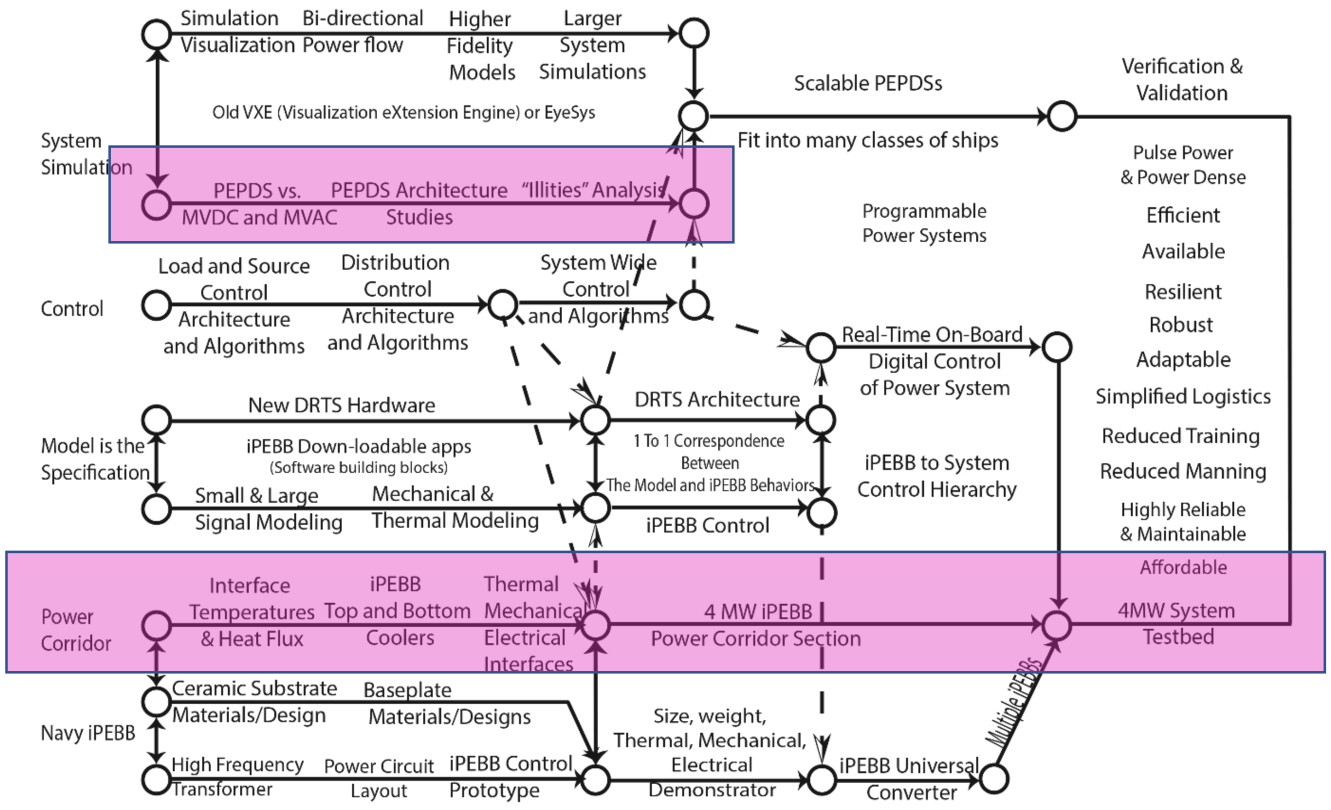
Multi-year Multi-university Research Program



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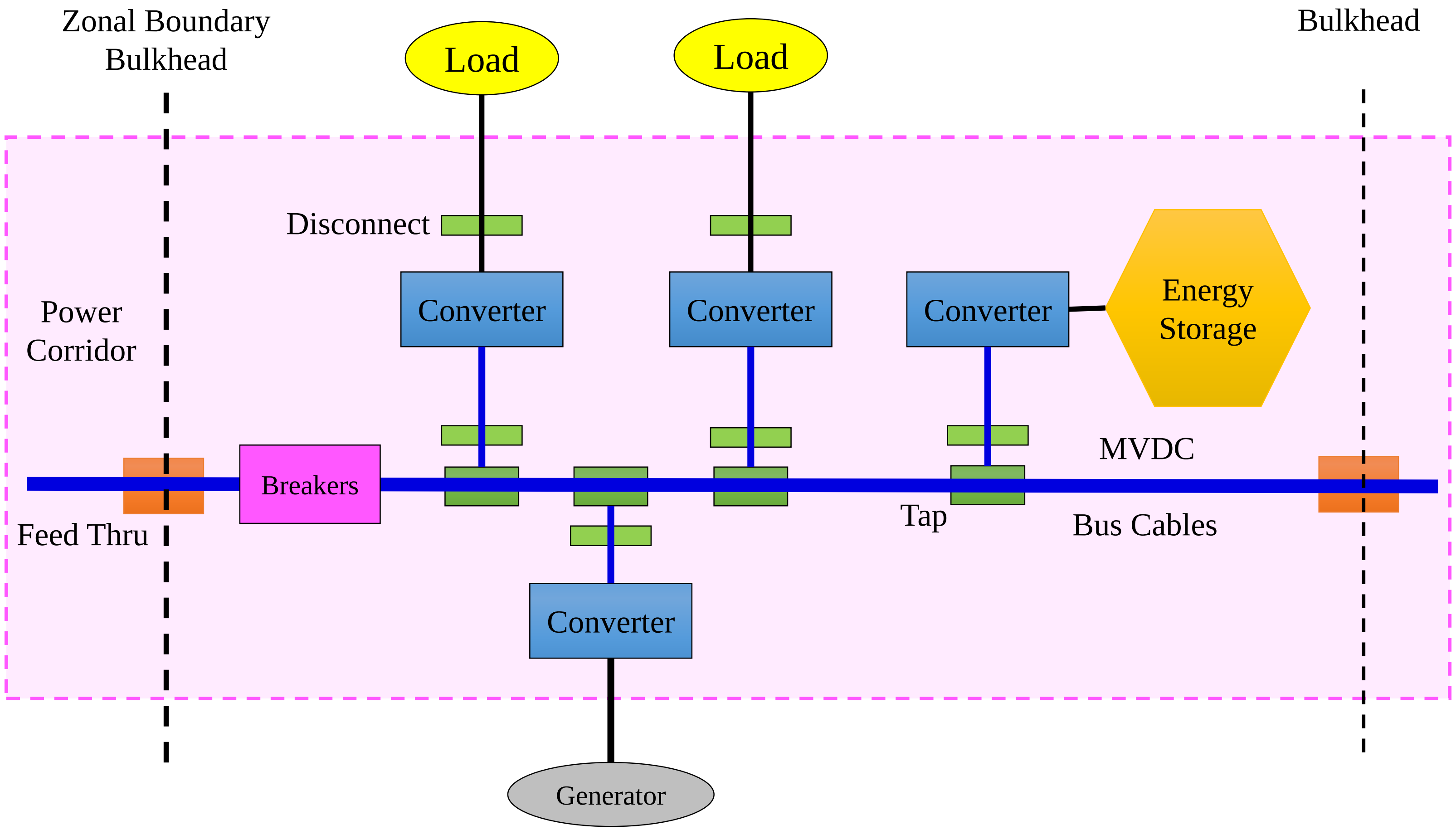
- Ship Integration

Navy integrated Power and Energy Corridor (NiPEC)



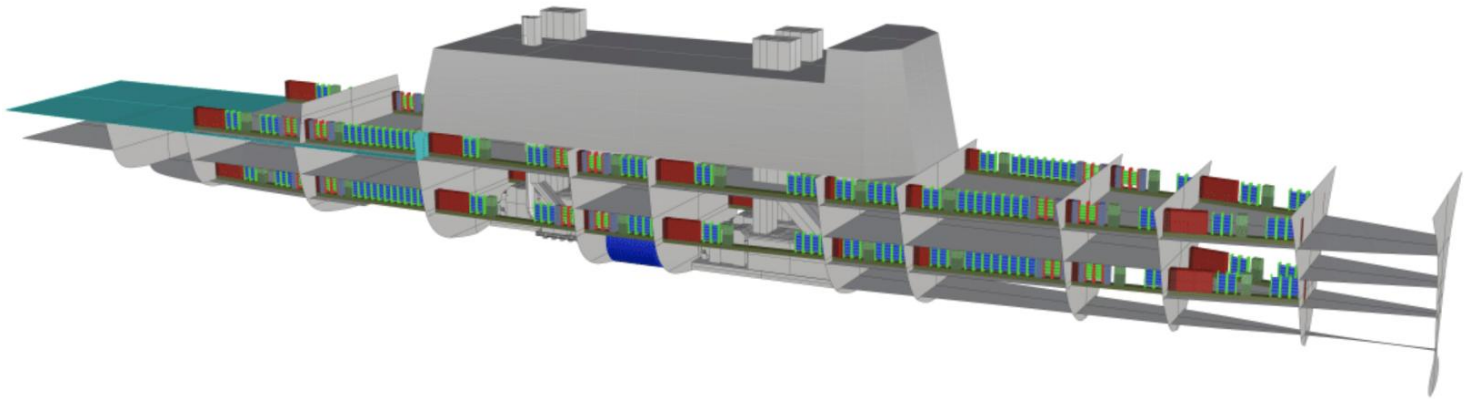
The concept:

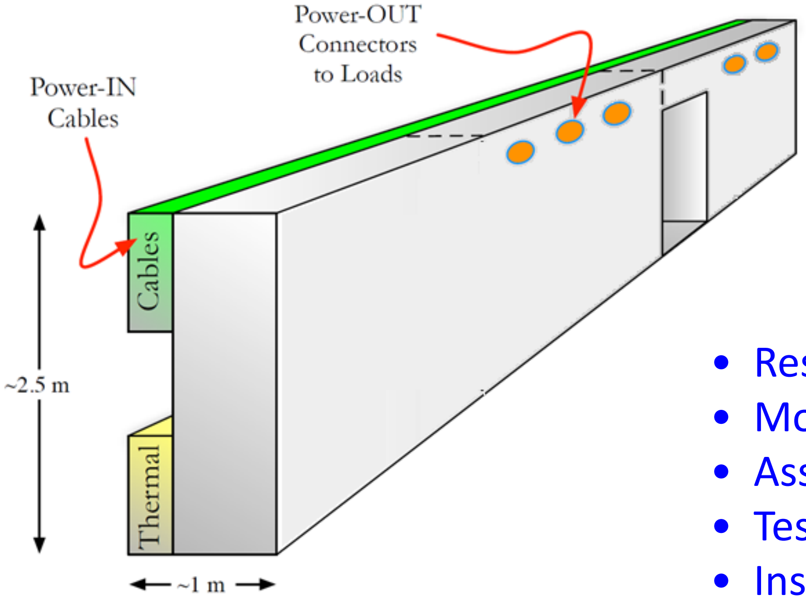
Incorporate in a single modular entity all the components of the electrical distribution system:

- Main bus cables
- Conversion
- Protection
- Isolation
- Control
- Energy Storage

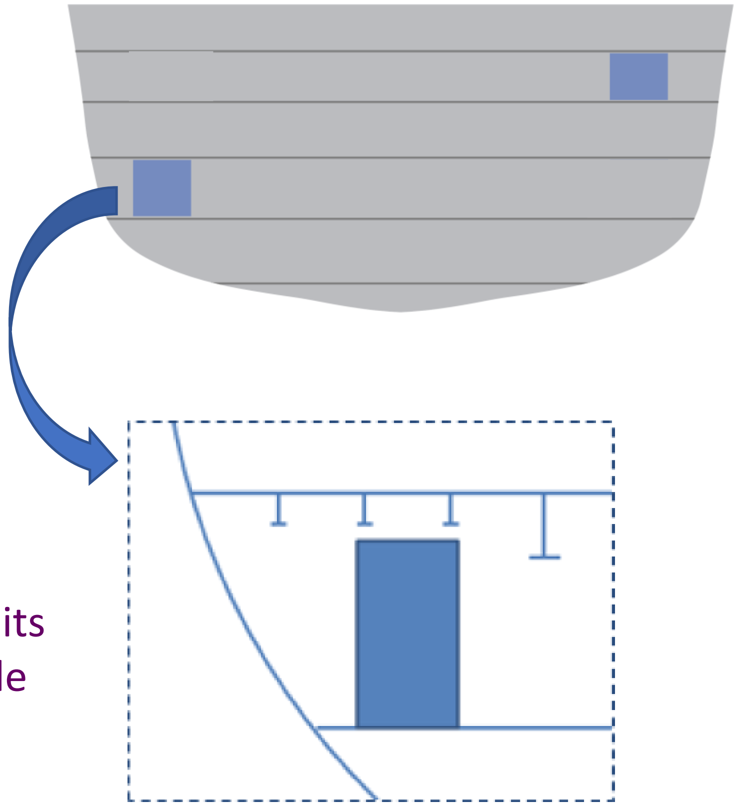
for the main bus power throughout the ship.

NiPEC Concept



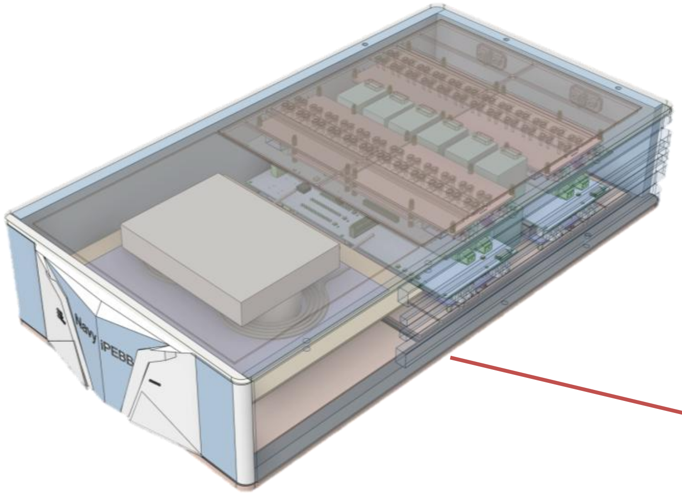


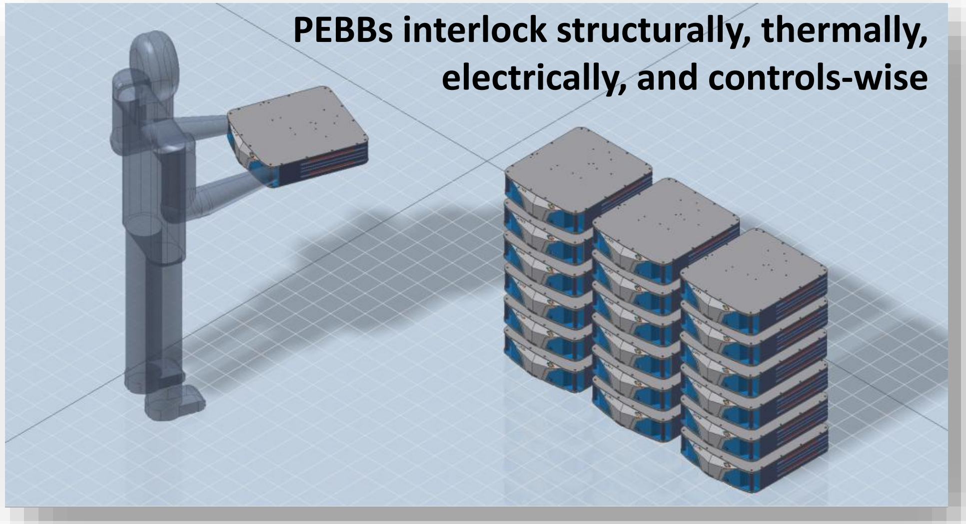
- Reserved space, early in design
- Modular construction, repeated units
- Assembled off-hull, clean, accessible
- Tested off-hull, sensitive, thorough
- Install into ship, as an assembly

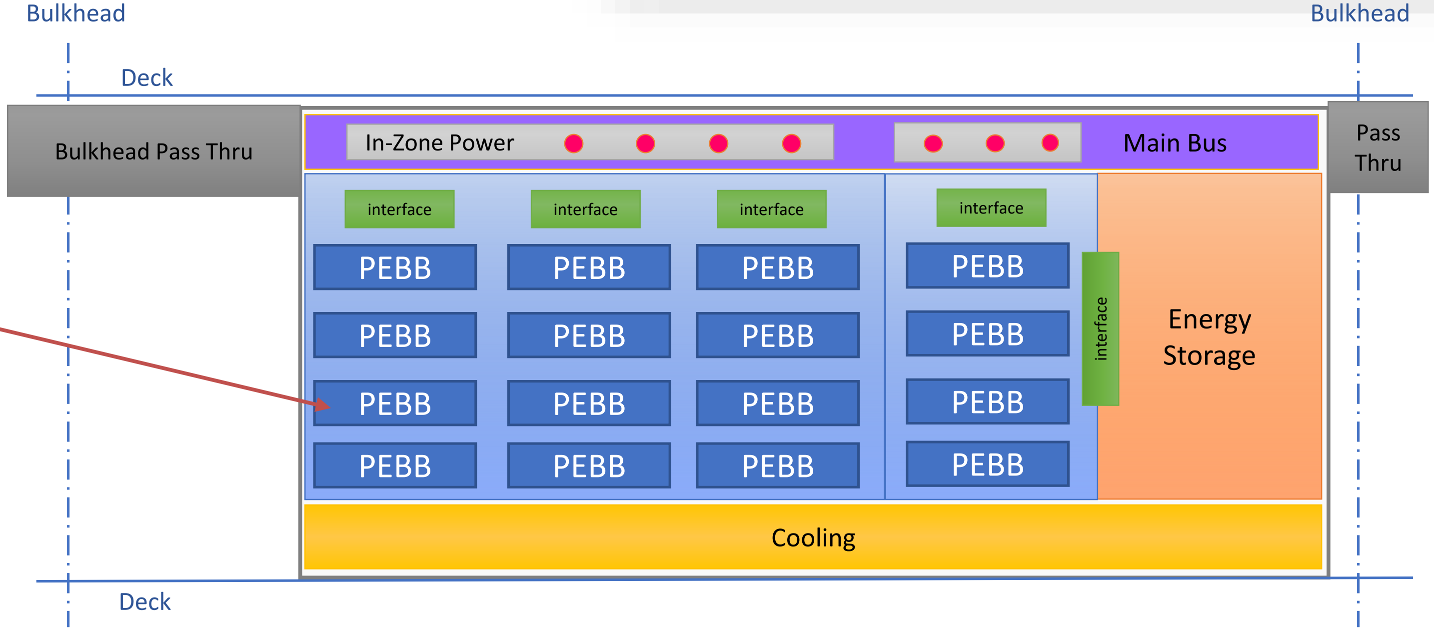


PEBB-Based NiPEC

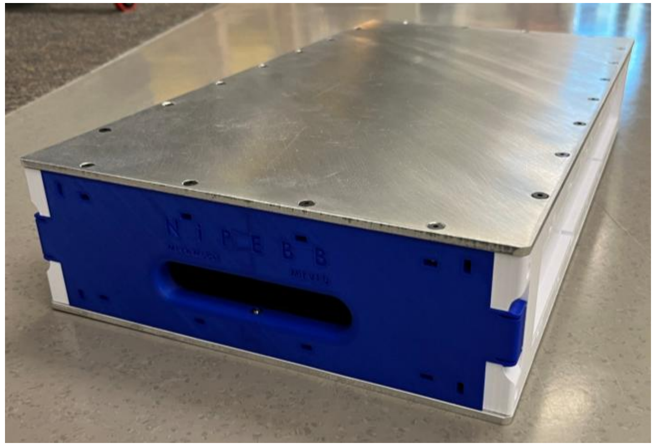
Least Replaceable Unit (LRU):
Power Electronics Building Block (PEBB) -
A modular, repeatable, programmable, sailor-carriable universal converter

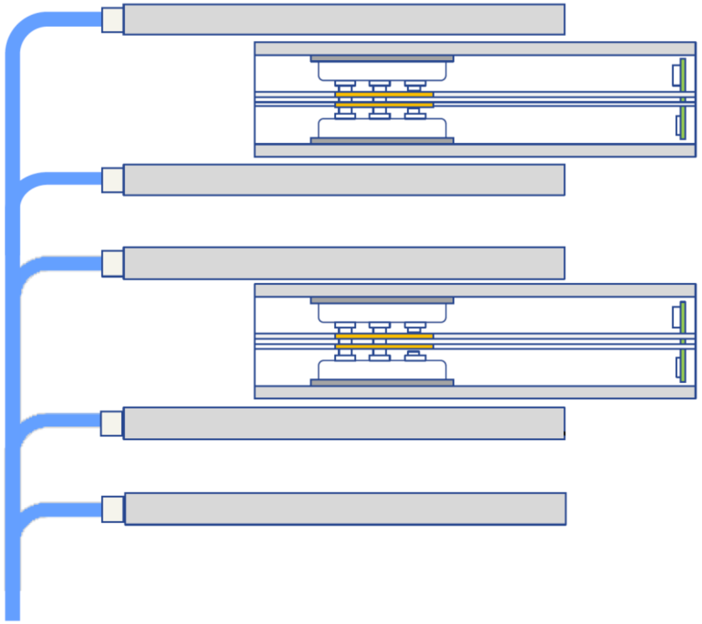






Indirect Liquid Cooling





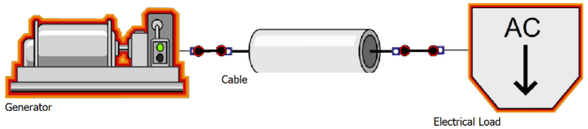
- **PEBB Cooling options**
  - Air cooling
  - Single-phase direct liquid cooling
  - Two-phase cooling
  - Indirect liquid cooling
- **Constraints**
  - No external connections
  - Minimize leak potential onto electronics
  - Weight
- **Indirect liquid cooling**
  - Liquid cooling via cold plate
  - Cold plate is built into the NiPEC structure
  - Thermal pad improves heat transfer between iPEBB and cold plate
  - iPEBB is inserted then mechanically forced into contact with cold plate

Smart Ship Systems Design (S3D)

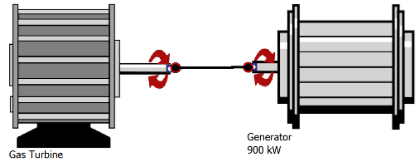
- **Early-stage tool for the design, simulation and analysis of ship systems**
  - Discipline-specific 2D views for electrical, mechanical, piping, and HVAC
    - Each discipline has its own view/abstraction of the system model
  - Extensive equipment catalog populated with mathematical models and properties for equipment pertinent to the appropriate systems
- **Performs power flow analyses**
  - Power demands, generation, and loss estimation
  - Thermal management
  - Connection validity checks
- **Integrated with LEAPS**
  - Navy's data repository
  - Available to all LEAPS-compatible tools
- **Developed by ESRDC**

ELECTRIC SHIP RESEARCH
ESRDC
AND DEVELOPMENT CONSORTIUM

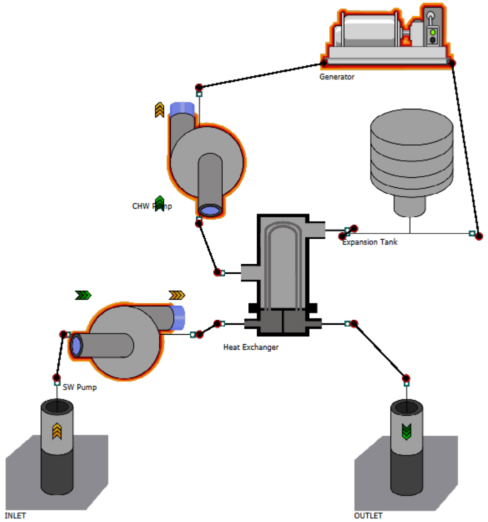
Electrical View



Mechanical View



Piping View



MIT Focus: Navy integrated Power and Energy Corridor (NiPEC)

Technical Approach:

- Building on previous research into the electrical/thermal/mechanical interfaces to the iPEBB: design, prototype and test a NiPEC/PEBB interface.
- Develop design of NiPEC segments.
- Perform ship-wide analysis and ship design impacts of NiPEC concepts.
- Develop design tools for PEPDS/NiPEC, integrated with S3D.
- Develop methods for condition monitoring and grid stabilization.

NiPEC-related Topics

1230	A Multi-Objective Design for PEBB-Based Power Corridors in Shipboard Applications	Marco Gallo, University of Genova, IT
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Papers

M. Gallo, C. M. Cooke, J. S. Chalfant, F. D'Agostino, "**A Multi-Objective Design for PEBB-Based Power Corridors in Shipboard Applications**", IEEE Electric Ship Technologies Symposium (ESTS) 2025, submitted.

M. Gallo, C. M. Cooke, J. S. Chalfant, F. D'Agostino, F. Silvestro, "**Linearization Techniques for Optimizing PEBB-Based DC Power Corridor Using Mixed-Integer Linear Programming**", 2025 AEIT HVDC, accepted.

Lohier, Sebastien and Julie Chalfant, "**Metaheuristic Optimization for Automatic Arrangement of Power Electronics Components in a Shipboard Electrical Distribution System**", *ASNE Intelligent Ships Symposium*, accepted.

Hernandez, David and Julie Chalfant, "**Lightweight Heat Pipe Cooling Solution for High-Frequency Transformer in Power Electronics Building Block**", *ASME Journal of Thermal Science and Engineering Applications*, accepted.

Robert M. Cuzner, David C. Gross, Hamed Shabani, Naqash Ali, Julie Chalfant and Mischa Steurer, "**Determining Parameter Objectives for MBSE Approach to Early Ship Design Exploration**", *IEEE Transactions on Transportation Electrification*. Accepted.

A. Lemmon, R. Khanna, J. Chalfant, A. Davoudi and A. M. Bazzi, "**Guest Editorial Special Issue on Electrified Ship Technologies**," in *IEEE Transactions on Transportation Electrification*, vol. 10, no. 4, pp. 7645-7650, Dec. 2024, doi: 10.1109/TTE.2024.3510993.

Andrea Alessia Tavagnutti, Hayden Atchison, Julie Chalfant, Chryssostomos Chryssostomidis, David Wetz, Giorgio Sulligoi, "**Incorporating Energy Storage in the Design of an All-electric Naval Vessel**", *IEEE Transactions on Transportation Electrification*, vol. 10, no. 4, pp. 7907-7917, Dec. 2024, doi: 10.1109/TTE.2024.3455896.

J. C. Ordonez, C. Sailabada, J. Chalfant, C. Chryssostomidis, C. Li, K. Luo, E. Santi, B. Tian, A. Biglo, N. Rajagopal, J. Stewart, C. DiMarino, "**Thermal Management for Ship Electrification - Approaches for Power Electronic Building Blocks and Power Corridors**", *IEEE Transactions on Transportation Electrification Special Issue on Electrified Ship Technologies*, vol. 10, no. 4, pp. 7918-7929, Dec. 2024, doi: 10.1109/TTE.2024.3391209.

Next Steps

PEPDS Tech Candidate Demonstrations

1. **1 MW Power Corridor- like demonstration platform at NSWCPD utilizing legacy IFTP equipment**
2. **Physical comparison of legacy PEBBS to NiPEBB demonstrating SWAP improvements, connectivity and differences in installation**
3. **Demonstrate a prototype PEBB tray with locking mechanism and visualize the reduced footprint from legacy equipment** (*Note: Ideally this would be a physical demonstrations, but we may need to default to CAD drawings*)
4. **Show a "full-scale" demonstration of the use-cases in the legacy demo using NiPEBB in RT simulation (*electro-thermal model*).** *Note: Model design, requirements, documentation and V&V will leverage processes developed during RCPC FNC*
5. **Show a "full-scale" demonstration of the use-cases in the legacy demo using NiPEBB CHIL with RT simulation (*electro-thermal model*).** *Note: This would include at least two physical NiPEBB controllers.*
6. **Show a "reduced-scale" demonstration of the use-cases in the legacy demo using NiPEBB PHIL with RT simulation (*electro-thermal model*).**
7. **Demonstrate tools for design of PEPDS/NIPEB/PEBB**

Research areas are mapped directly to technical risks outlined in the TC proposal in order to be addressed/mitigated.

#	Baseline	Threshold	Objective
1	X	X	X
2	X	X	X
3	X	X	X
4	X	X	X
5		X	X
6			X

Projects/Tasks

Tech Candidate

- PEBB Thermal Management
  - Cold plate design
  - Rack-level cooling design
  - Prototype cooling system for single NiPEBB
- PEBB Interfaces
  - Establish connector parameters.
  - Design or evaluate appropriate connectors
  - Prototype or purchase as necessary and arrange for test
- PEBB Latching
  - Establish latching mechanism parameters
  - Design and prototype latching mechanism

ESRDC

- Ship System Design based on NiPEC/PEPDS
  - Sizing for NiPEC segment:
    - Sizing/arrangement algorithm for NiPEC segment.
    - Sizing functions for non-LRU electrical components within NiPEC segment
    - Sizing functions for non-electrical components within NiPEC segment
  - Ship Designs for Application of NiPEC
  - PEBB-based Converter Design

Thank you

Support from

the Office of Naval Research under Grant No. N00014-21-1-2124

is quite gratefully acknowledged.

PEBB-based Power Corridor Sizing Algorithm

Project Presentation

PhD. Student: Marco Gallo
Supervisors: Julie S. Chalfant and Chathan M. Cooke
Date: 21/05/2025

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Background & Motivations

1. Modern ships totally dependent on **electric power**
    - For example, power corridors for electric power distribution
2. Power electronic modules provide conversion from HV bus to load
    - Called **PEBBs** (Power Electronic Building Blocks)
    - Example designs presently under development at VT (**PEBB 1000**, **PEBB 6000**, and **iPEBB**)
3. Challenge: What power capability should these modules have?
    - Is one size sufficient?
    - Different loads may require different power ratings and flexibility.
4. This work proposes an **optimization algorithm** to find the best number and size of PEBBs.

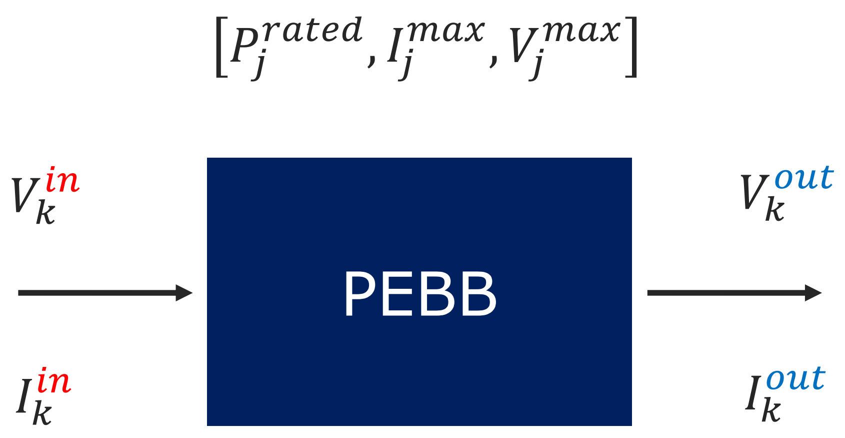
System Description – PEBB definition

Each PEBB is characterized by three key parameters:

- **Rated power:** P_j^{rated} $[MW]$
- **Maximum current:** I_j^{max} $[kA]$
- **Maximum voltage:** V_j^{max} $[kV]$

The dc power is defined as:

- Input → $P_k^{in} = V_k^{in} I_k^{in}$
- Output → $P_k^{out} = \eta_k V_k^{out} I_k^{out}$ → efficiency dependence



Modelling Assumptions

- **dc power system**: Only dc bus distribution and dc loads are modeled; ac behavior can be included in the future.
- **Uniform PEBB parameters**: Each PEBB cluster operates at the same rated power, voltage, and current.
- **Converter model**: PEBBs are modeled as ideal buck converters ($V^{in} \geq V^{out}$).

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System Description – Cluster definition

A PEBB **cluster** is defined as: *"A group of PEBBs, each with the same rated power, voltage and current, that interfaces the power corridor with a load or a group of loads."*

A PEBB cluster adapts bus and load requirements through:

- $n_k^{s,in}$ PEBBs in **series** on the **input** side

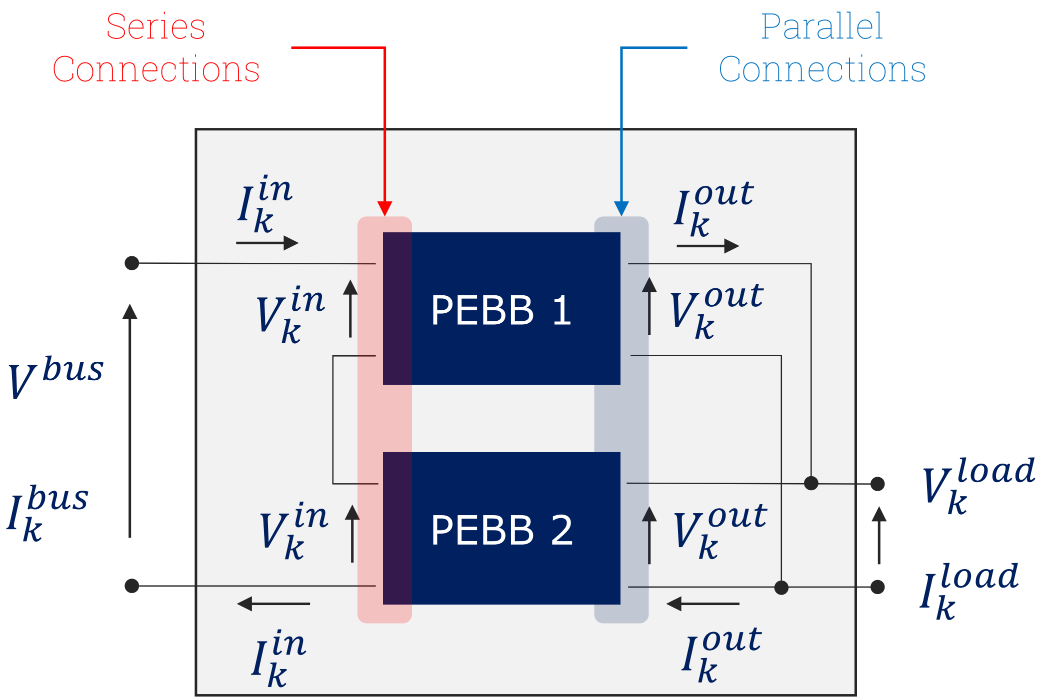
  $\rightarrow V^{bus} = n_k^{s,in} V_k^{in}$

- $n_k^{p,in}$ PEBBs in **parallel** on the **input** side

  $\rightarrow I_k^{bus} = n_k^{p,in} I_k^{in}$

- On the **output** side

  $\rightarrow V_k^{load} = n_k^{s,out} V_k^{out};\ I_k^{load} = n_k^{p,out} I_k^{out}$



PEBB Cluster

Power Corridor Example

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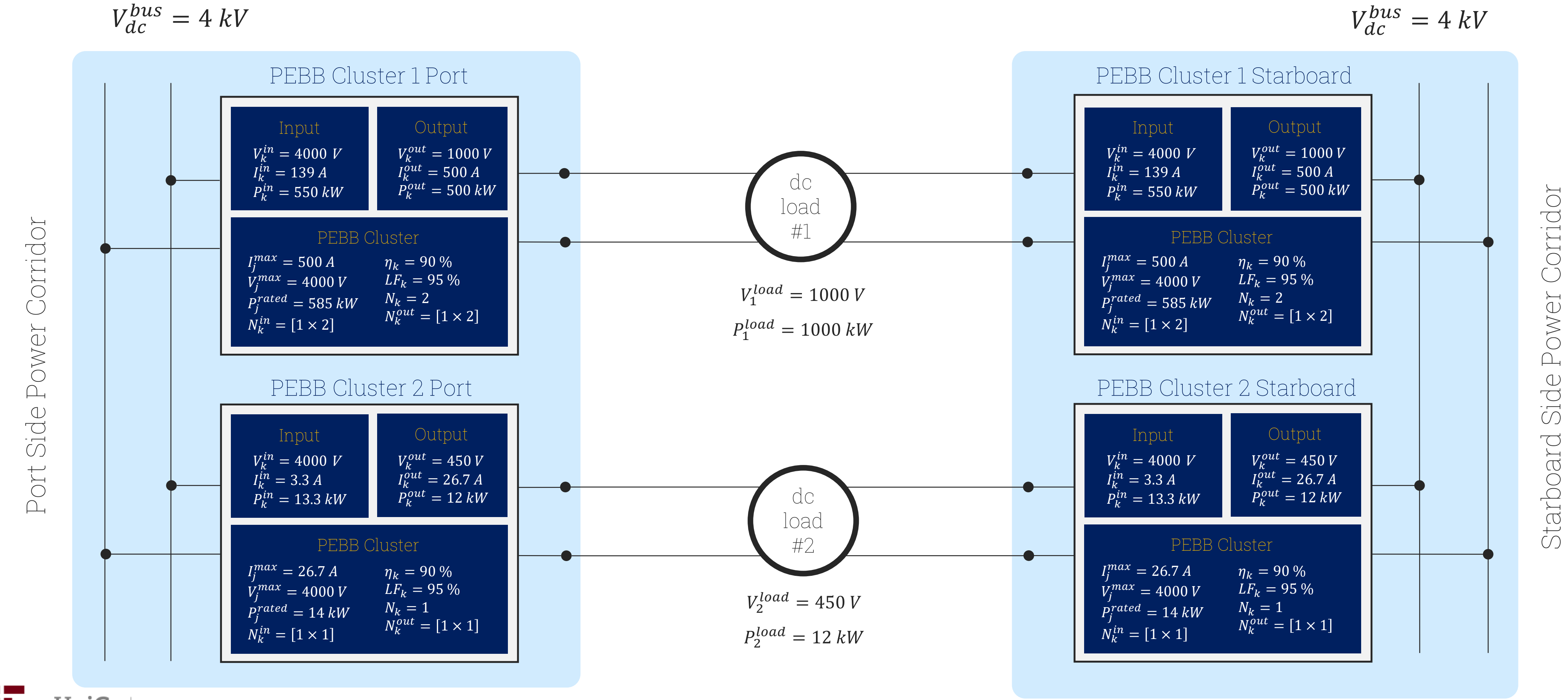
PEBBs interface loads with the **power corridor**, ensuring voltage and current are properly matched. In the example, **two dc loads** are connected through **redundant** PEBB clusters → need for **optimization**



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Metric Definition

To explore trade-offs in PEBB selection, three key metrics are defined:

- **Rated Power** - J_P - affects how many PEBBs are needed, too many or too few can affect system design.
- **Efficiency** - J_Ω - varies with load and is modeled using B-spline curves shaped by key operating points.
- **Volume** - J_η - relates to power level but follows a non-linear trend; realistic fitting functions are used to capture this.
- **Penalty Function** - J_γ - if the total PEBB volume inside a bulkhead region exceeds the limit, a penalty is applied.

$$J = \frac{1}{w_P + w_\Omega + w_\eta + w_\gamma}\left(J_P w_P + J_\Omega w_\Omega + J_\eta w_\eta + J_\gamma w_\gamma\right)$$

$$J_P = \frac{1}{P^{max} J}\sum_{j=1}^{J} P_j^{rated}$$

- Maximum allowable power P^{max}
- Maximum number of PEBB ratings J

$$J_\Omega = \frac{1}{N^{max}\,\Omega^{max}\,K}\sum_{k=1}^{K} \Omega_k^{tot}$$

- Maximum allowable volume Ω^{max}
- Maximum number of PEBB N^{max}
- Total PEBB cluster volume Ω_k^{tot}

$$J_\eta = \frac{1}{K(1-\eta^{min})}\sum_{k=1}^{K}(1-\eta_k)$$

- Minimum PEBB efficiency η^{min}
- PEBB efficiency η_k
- Total number of clusters K

$$J_\gamma = \frac{1}{B}\sum_{b=1}^{B}\Gamma_b$$

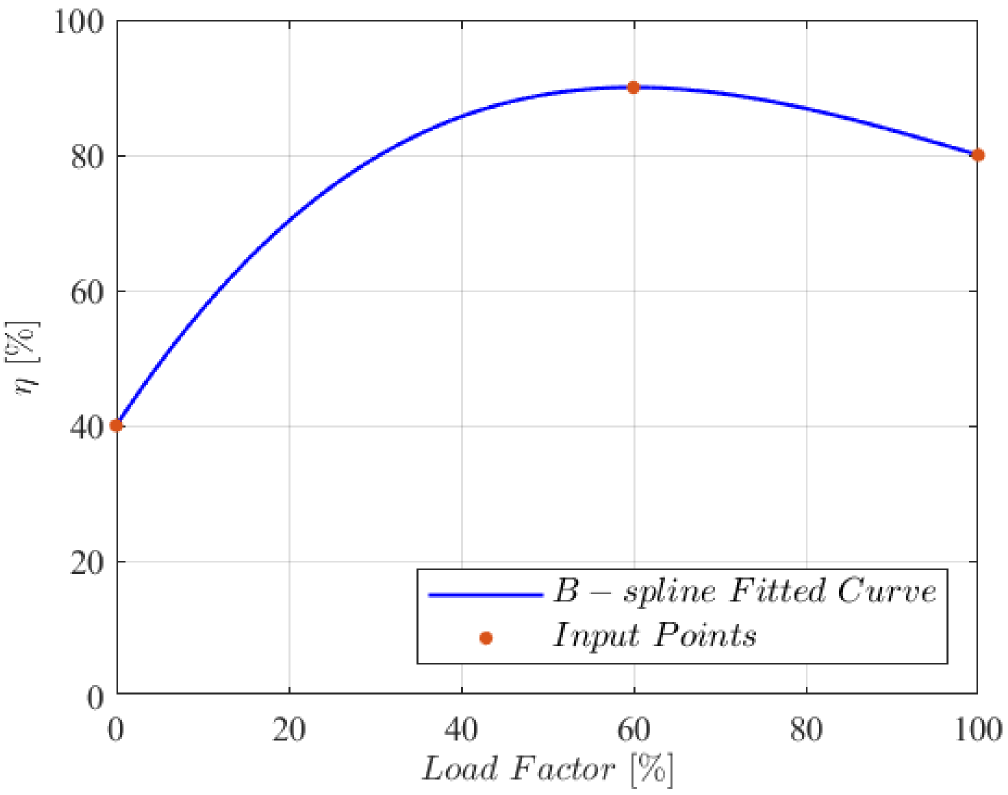
- Total number of bulkhead regions B
- Related bulkhead penalty Γ_b

Efficiency and Volume

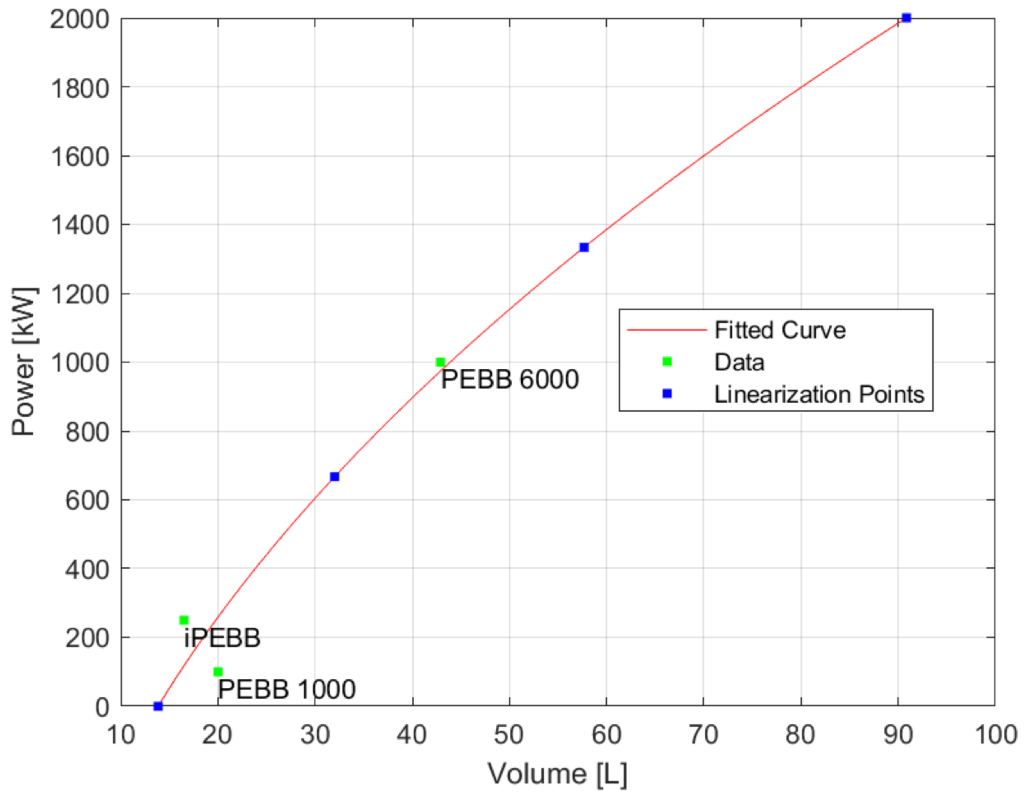
Efficiency and volume are related to the working point of the single PEBB and the rated power, respectively.

- **Efficiency** → a B-spline fit three points (initial, maximum efficiency and final). Knots can be adapted to change the shape.
- **Volume** → regression based on the 3 existing PEBBs data using a defined input function → $P^{rated} = a\sqrt{\Omega_k} + b$

Efficiency Curve



Volume Curve



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Matlab & GAMS Integrated Tool

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What is **MATLAB**?

- High-level programming language and environment
- Designed for numerical computing, data analysis, and visualization
- Widely used in engineering, science, and finance
- Supports matrix operations, algorithm development, and simulation

What is **GAMS**?

- General Algebraic Modeling System (GAMS)
- High-level language for mathematical optimization
- Focused on linear, nonlinear, and mixed-integer programming
- Used in energy systems, economics, supply chain, and logistics.

PEBB-based power corridor Tool (v.04)

Tool Version date: 27 December 2024

Author: Marco Gallo

Given an input load distribution, the Tool:

1. aims to find the optimal size of the PEBBs for each PEBB stack;
2. optimizes the configuration of series and parallel PEBB connections.

It is based on a optimization process where constraints and an objective function are defined. The formulation is based on a Mixed Integer Linear Programming (MILP) problem.

Notes

- AC modelling is not implemented in the algorithm;
- The power corridor bus distribution is modelled for DC systems;
- For each PEBB stack, the power, voltage and current level is the same;
- PEBB are modelled as buck converter;
- The input voltage of the PEBB is equal to the rated voltage;

Select what is your operating system

Operating System	Windows
GAMS Version	48

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Why Matlab into GAMS?

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Each environment is used for what it does best:

- **Matlab** : flexible scripting, data manipulation, and plotting.
- **GAMS**: efficient and clear optimization modeling

Math

$$constraint \rightarrow Y_k = 2X_k$$

GAMS

```
constraint(k) .. Y(k) =e= 2*X(k);
```

Matlab

- Visualization
- Advanced Toolbox
- Debugging
- Flexible Data Import/Export
- Process Automation

GAMS Matlab Control API

Use of Java Libraries to exchange data

GAMS

- High-level computer programming languages
- Tailored for Linear, Non-Linear and Mixed-Integer Problems

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Mixed Integer Linear Programming (MILP)

The PEBB configuration problem has been formulated and solved as a Mixed-Integer Linear Programming (**MILP**) problem.

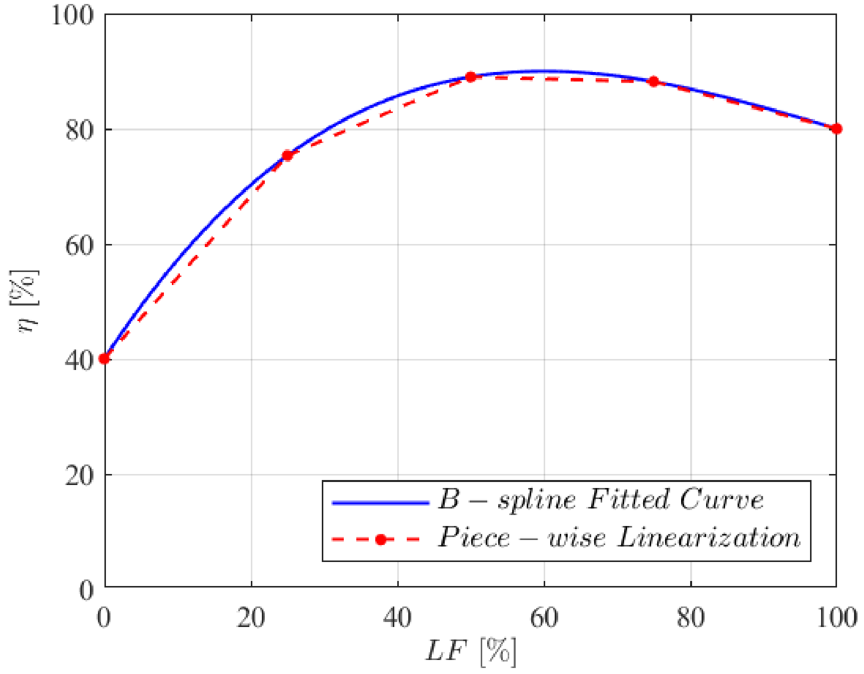
The original formulation includes several **non-linear** relationships arising from **power-efficiency** curve, power definition, and PEBB connections.

To enable MILP solvers, these non-linearities were reformulated using linearization techniques such as:

- **Piecewise** linear approximations
- **Binary** encoding strategies
- **Auxiliary** variable substitutions

The full methodology, including mathematical details and formulation steps, is thoroughly presented in the **HVDC** conference.

PEBB power vs efficiency curve



Linearization Techniques for Optimizing PEBB-Based DC Power Corridor Using Mixed-Integer Linear Programming

M. Gallo*, C. M. Cooke†, J. S. Chalfant†, F. D'Agostino*, F. Silvestro*
*IEES Laboratory, DITEN, University of Genova, Genova, Italy
†Design Laboratory, MIT Sea Grant College Program, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA
email: marco.gallo@edu.unige.it, cmcooke@mit.edu, chalfant@mit.edu, fabio.dagostino@unige.it, federico.silvestro@unige.it

Genova, May 29-30

AEIT HVDC international conference 2025

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Multi-objective function weighting factors

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Washington, Aug 5-8

To analyze how objective weights influence the optimal solution, a simplified test case was considered:

- **Single DC load**: 100 kW @ 1 kV
- **DC power corridor**: 4 kV

By varying the weights in the **multi-objective function** (power, efficiency, volume), the algorithm generates **different optimal PEBB configurations**, balancing performance according to design priorities.

This example highlights the core value of a multi-objective approach: it enables the exploration of trade-offs, helping designers balance different performance criteria. The PEBB sizing methodology and this analysis will be presented at the **IEEE ESTS Conference** in **Washington, August 2025**, titled “A Multi-Objective Design for PEBB-Based Power Corridors in Shipboard Applications”

Weighting Factors			Results					
Power	Efficiency	Volume	Prated [kW]	Vmax [kV]	Imax [A]	Efficiency [%]	Number of PEBBs	Total Volume [L]
✔	✔	✔	64.3	4000	100	90.9	2	30.5
✘	✔	✘	87.7	4000	100	95	2	31.6
✘	✘	✔	127.4	4000	100	90.5	1	16.7
✔	✘	✘	32.5	2000	50	91.3	4	58.2

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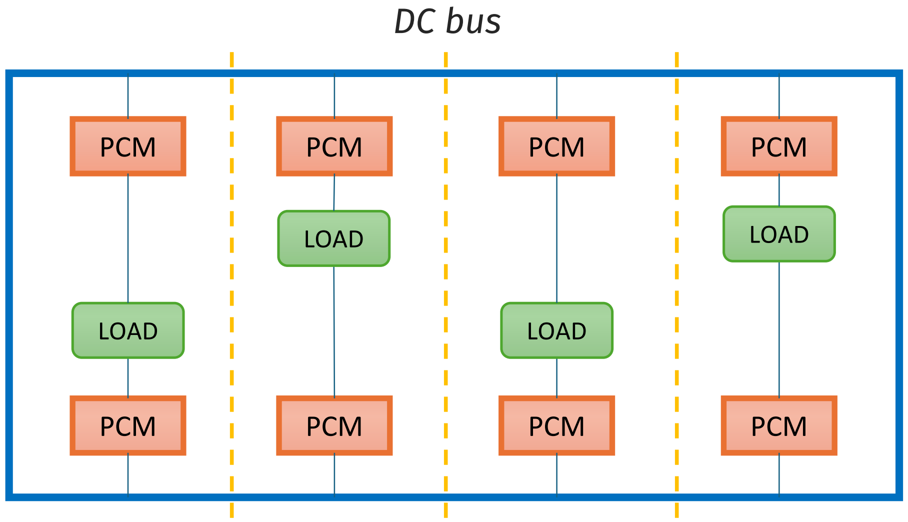
Ongoing Work

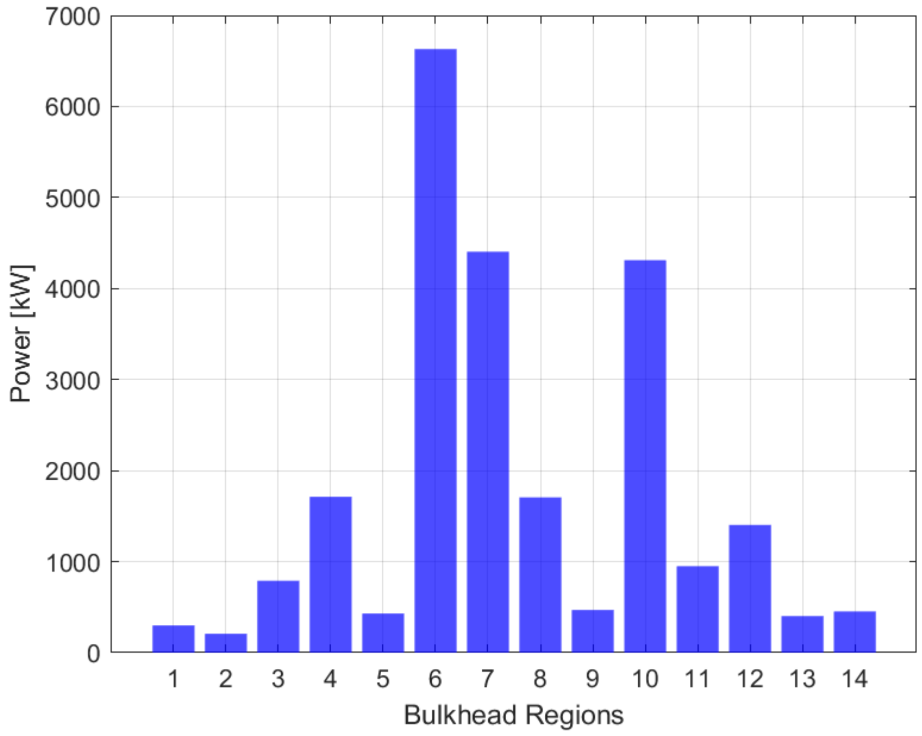
Objective: Test the algorithm performance on a realistic scenario

System: Notional Ship **(as in [1])**

Load Selection

- Only **dc loads > 100 kW** considered
- **Grouped** into clusters within a bulkhead region





[1] J. Chalfant, M. Ferrante, C. Chryssostomidis, "Design of a Notional Ship for Use in the Development of Early-Stage Design Tools," in IEEE Electric Ship Technologies Symposium, IEEE ESTS 2015, Alexandria, VA, June 21-24, 2015

Results Comparison (for specific weighting and loads)

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PEBB

Power Rating [kW]	Maximum Voltage [V]	Maximum Current [A]	Volume [L]
795.5	4000	600	36.4

Metric

Average Efficiency [%]	Sum Power ratings [kW]	Total volumes [m3]	Total number	Number of ratings
91.2	**795.5**	**1.637**	**45**	**1**

VS

PEBB

Power Rating [kW]	Maximum Voltage [V]	Maximum Current [A]	Volume [L]
1028.5	4000	733.3	45
296.2	4000	200	21

Metric

Average Efficiency [%]	Sum Power ratings [kW]	Total volumes [m3]	Total number	Number of ratings
93.0	**1324.7**	**1.632**	**40**	**2**

1 PEBB rating vs 2 PEBB ratings

Pros

- Improved average efficiency (+1.8%)
- Number of PEBBs decreased (-5)
- Lower volume

Cons

- More components to manage

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Bulkhead Region #10 Focus

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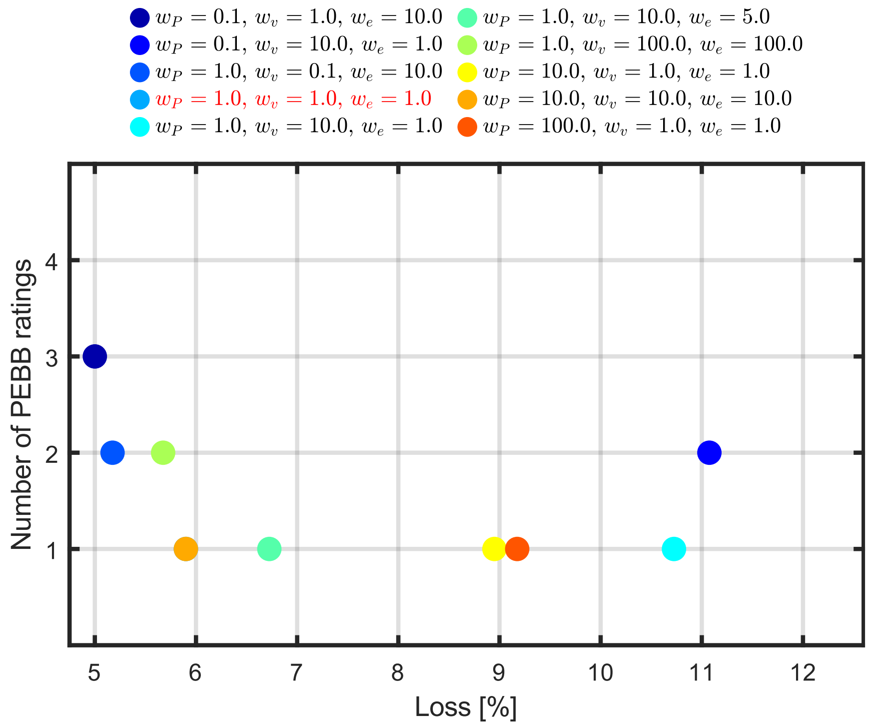
What's the effect on the **weighting factors** on a singled bulkhead region (e.g. bulkhead #10)?



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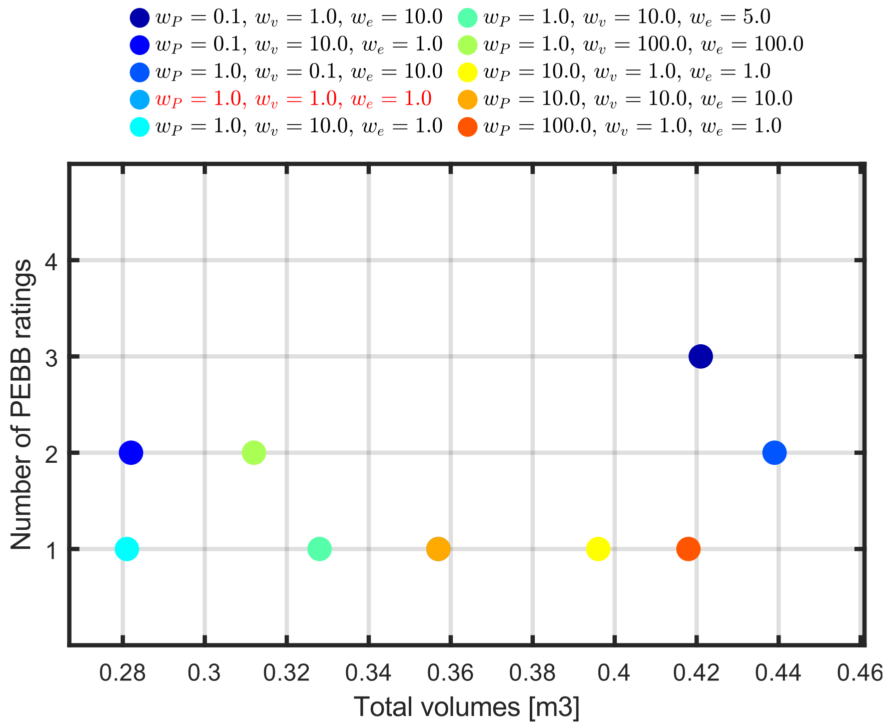

- Multiple solutions show that increasing the number of PEBB ratings can lead to **reduced losses**.
- A similar trend is observed for the **total volume** under varying weight configurations.

MIT UniGe | DITEN

Conclusions

Sea Grant MIT

- **A PEBB-based power corridor** architecture has been proposed and modeled.
- A **multi-objective** formulation was developed to optimize PEBB power, voltage, and current.
- Key metrics have been defined: PEBB **rated power**, **efficiency**, and **volume**.
- The impact of different objective weights was analyzed, showing **trade-offs** among metrics.
- Preliminary results show that using **two distinct PEBB ratings** leads to **better** performance, with higher efficiency and lower volume compared to using a **single rating**.

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Thank you for the attention!

Any questions?

PhD. Student: Marco Gallo
Supervisors: Julie S. Chalfant and Chathan M. Cooke
Date: 21/05/2025

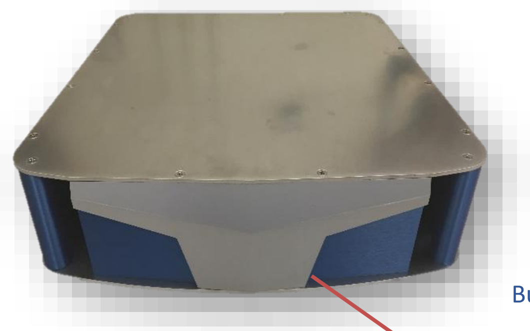
Massachusetts Institute of Technology

The views expressed are those of the authors and do not reflect the official policy or position of the U.S. Department of Defense or the U.S. Government.

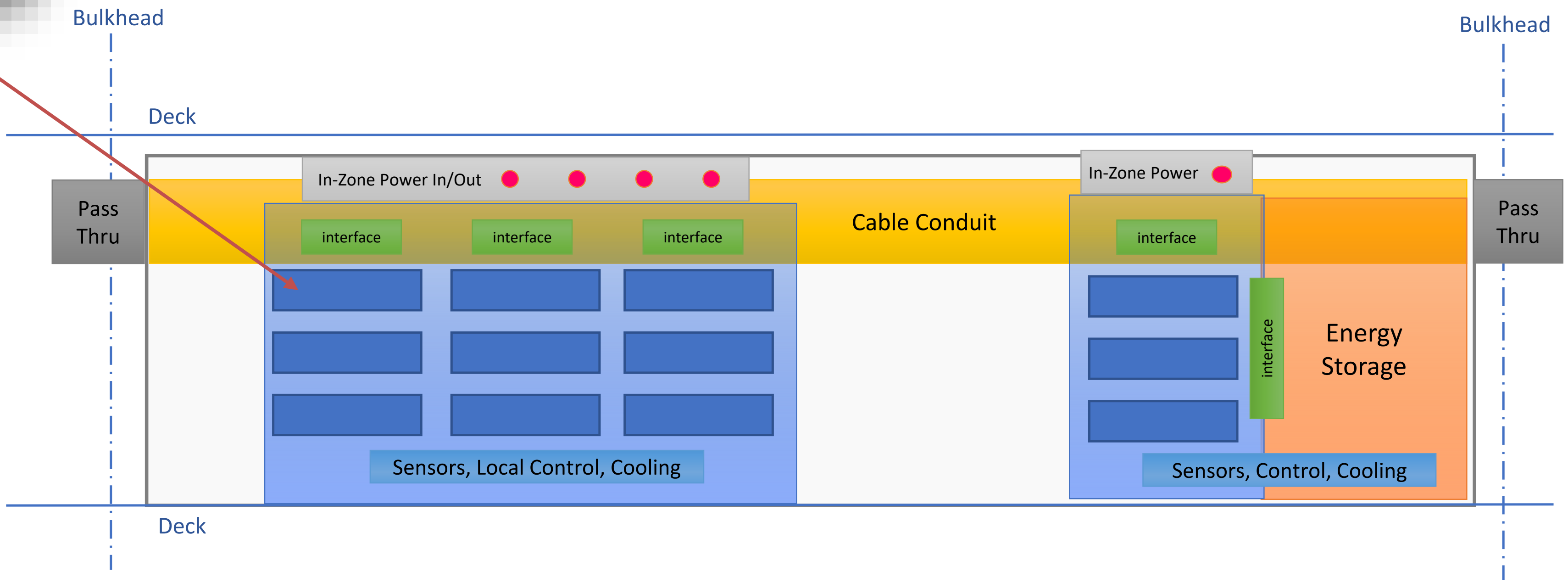
Metaheuristic Optimization for Automatic Arrangement of Power Electronics Components in a Shipboard Electrical Distribution System

Sebastien Lohier
Julie Chalfant

Motivation

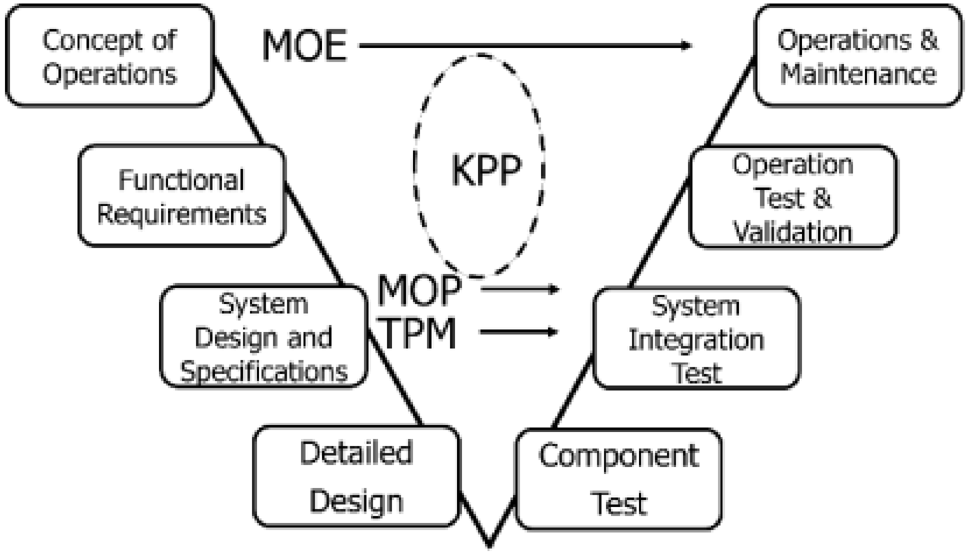


Least Replaceable Unit (LRU):
Power Electronics Building Block (PEBB) -
A modular, repeatable, programmable, sailor-carryable universal converter



Motivation

- Early-stage ship design requires thousands of experiments to characterize the design space
- Want a method to do this quickly and accurately enough to make broad design choices

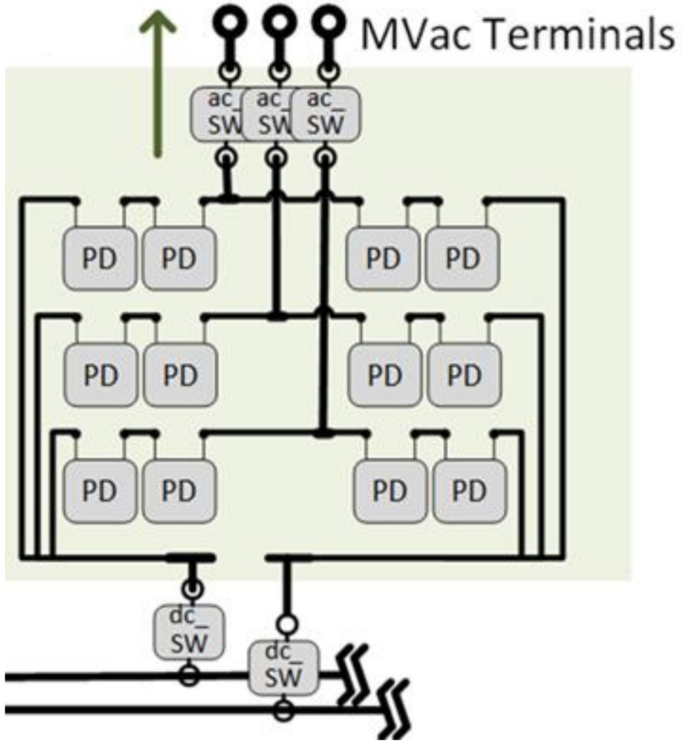


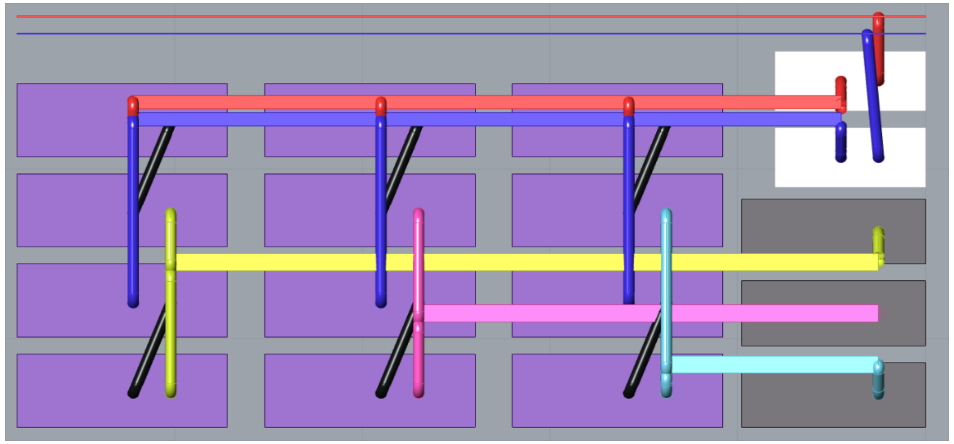
The Problem

Problem Statement: Accomplish a *rapid* arrangement to give ballpark sizing/cable length at level of fidelity appropriate to early-stage design. Target is S3D model statistics for dimensions, weight, power and cooling.

Input:
- Power
- Voltage (in/out)
- LRU Sizes

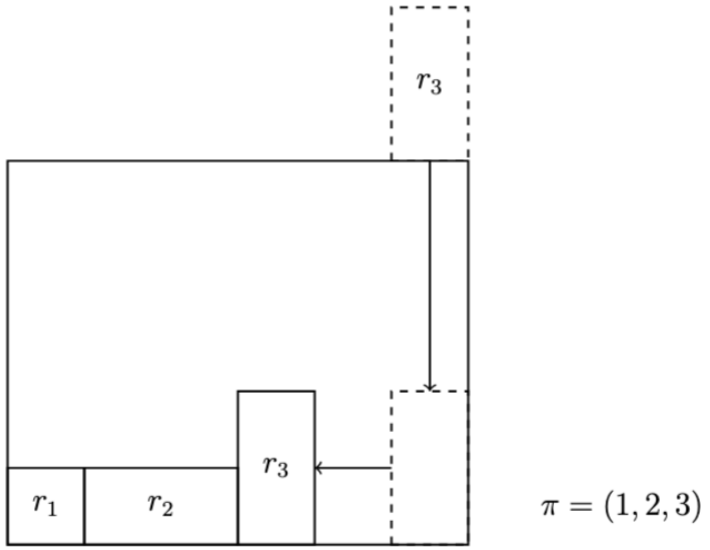
Output:
- LRU Arrangement
- Total Volume
- Total Weight



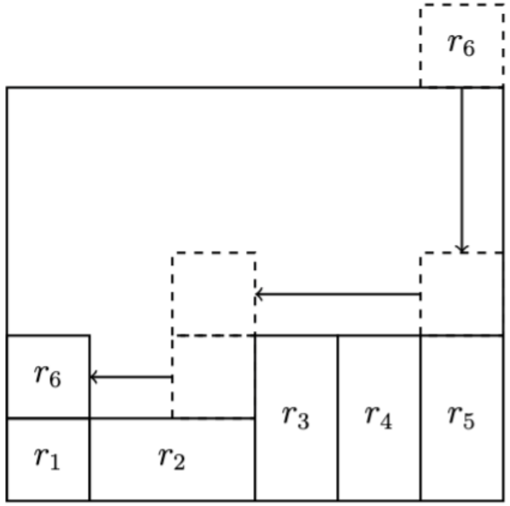


Placement Function

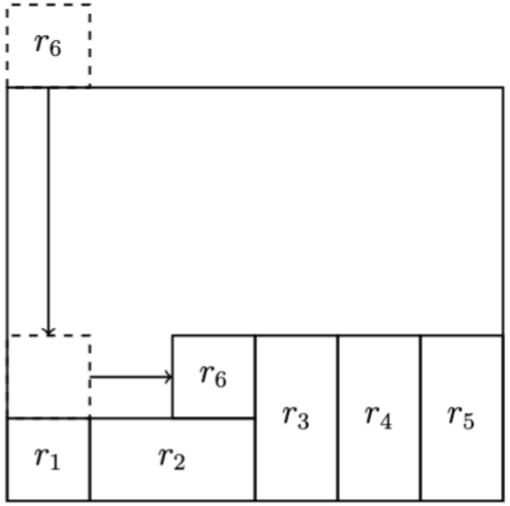
- To minimize volume, we utilize a modified Bottom-Left (BL) placement algorithm
- Additionally, a placement can be described purely from the ordering of blocks

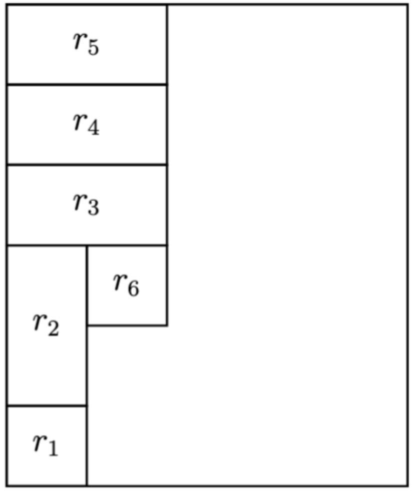


Placement Continued



$\pi = (1, 2, 3, 4, 5, 6)$

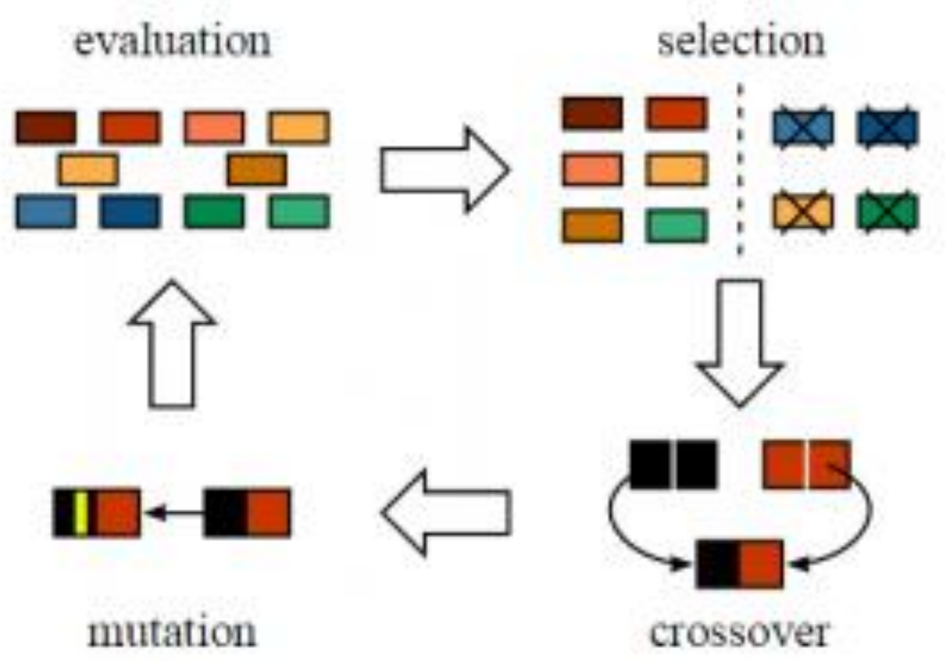




$\pi = (1, 2, 3, 4, 5, 6)$

Genetic Algorithm

- Computer algorithm aiming to simulate the evolutionary process of animals
- Successive generations are generated from the most evolutionary fit parents



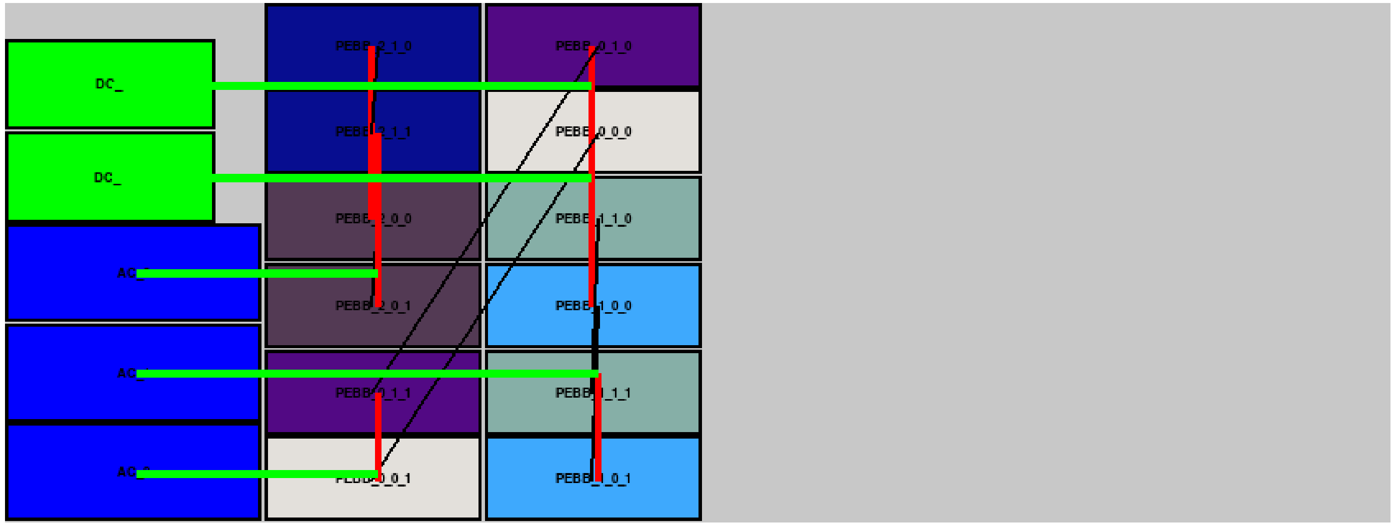
Scholz, Jan. "Genetic algorithms and the traveling salesman problem a historical review." *arXiv preprint arXiv:1901.05737* (2019).

Genetic Algorithm Cont.

- Fitness Function– This determines the metric by which individuals in a population is graded
- Crossover Operator – This is the function which given an input of two parents, will generate an offspring
- Mutation Operator– Some random process which creates a random change for each offspring

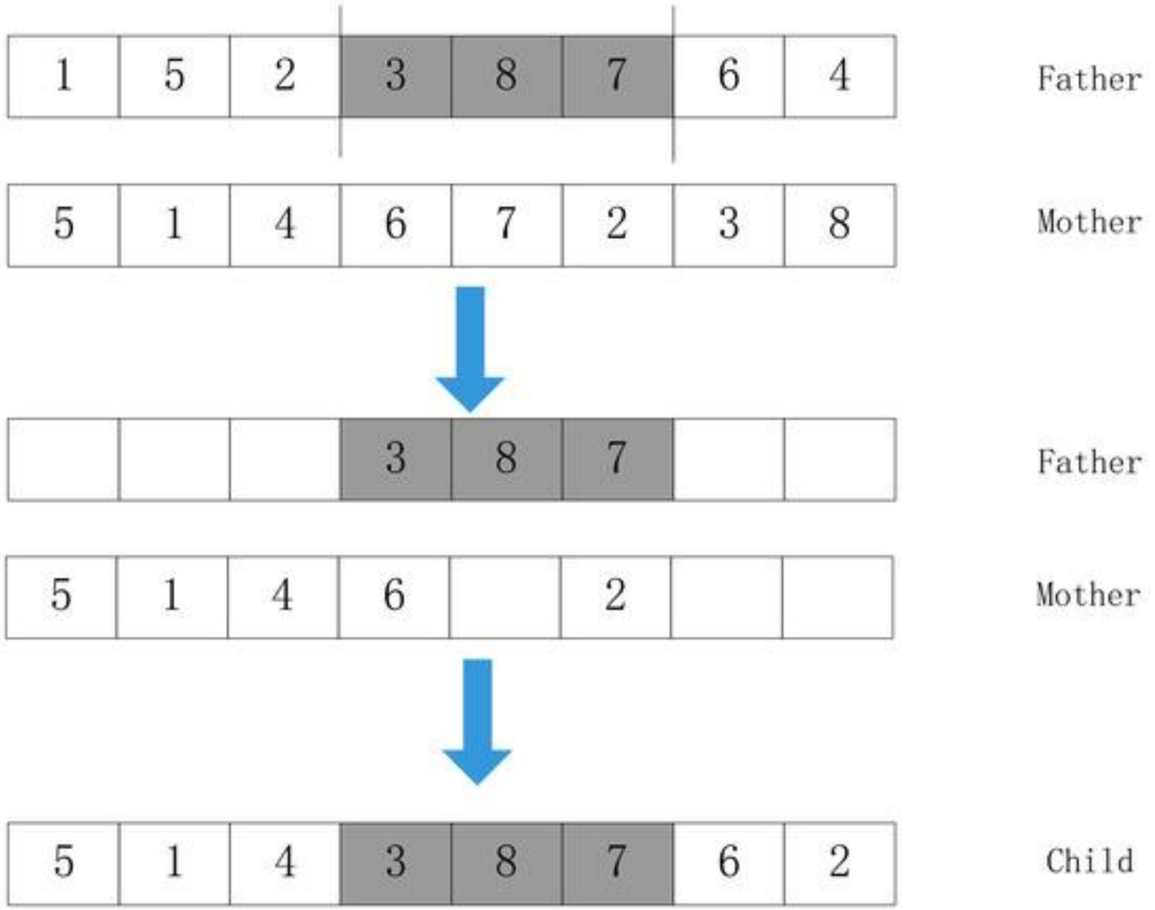
Fitness Function

$$
\begin{aligned}
F(\pi) = & \left(\frac{1}{\text{Busbar Routing Distance}}\right)^{\tau} * \\
& \left(\frac{1}{\text{Wire Routing Distance}}\right)^{\alpha} * \\
& \left(\frac{1}{\text{DC Block Distance}}\right)^{\beta} * \\
& (\text{DC Height})^{\gamma} * \\
& \left(\frac{1}{\text{AC Distance}}\right)^{\epsilon} * \\
& \left(\frac{1}{\text{Volume}}\right)^{\mu} * \\
& 1.1^{-(\text{PEBB/Switch Overlap}) * \theta} * \\
& \left(\frac{1}{\text{Switch Width}}\right)^{\lambda}
\end{aligned}
$$



Breeding and Mutation

- Order Based Cross-Over is used for breeding
- For a mutation operator we slide a random subarray of the ordering by a random offset

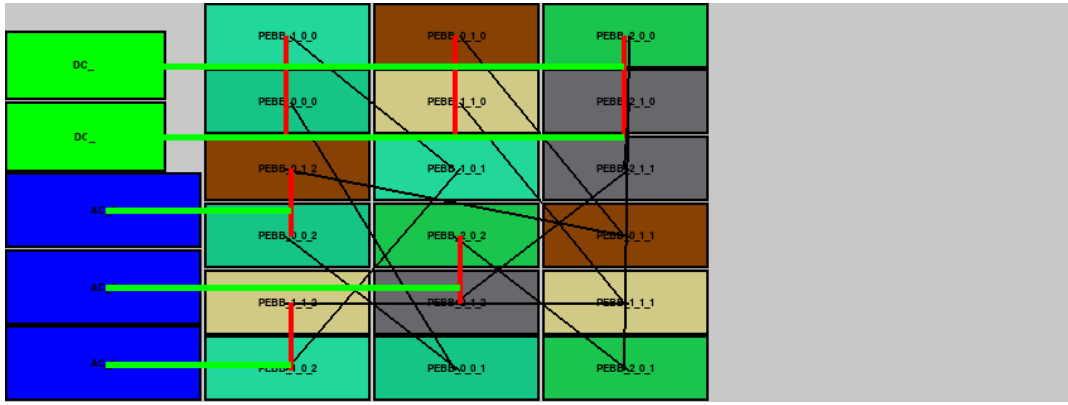


Chen, Chien-Ming, et al. "A genetic algorithm for the waitable time-varying multi-depot green vehicle routing problem." *Symmetry* 15.1 (2023): 124.

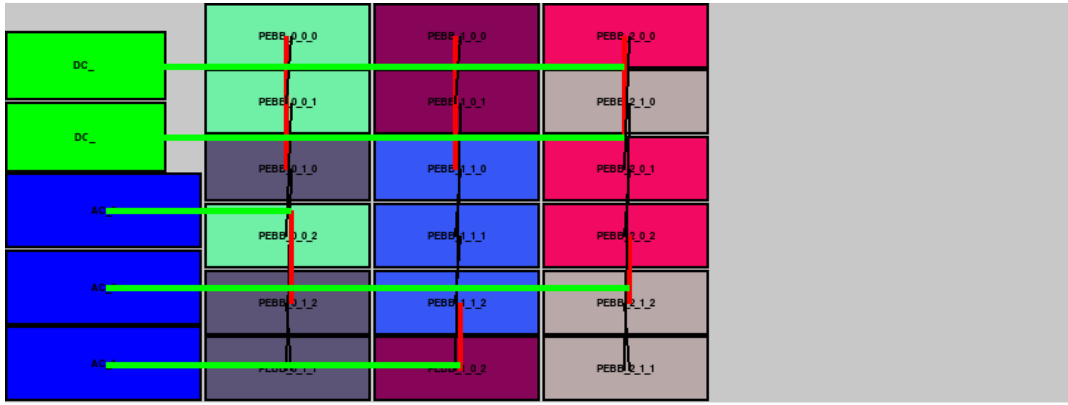
Hybrid Approach

- Genetic Algorithm is used to find a placement which best satisfies all our metrics
- Then Simulated Annealing is used to fine tune the placements of PEBB's to reduce routing distance

Before

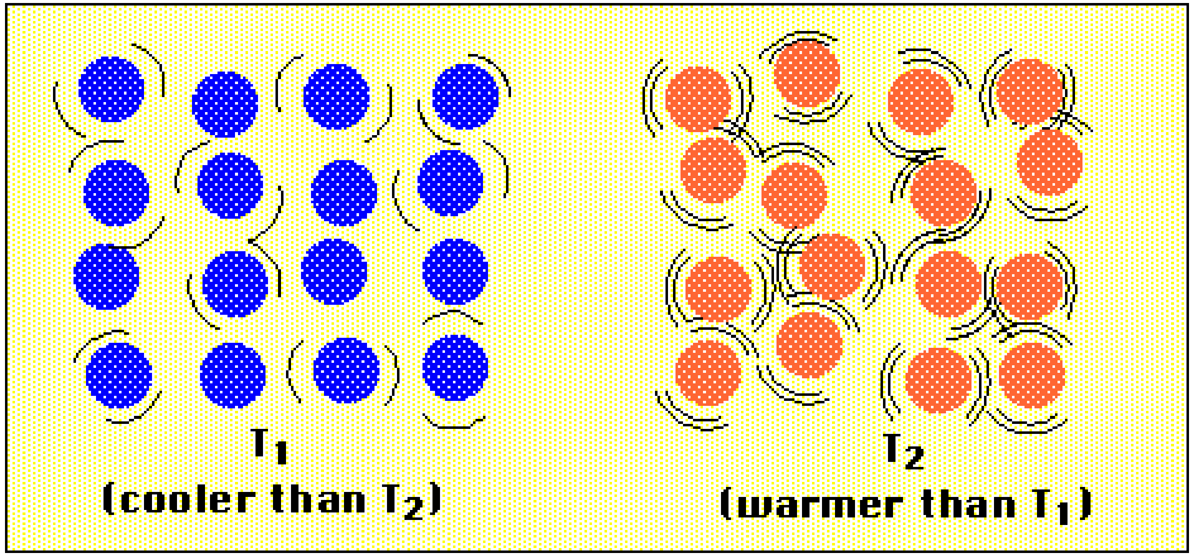


After



Simulated Annealing

- Aims to simulate the annealing process in metallurgy
- Solutions begin very "**hot**" allowing for suboptimal changes
- As the algorithm continues it cools down only allow more and more conservative changes



$$P(\text{accept}) = e^{\frac{-\Delta E}{T}}$$

"**Hands-On-Physics**" - https://hop.concord.org/htu/htu.concepts.flow.html

Simulated Annealing

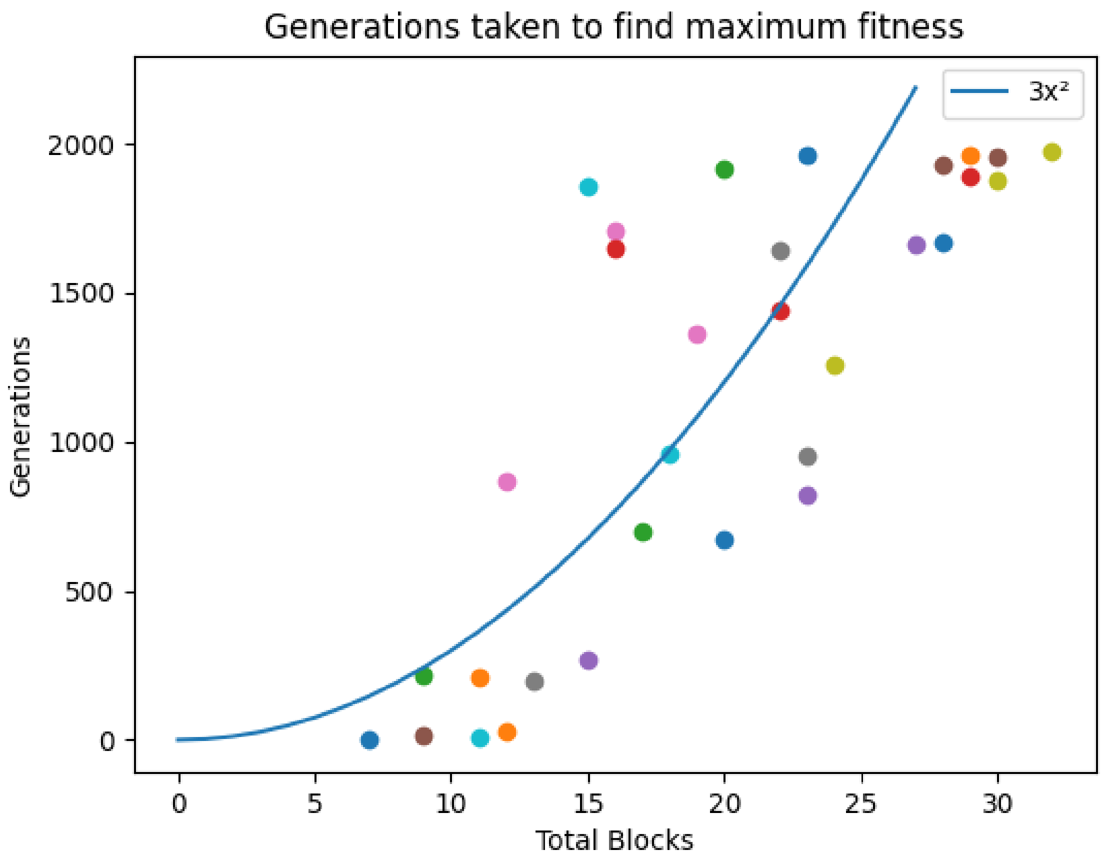
$$E(\pi) = \alpha * (\text{Wire Routing Distance}) + \beta * (\text{Busbar Routing Distance})$$

- This process only considers the routing distance of a given placement.
- In this stage changes are made only in position of PEBBS. Using the mutation operator from the Genetic Algorithm

Parameter Optimization

Genetic Algorithm Parameters	
Population Size	100
Mutation Probability	0.75
Busbar Routing Distance	3
Wire Routing Distance	5
DC Block Distance	3
DC Height	1
AC Distance	3
Volume	1
PEBB/Switch Overlap	6.734
Switch Width	1

Simulated Annealing Parameters	
Iterations per Temperature	400
Start Temperature	50
End Temperature	1
Cooling Rate	0.992



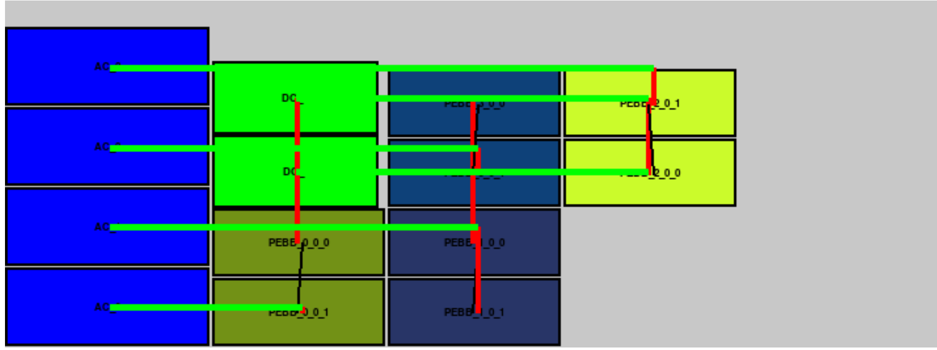
Variance of Results

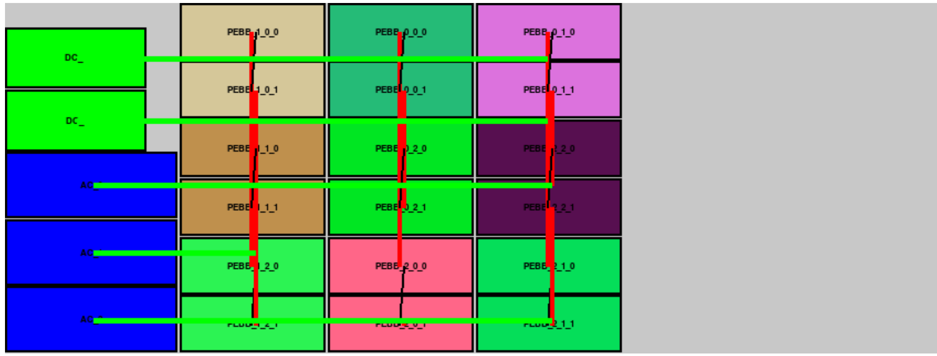
- Solutions have shown to be consistent between runs.
- The various values were calculated through 100 runs of the same problem

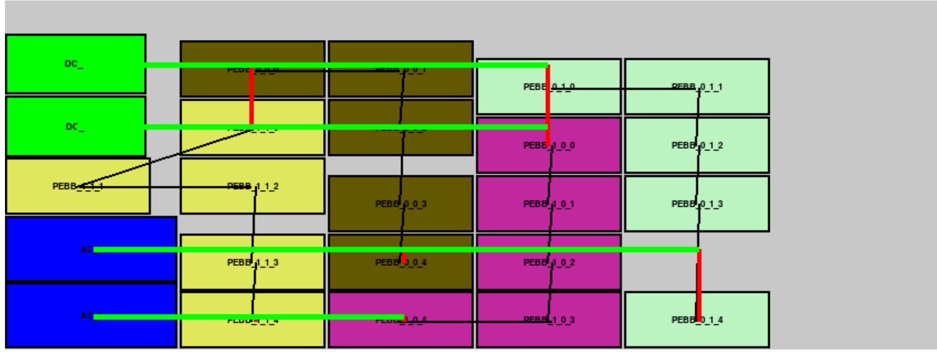
*Units are in kg and decimeters

Parameter	Mean	Standard Deviation	% of Mean
Busbar Routing Distance	307.74	24.40	7.92%
Wire Routing Distance	142.65	12.2	8.55%
DC Distance	12.25	0	0%
AC Distance	164.04	13.47	8.21%
Volume	1193	0	0%
Normalized DC Height	0.81	0	0%
Overlap	0.09	0	0%
Switch Range	9.80	0	0%
Weight	1678.35	25.95	1.5%

Examples



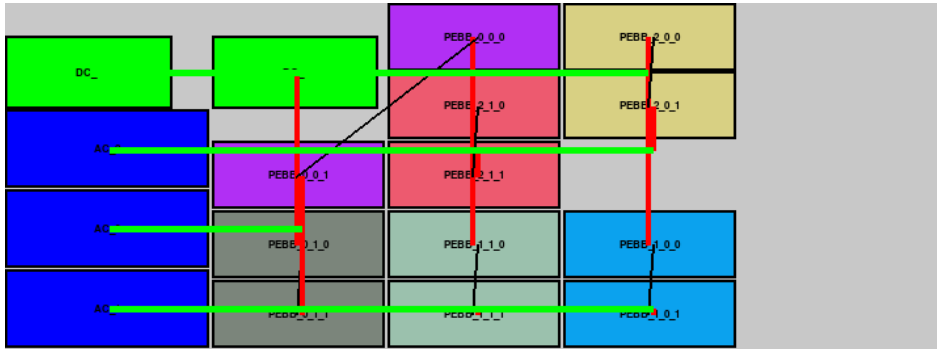


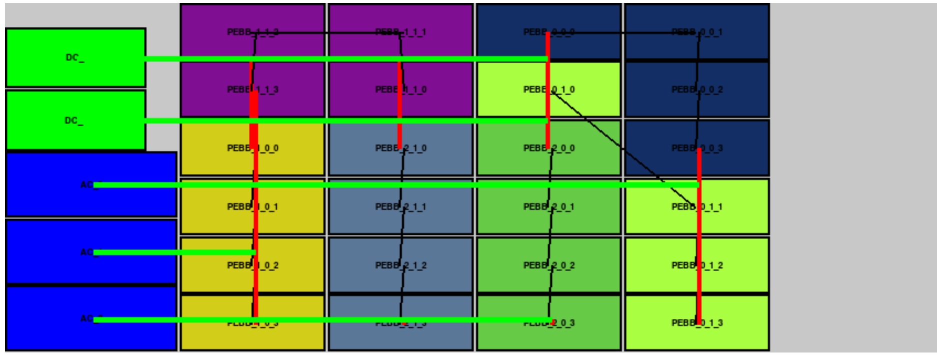


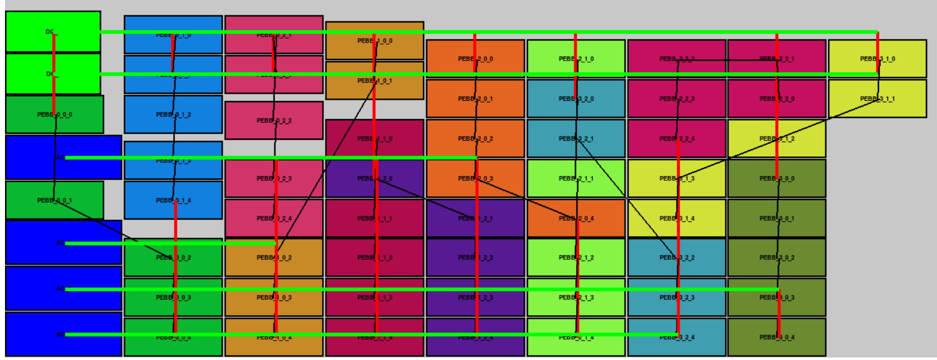
Many random examples.

Note:

- PEBB clustering
- DC switches high in space
- Minimize length
- Use full height



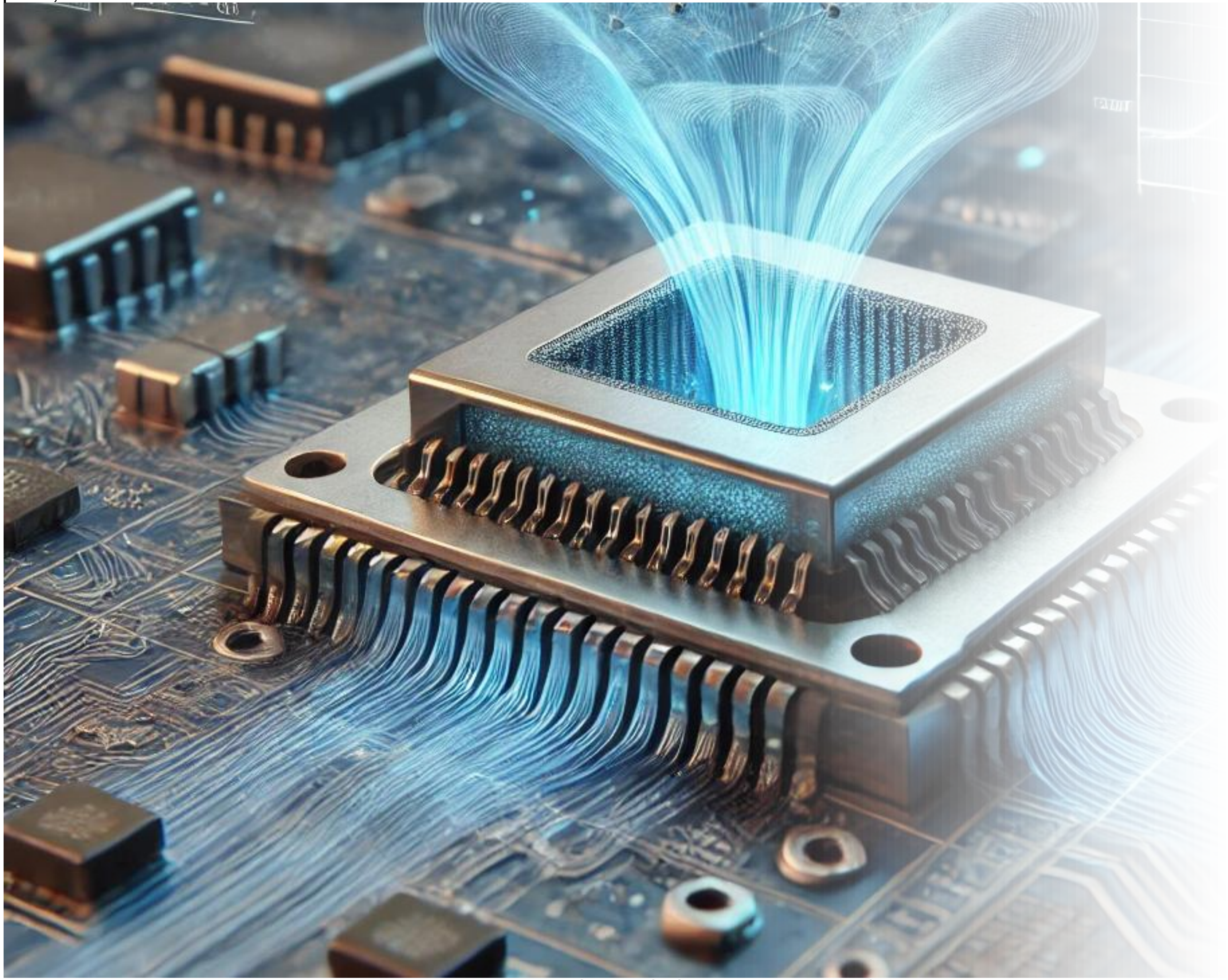




Thank you

This work is supported by:

- the Office of Naval Research Grant No. N00014-21-1-2124
- the National Oceanic and Atmospheric Administration (NOAA) Grant No. NA22OAR4170126



Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks

Aniruddha Bora
Postdoctoral Research Associate
Brown University

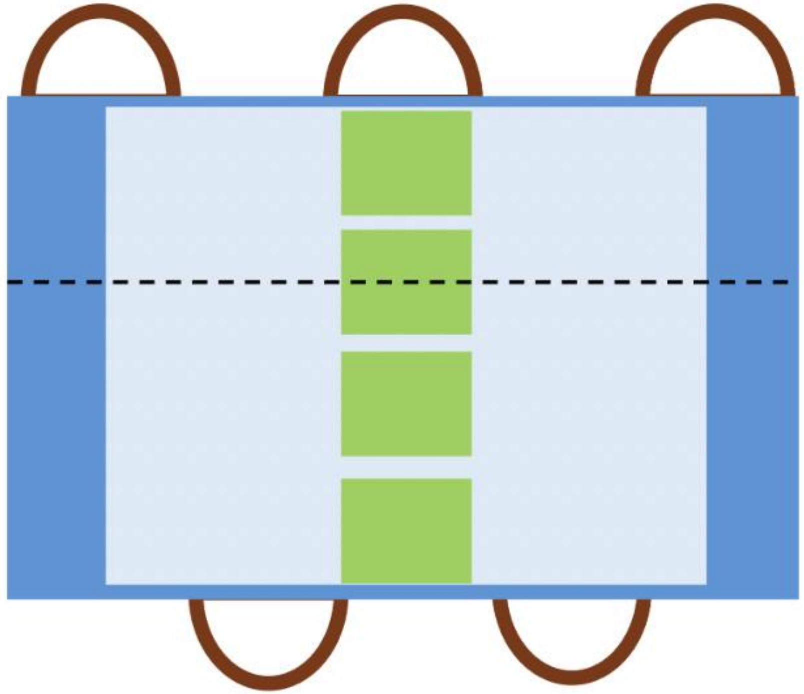
Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks: A Systematic Study on Coolant Velocity Estimation

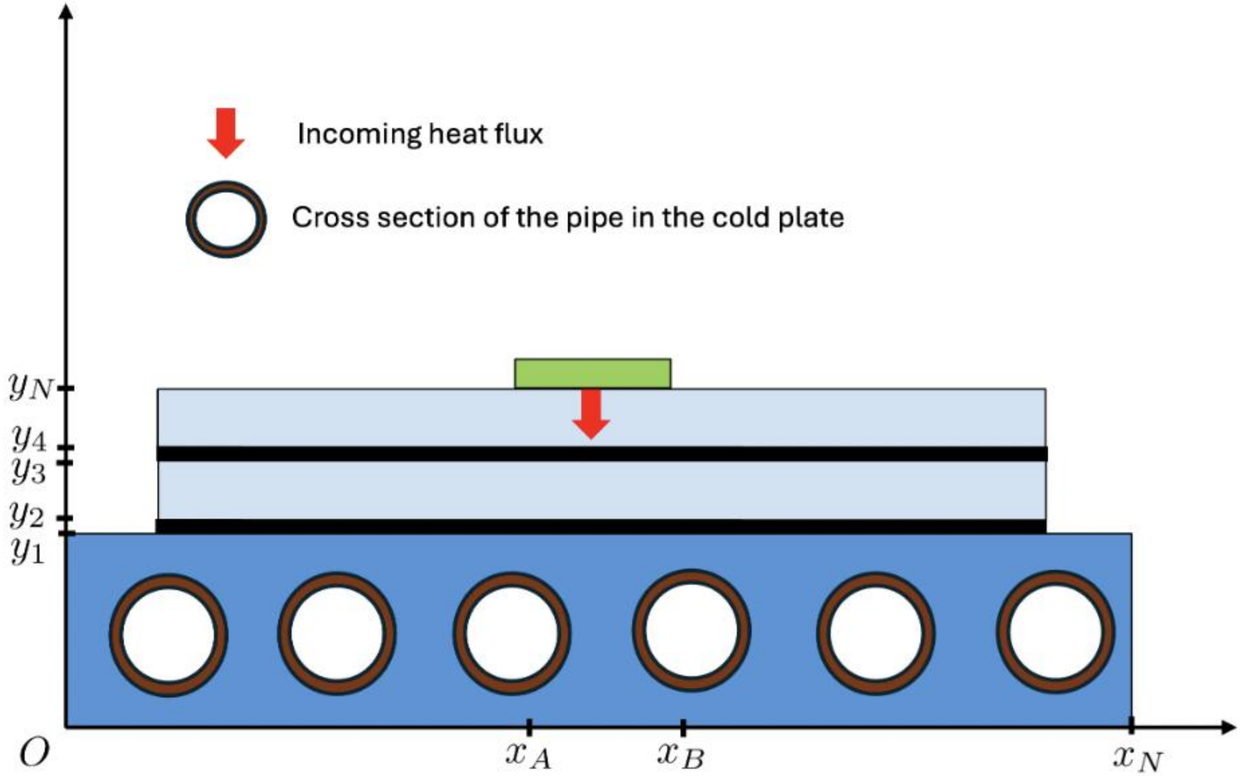
Isabel K. Alvarez   Dr. Julie Chalfant   Dr. Chryssostomos Chryssostomidis

MIT Sea Grant Design Laboratory Massachusetts Institute of Technology Cambridge, MA, USA

Bora A, Alvarez I, Chalfant J, Chryssostomidis C. **Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks: A Systematic Study on Coolant Velocity Estimation**.

Problem Statement





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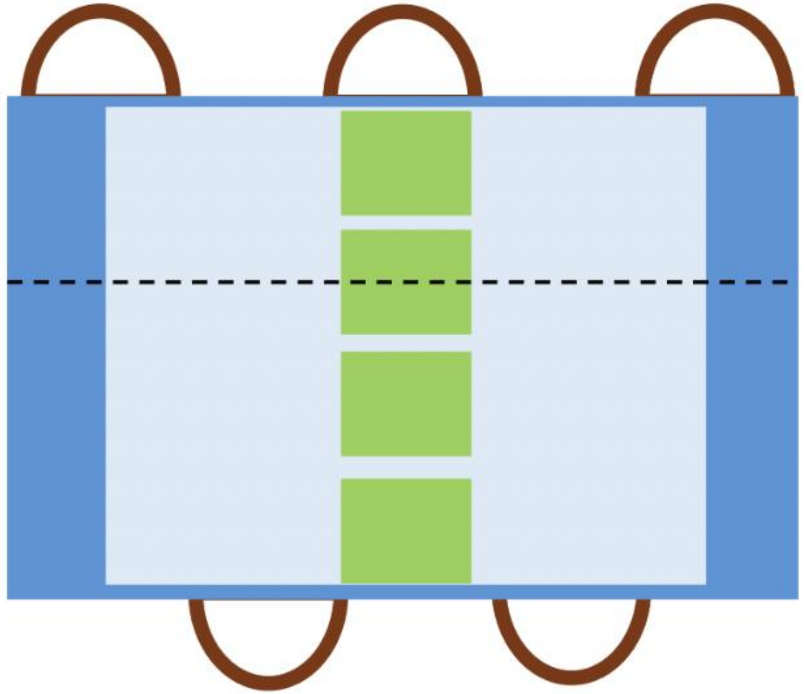
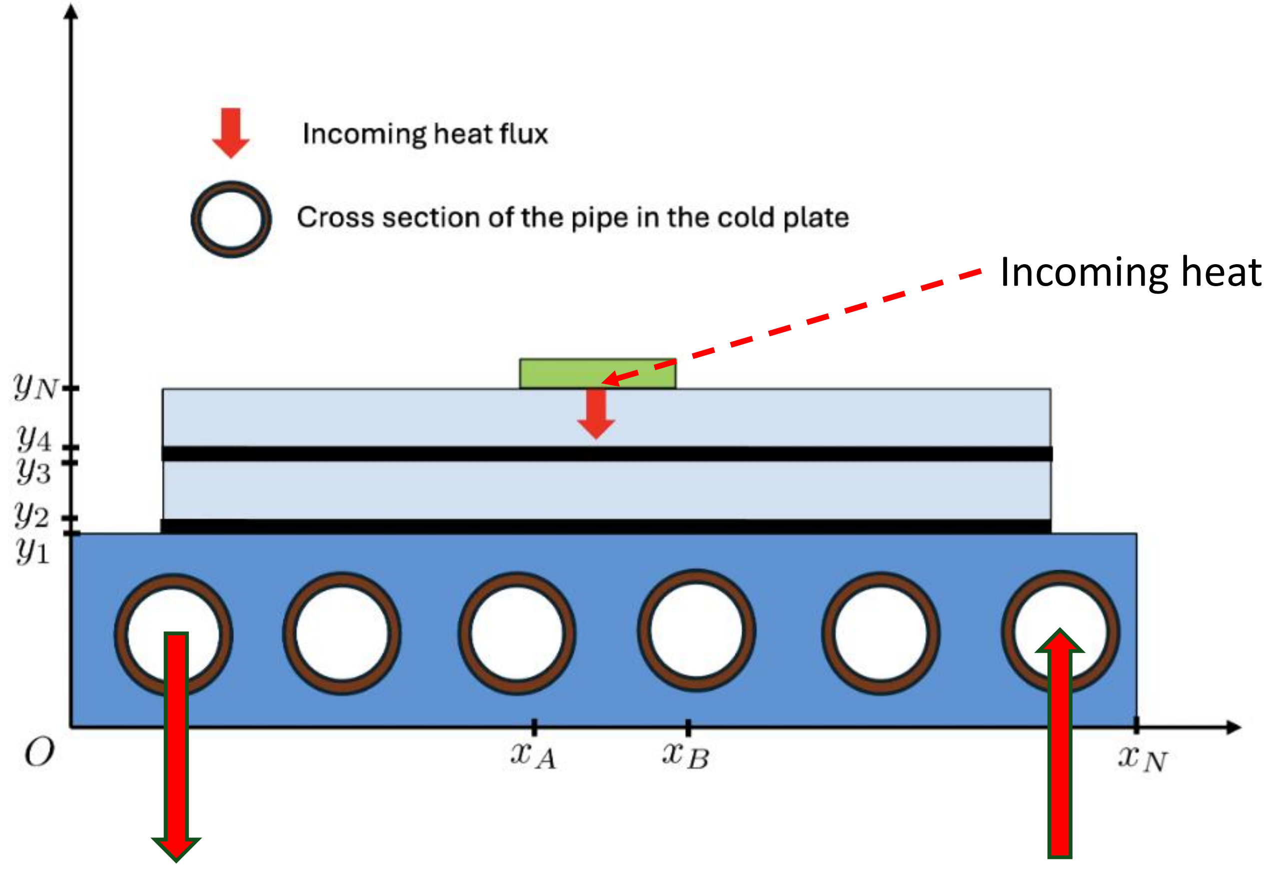




Bora A, Alvarez I, Chalfant J, Chryssostomidis C. Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks: A Systematic Study on Coolant Velocity Estimation.

Problem Statement

$$k_i(u^i_{xx} + u^i_{yy}) = 0, \qquad 0 \leq x \leq x_N, \quad 0 \leq y \leq y_N,$$

where u^i and k_i are the temperature and thermal conductivity for the i^{th} layer, respectively

$$\frac{\partial u(x, y_L)}{\partial y} = \alpha, \qquad x_A \leq x \leq x_B, \quad y = y_N,$$

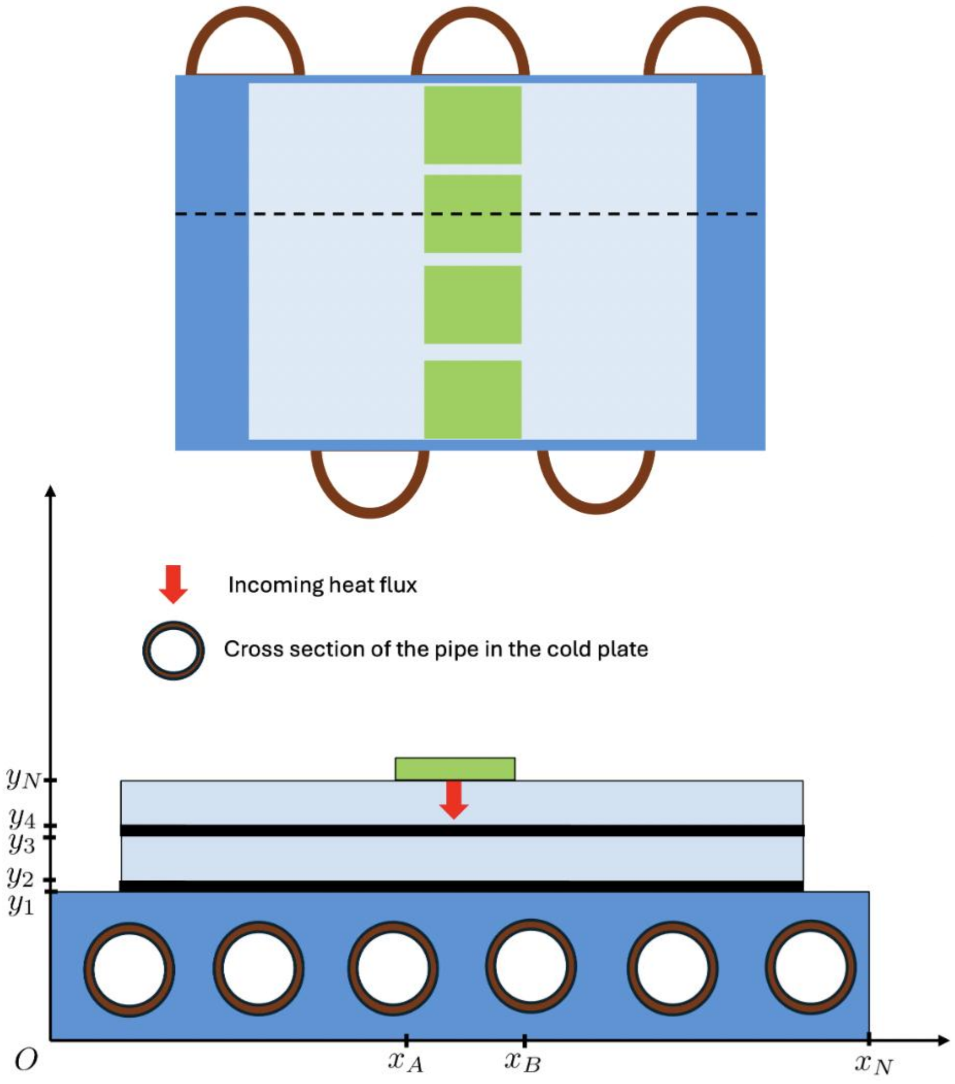
perfectly thermal interface conditions which imply that there is no heat lost when it moves from one layer to the next,

$$u^i(x,y) = u^j(x,y), \qquad (x,y) \in \text{interface}$$

$$k_i \frac{\partial u^i(x,y)}{\partial n} = k_j \frac{\partial u^j(x,y)}{\partial n}, \qquad (x,y) \in \text{interface}$$

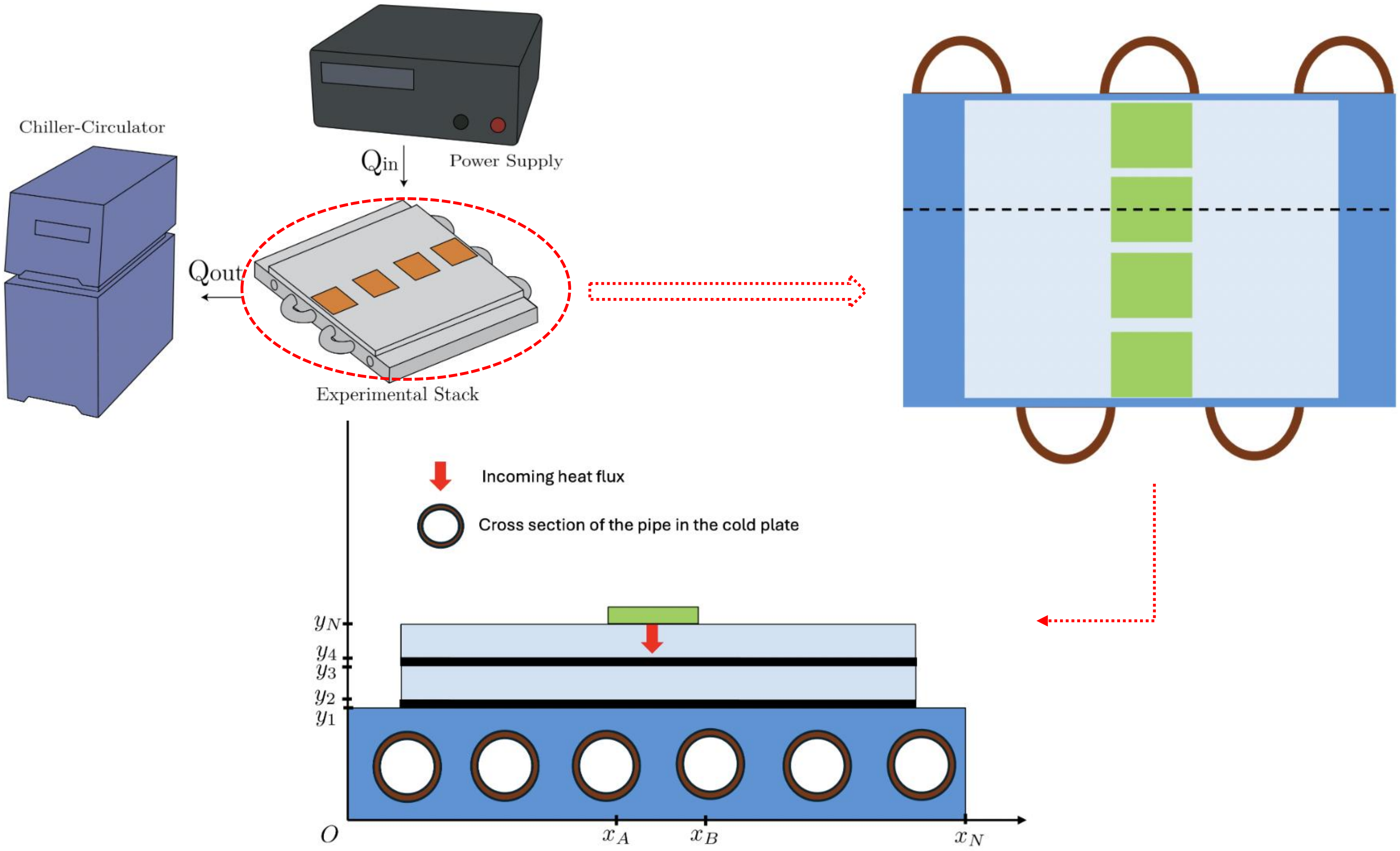
The convective boundary condition

$$-k_i \frac{\partial u^i(x,y)}{\partial n} = \boxed{h}(u^i - u^j), \quad (x,y) \in \text{inner surface of pipes}$$



Bora A, Alvarez I, Chalfant J, Chryssostomidis C. Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks: A Systematic Study on Coolant Velocity Estimation.

Experimental Setup



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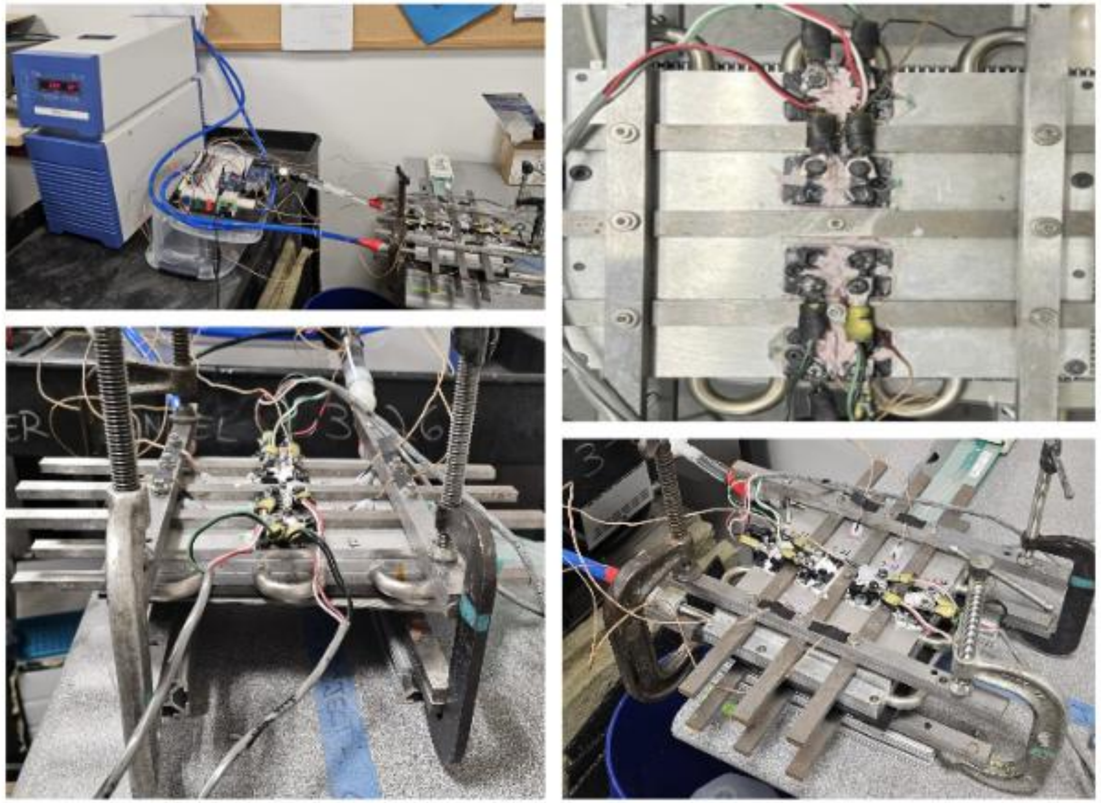

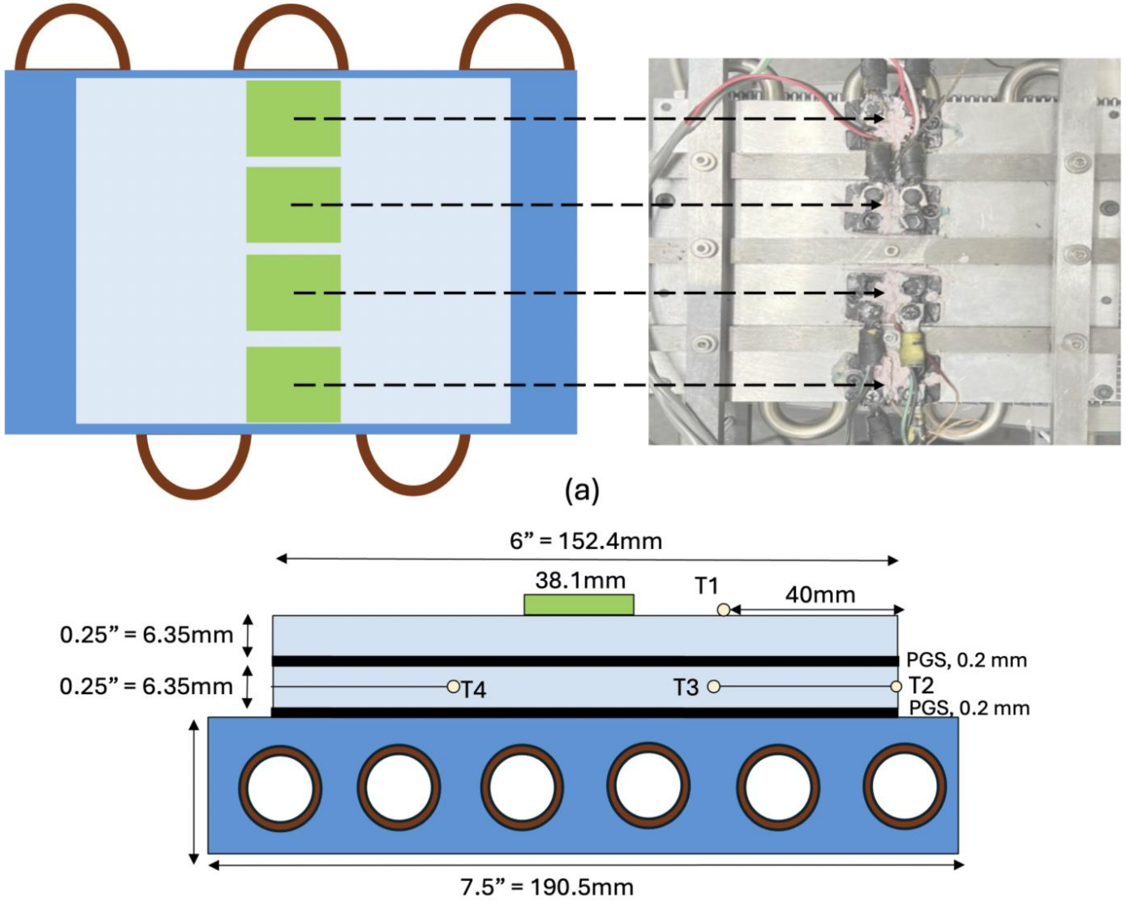

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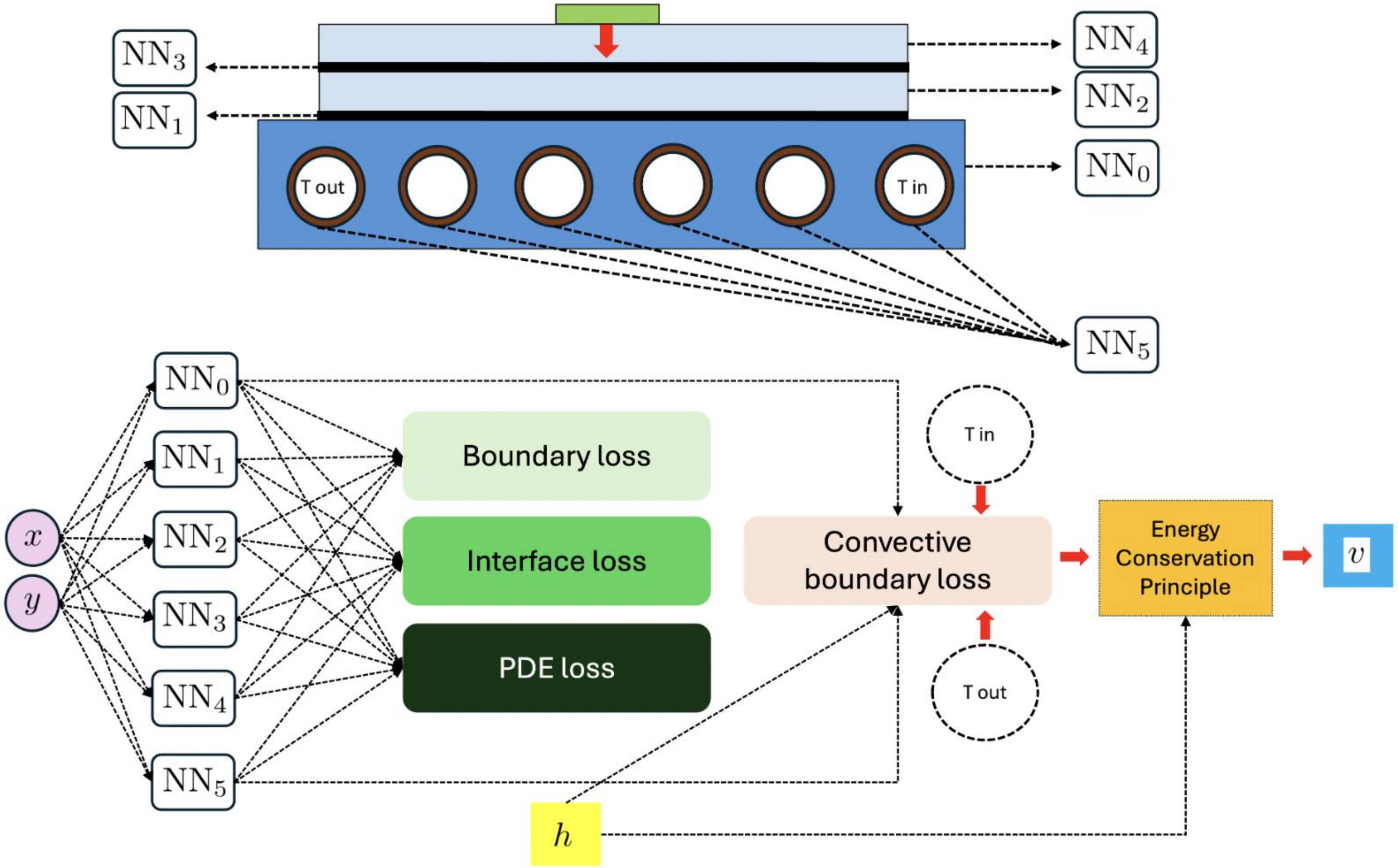
PINNs Setup



$$v_{\mathrm{NN}} = \frac{h \cdot A_1 \cdot \sum_{i=1}^{6} \Delta T_i / 6}{\rho \cdot A_2 \cdot C_p \cdot \Delta T_2}$$

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An analytical example: to validate prediction of h

Let us consider the steady-state heat conduction equation in two dimensions

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0, \quad \text{for } 0 < x < W,\ 0 < y < H$$

with Dirichlet boundary condition

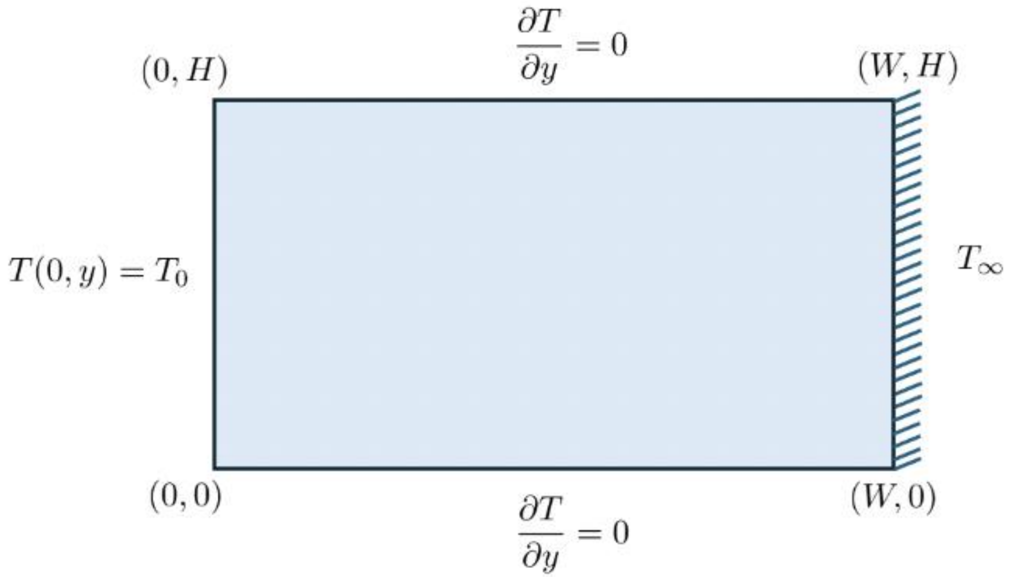
$$T(0, y) = T_0, \quad \text{for } 0 \leq y \leq H$$

insulated boundary condition

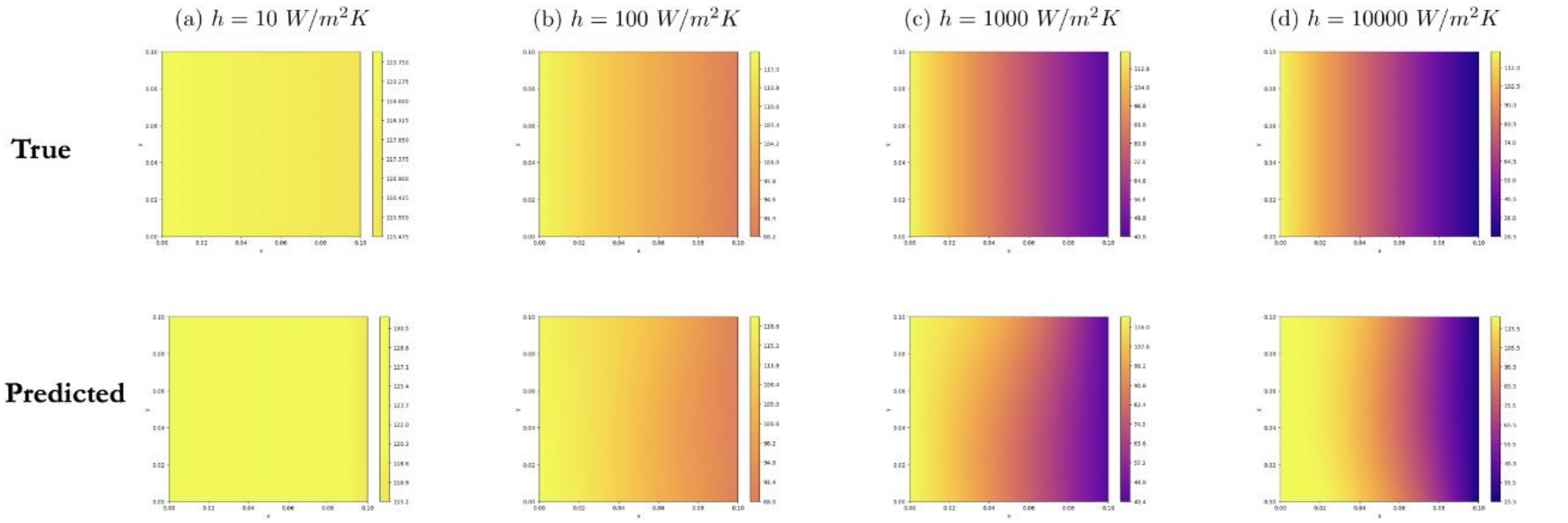
$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = 0, \quad \left.\frac{\partial T}{\partial y}\right|_{y=H} = 0, \quad \text{for } 0 \leq x \leq W$$

and convective boundary condition

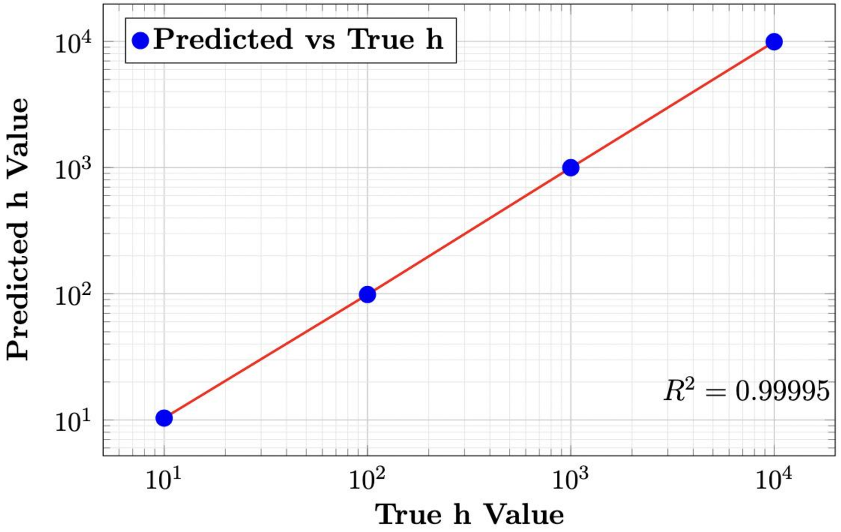
$$-k\left.\frac{\partial T}{\partial x}\right|_{x=W} = h[T(W, y) - T_\infty], \quad \text{for } 0 \leq y \leq H$$



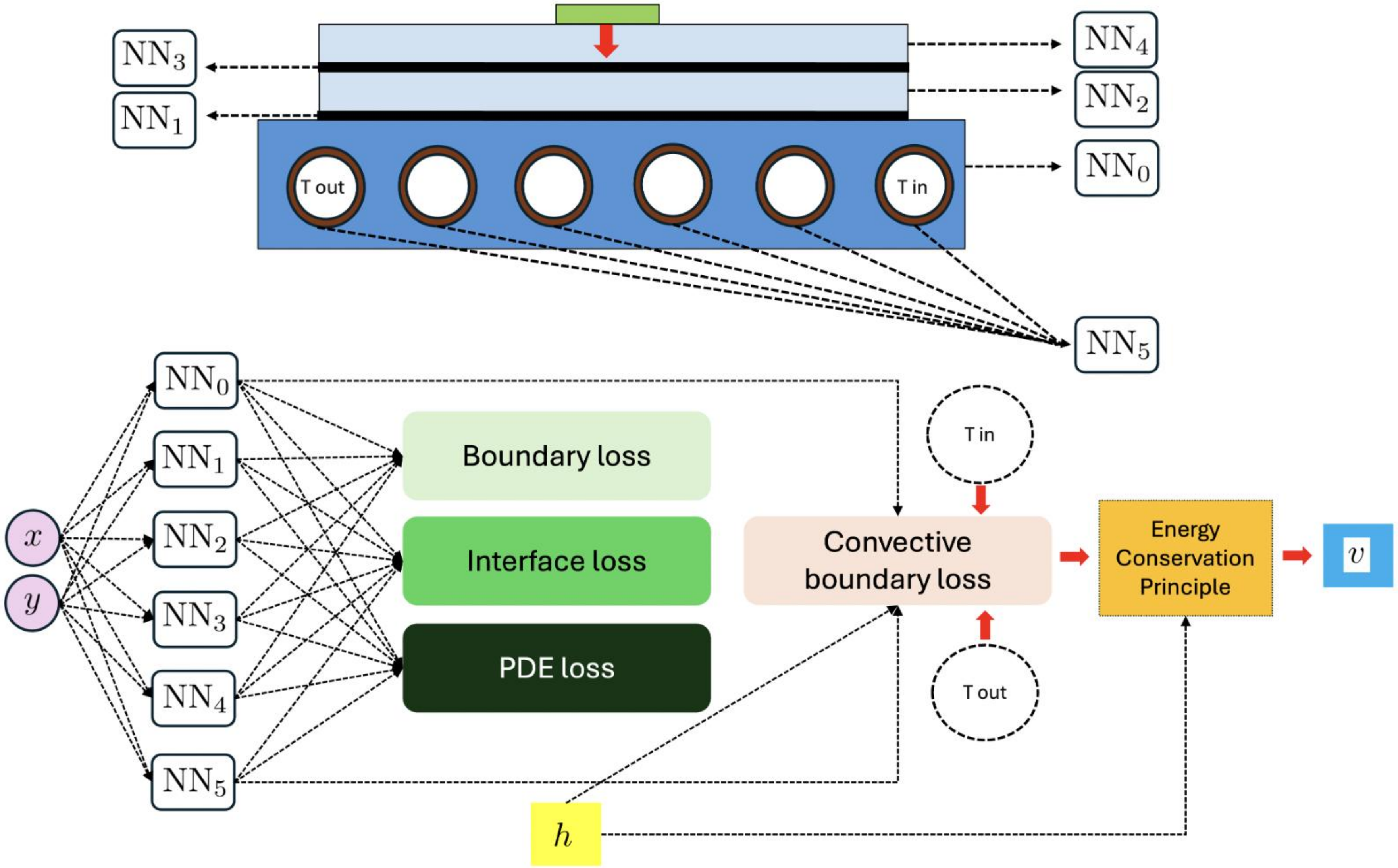
Results: Analytical Example



h (W/m^2K) value predicted	true h (W/m^2K) value	error %
10.35	10	3.5
98.731	100	1.269
998.26	1000	0.174
9942.24	10000	0.5776



Coming back to original PINNs Setup



$$v_{\mathrm{NN}} = \frac{h \cdot A_1 \cdot \sum_{i=1}^{6} \Delta T_i / 6}{\rho \cdot A_2 \cdot C_p \cdot \Delta T_2}$$

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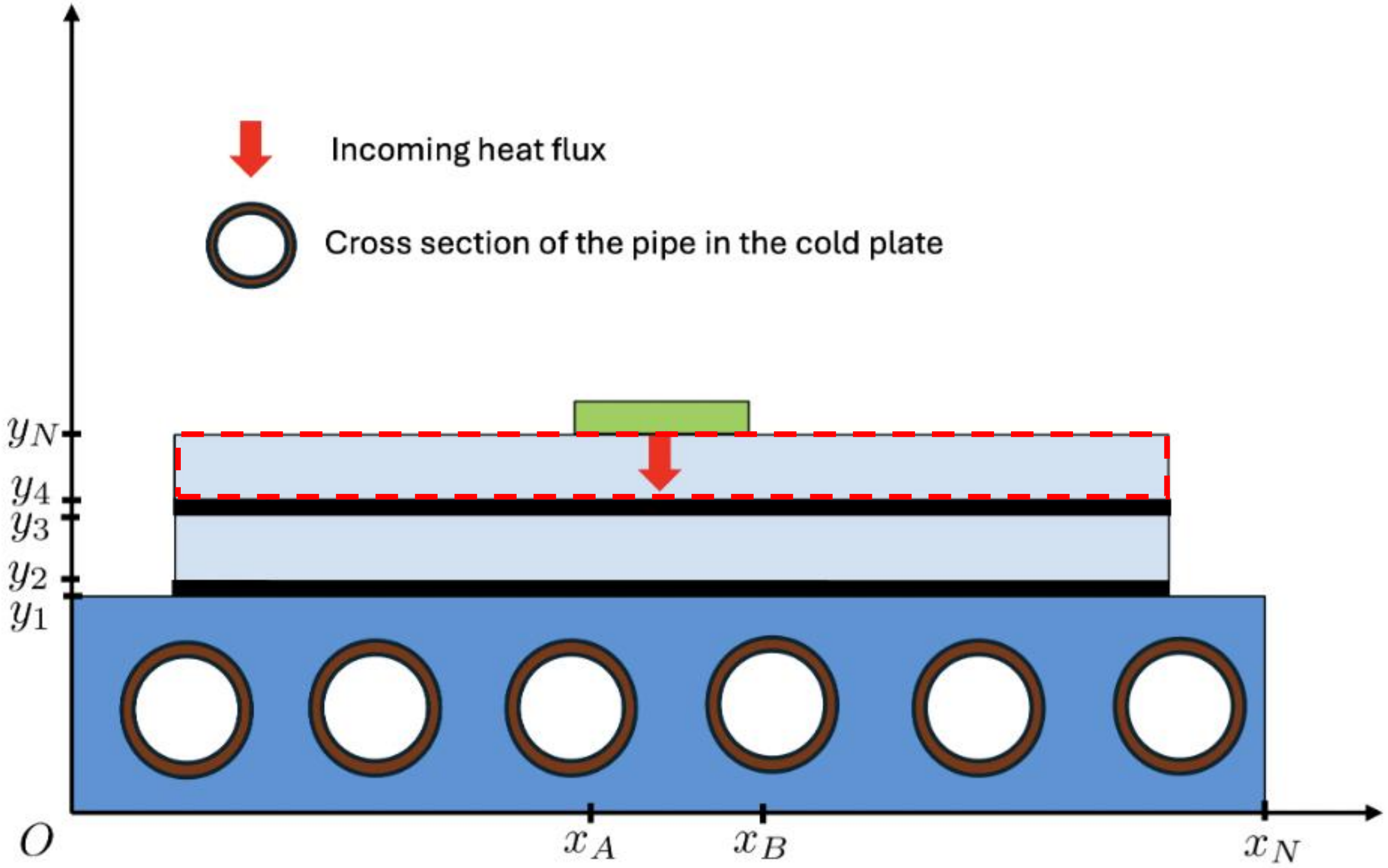
Training strategy



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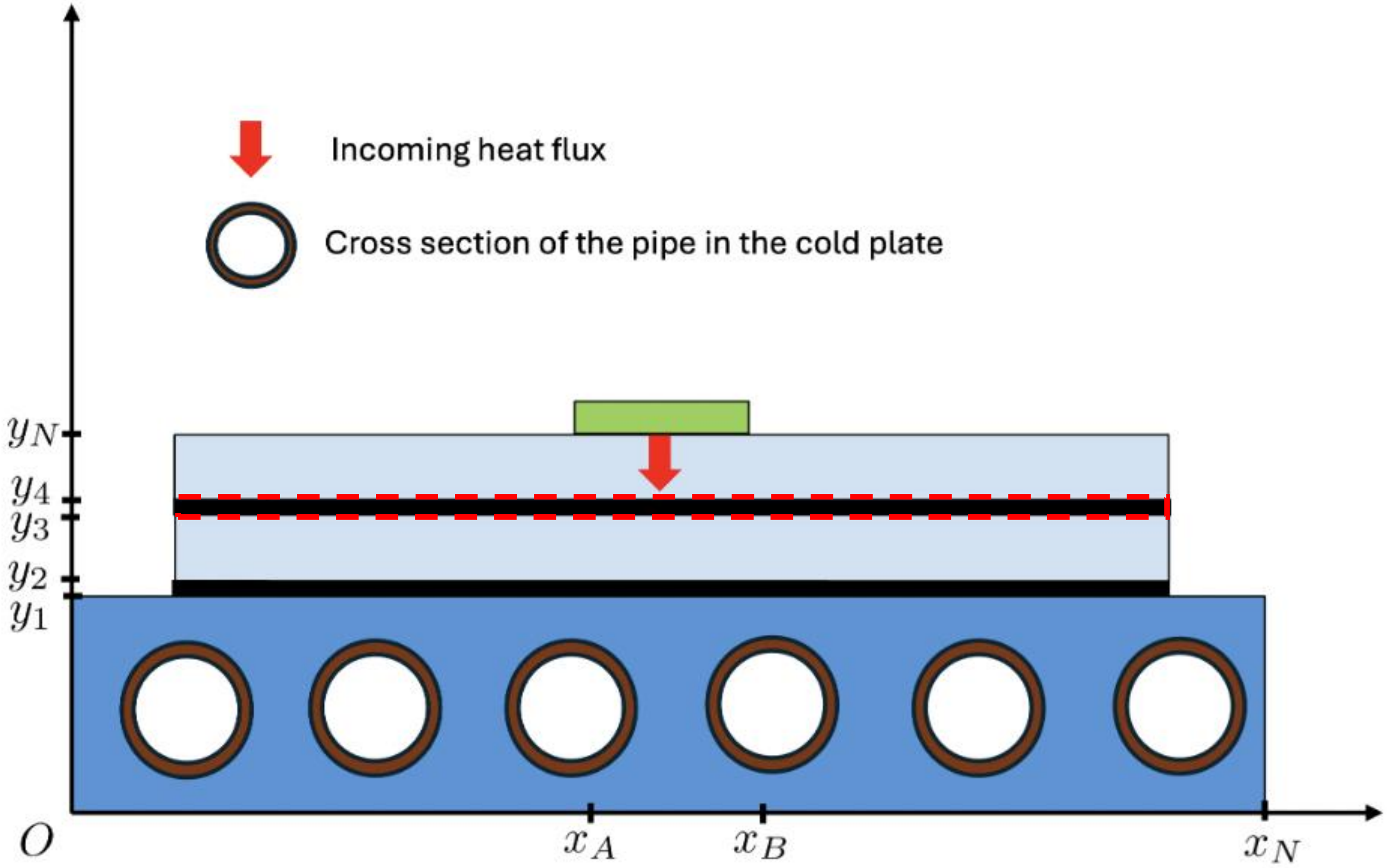

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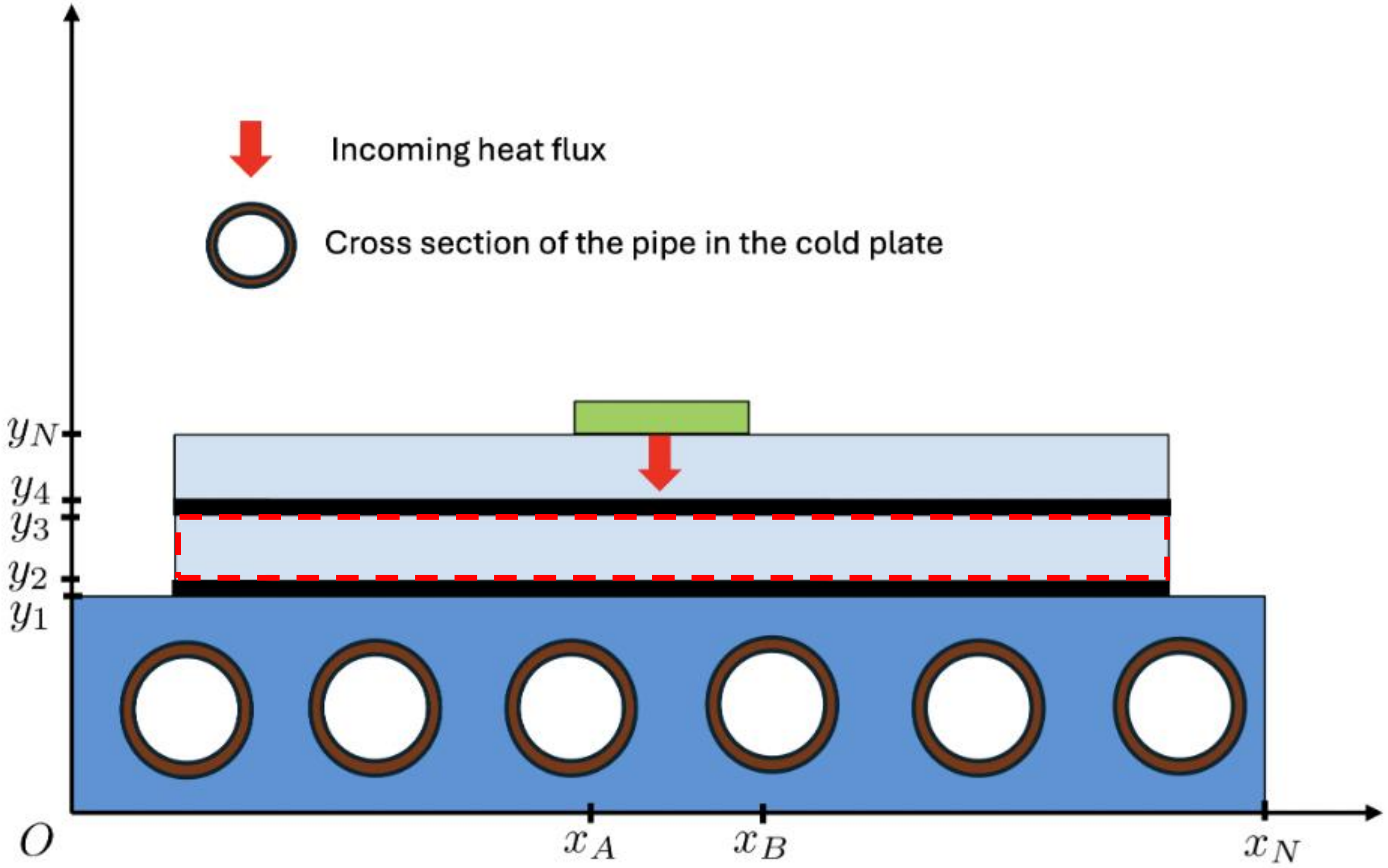

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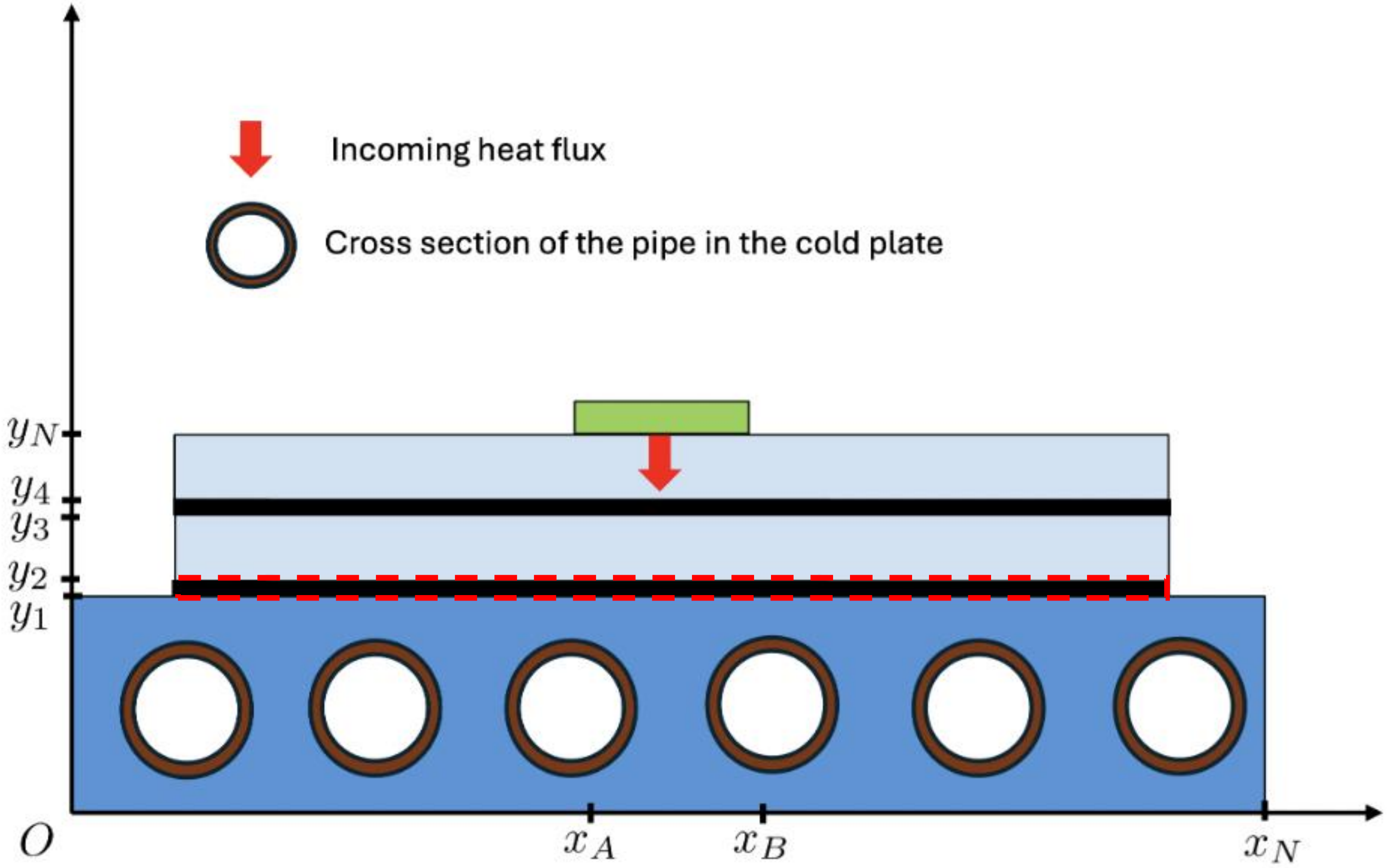

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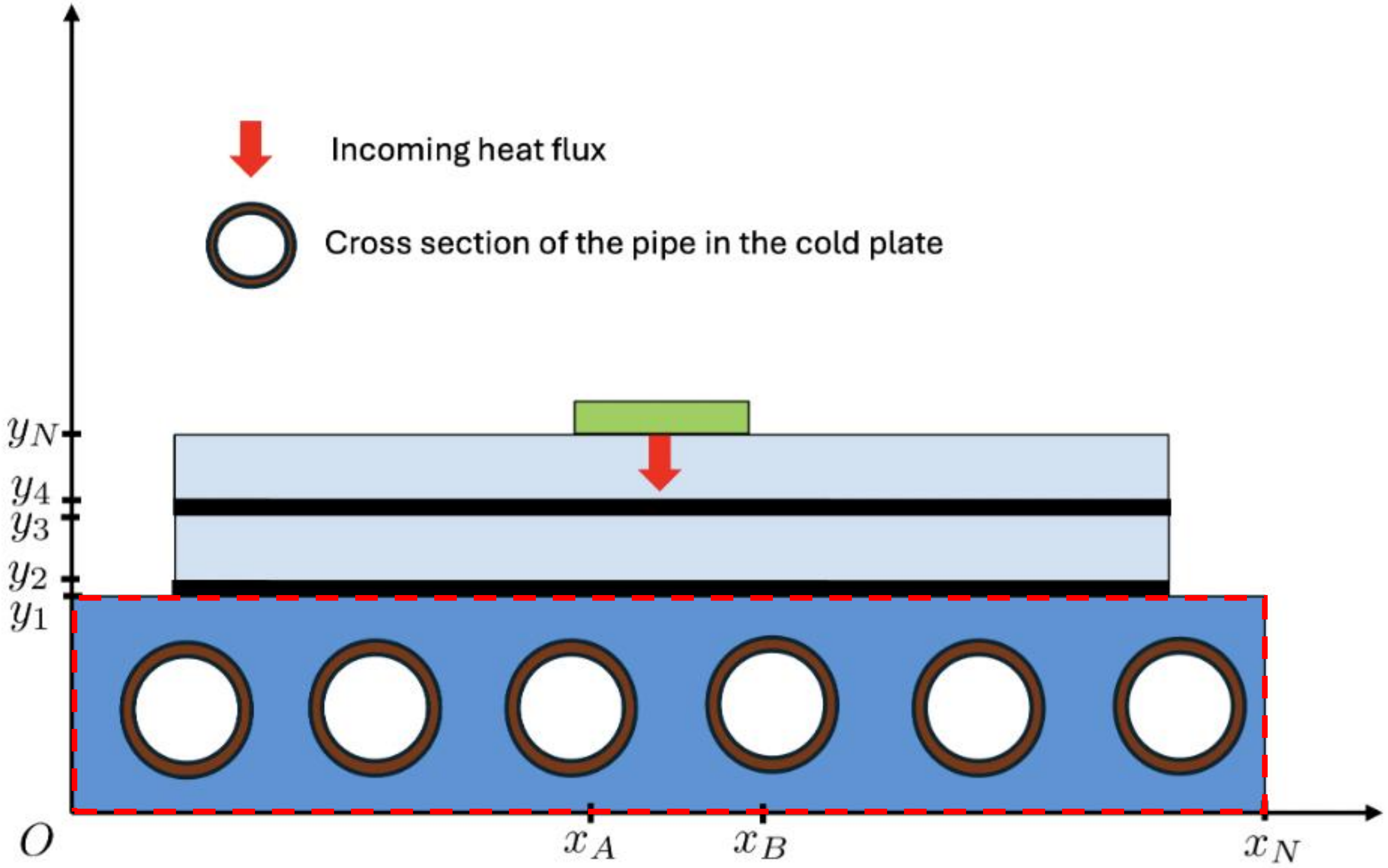
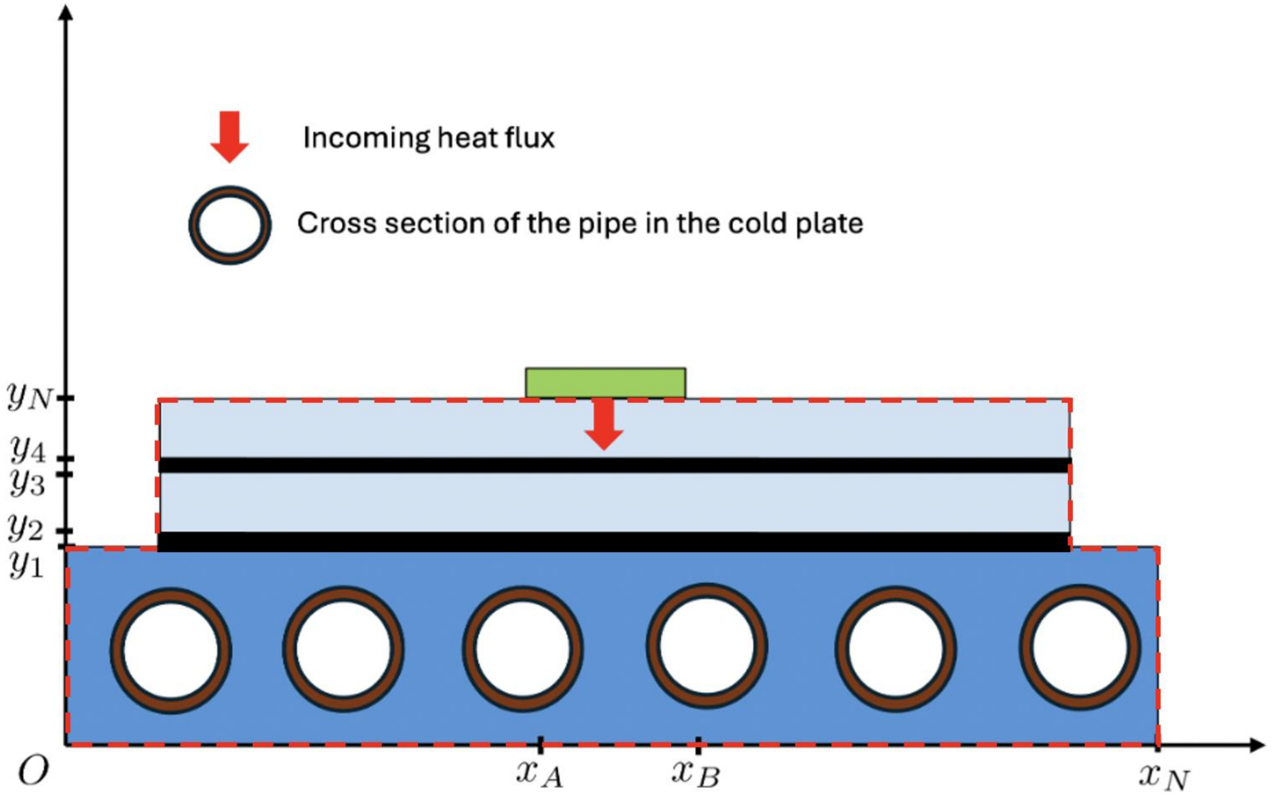


Bora A, Alvarez I, Chalfant J, Chryssostomidis C. Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks: A Systematic Study on Coolant Velocity Estimation. (Submitted to International Journal of Heat and Mass Transfer. 2025.)

Training strategy



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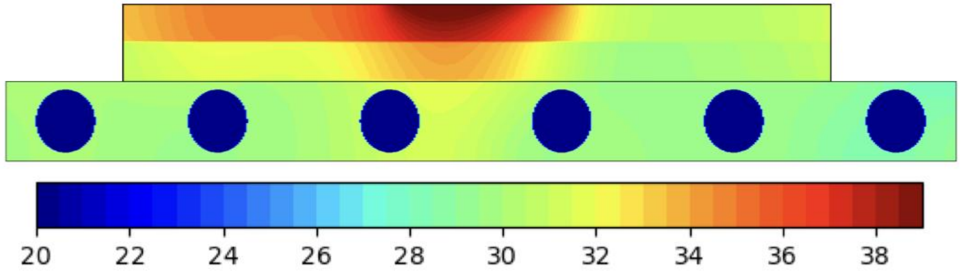
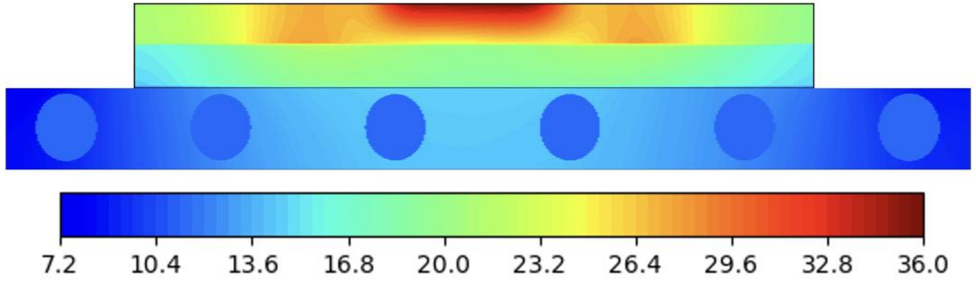
Comparison between with and without sequential training

without sequential training



with sequential training



- **Better temperature agreement**
- **Less sensitive to initialization**

Results (without any data)

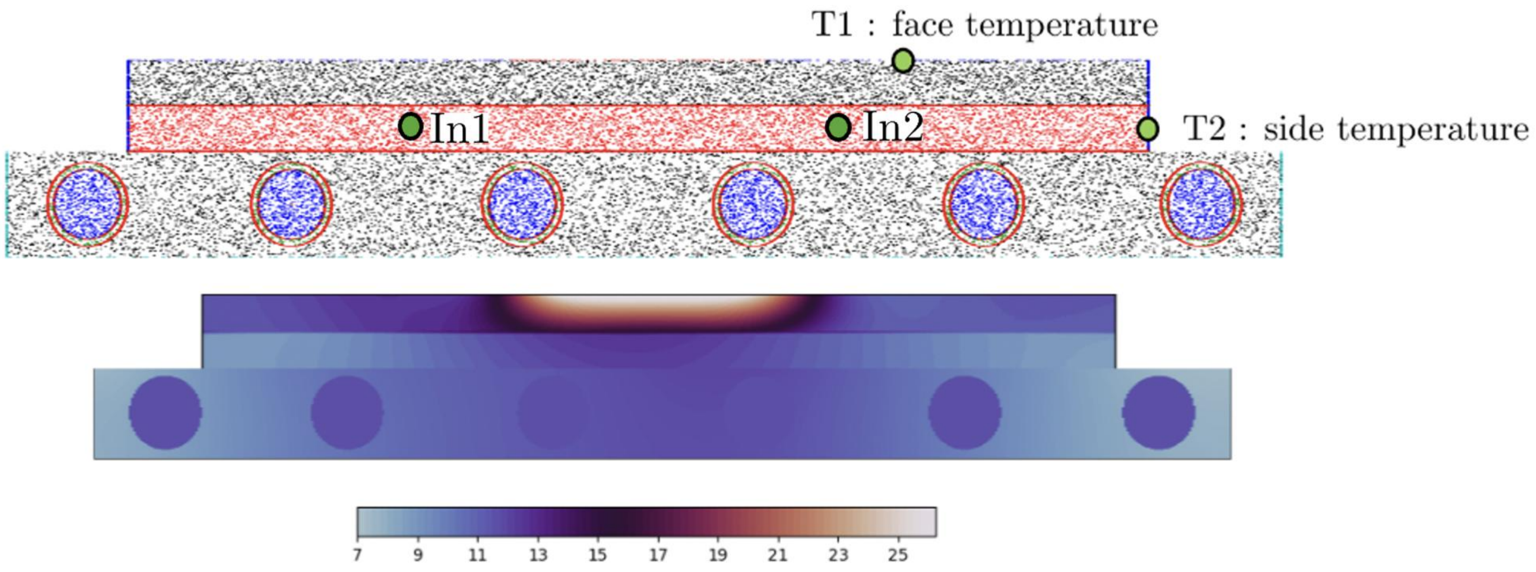


Table 2: Case A13_4 (No data used, $r = 0.005$ mm, $C_p = 4188.5\, J/Kg - K$, $\rho = 999.1\, Kg/m^3$)

Trial	h_{nn} (W/m^2K)	v_{nn} (m/s)	v_{exp} (m/s)	Side (°C) Pred	Side (°C) Exp	Face (°C) Pred	Face (°C) Exp	In1 (°C) Pred	In1 (°C) Exp	In2 (°C) Pred	In2 (°C) Exp
1	3170.89	0.33	0.296	13.52	23.57	14.65	27.48	13.56	25.85	13.89	25.90
2	3281.05	0.32	0.296	13.65	23.57	13.91	27.48	13.10	25.85	13.35	25.90
3	3165.11	0.34	0.296	14.65	23.57	14.21	27.48	14.23	25.85	13.47	25.90
Mean	3205.68	0.33	0.296	13.94	23.57	14.25	27.48	13.63	25.85	13.57	25.90
Std	65.34	0.01		0.62	-	0.37	-	0.56	-	0.28	-

Bora A, Alvarez I, Chalfant J, Chryssostomidis C. Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks: A Systematic Study on Coolant Velocity Estimation.

Results (with data)

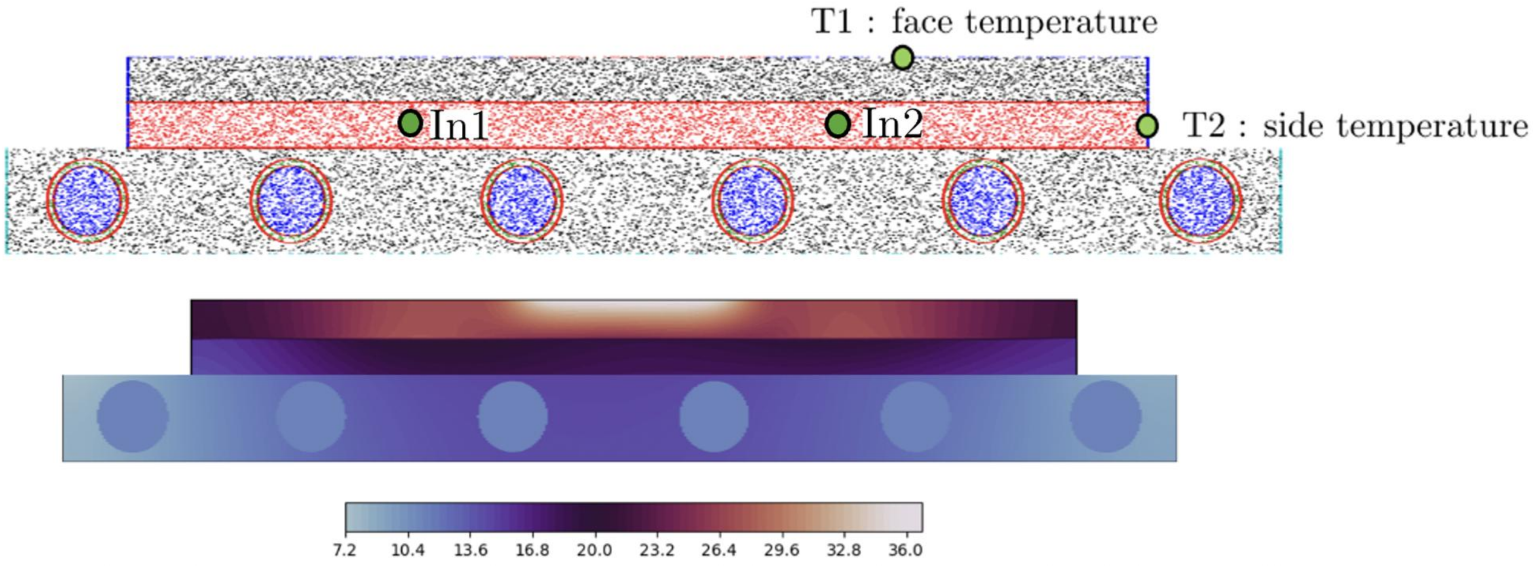
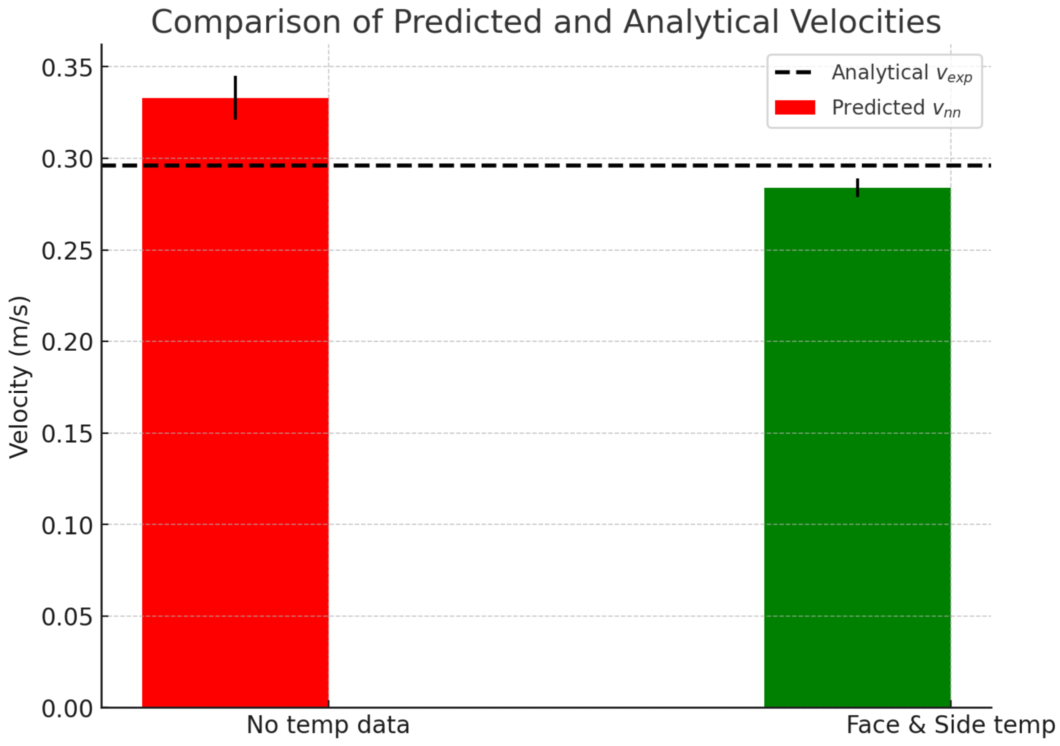


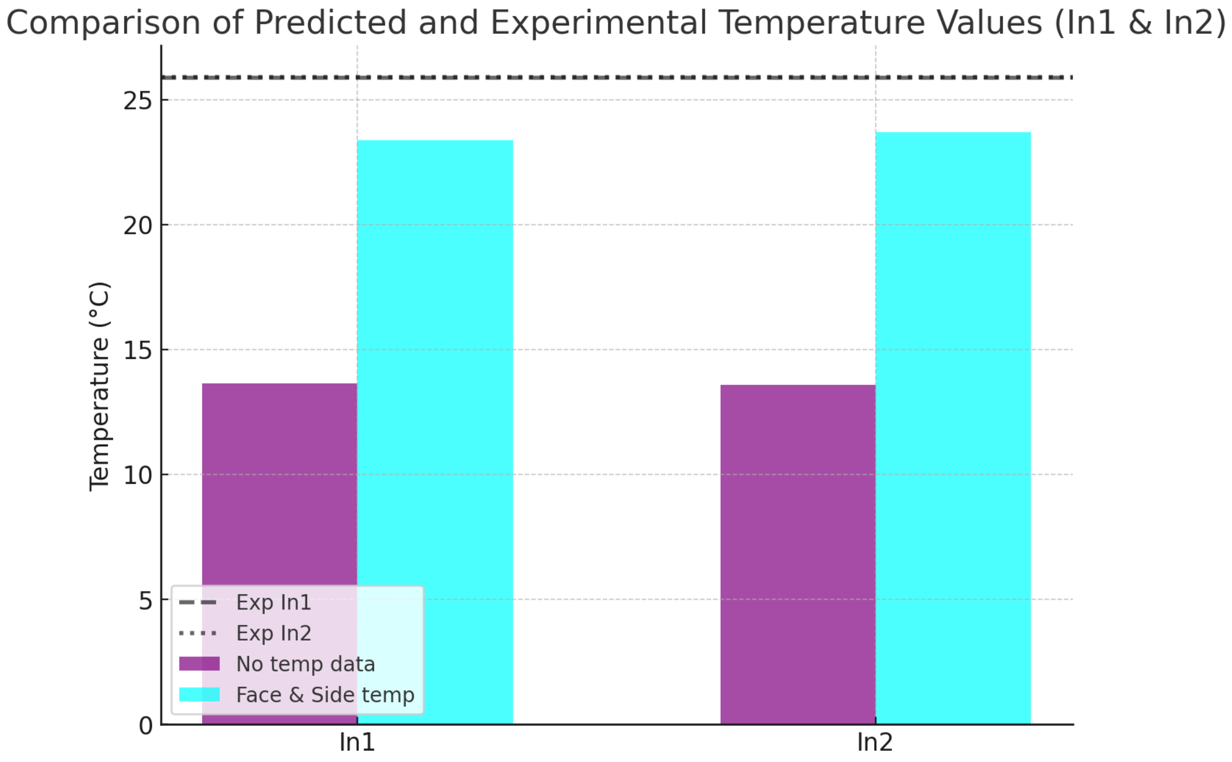
Table 3: Case A13_4 (Face and Side temp data used, $r = 0.005$ mm, $C_p = 4188.5\, J/Kg-K$, $\rho = 999.1\, Kg/m^3$)

Trial	h_{nn} (W/m²K)	v_{nn} (m/s)	v_{exp} (m/s)	Side (°C) Pred	Side (°C) Exp	Face (°C) Pred	Face (°C) Exp	In1 (°C) Pred	In1 (°C) Exp	In2 (°C) Pred	In2 (°C) Exp
1	2913.79	0.28	0.296	22.41	23.57	26.77	27.47	23.01	25.86	23.54	25.90
2	2957.04	0.29	0.296	22.35	23.57	27.11	27.47	22.81	25.86	22.99	25.90
3	2918.29	0.28	0.296	23.11	23.57	26.42	27.47	24.32	25.86	24.51	25.90
Mean	2929.71	0.28	0.296	22.62	23.57	26.76	27.47	23.38	25.86	23.68	25.90
Std	23.77	0.005	-	0.422	-	0.345	-	0.82	-	0.78	-

Bora A, Alvarez I, Chalfant J, Chryssostomidis C. Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks: A Systematic Study on Coolant Velocity Estimation.

Results Comparison

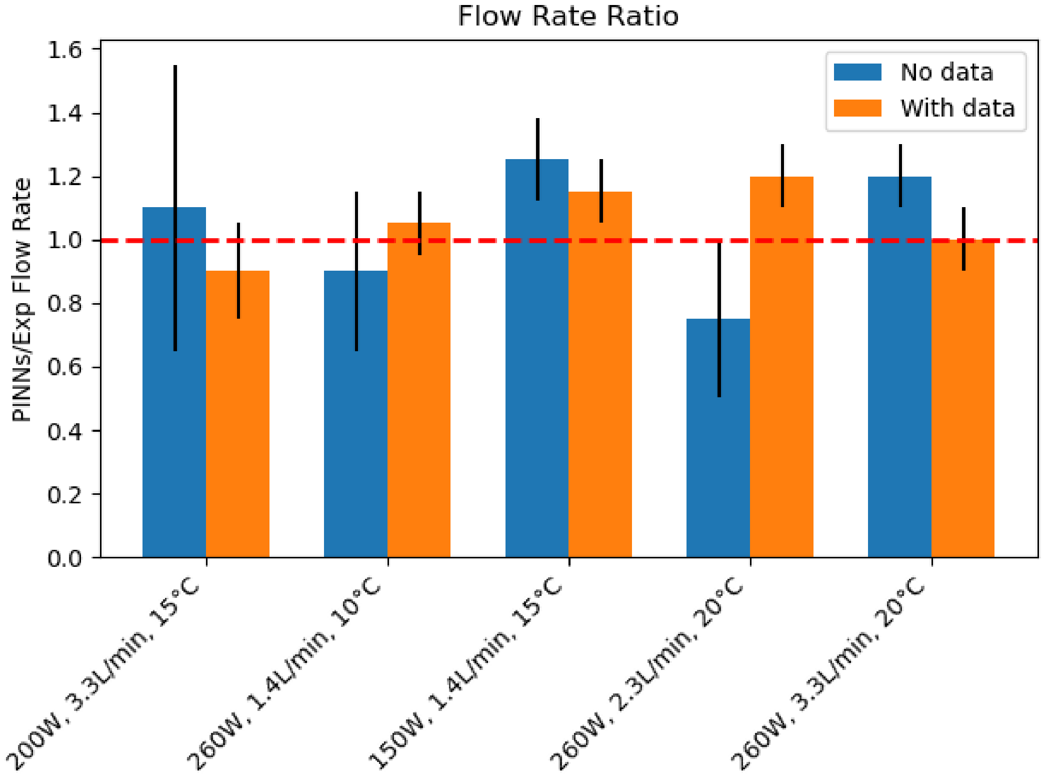


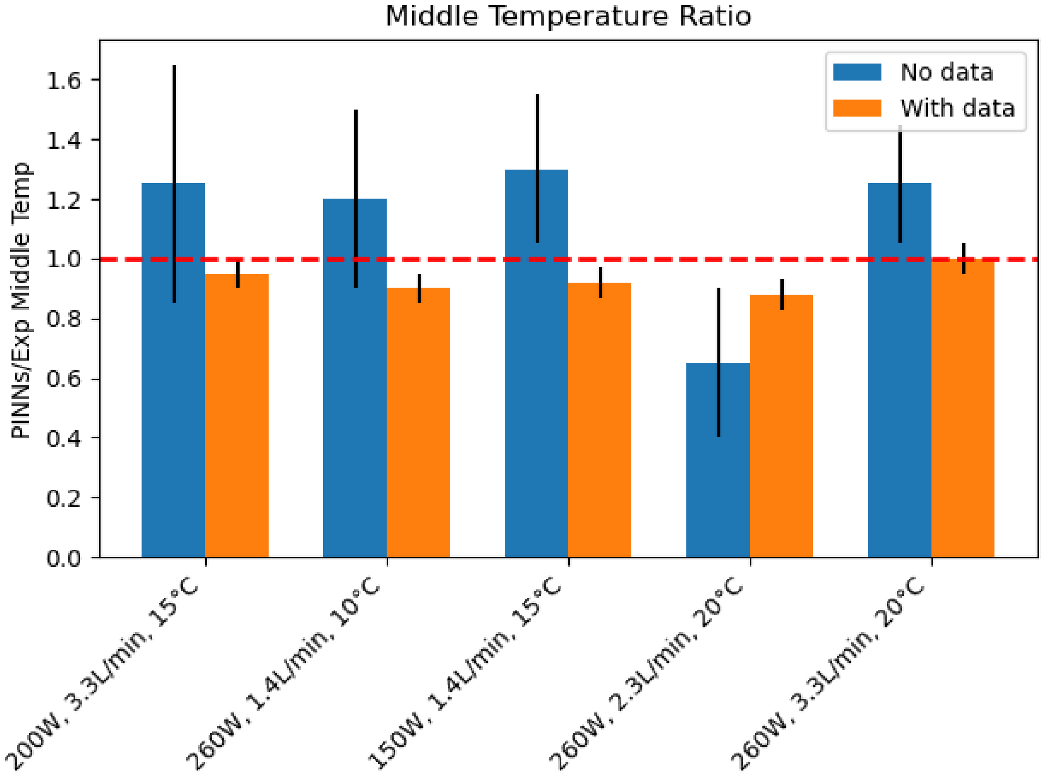


Bora A, Alvarez I, Chalfant J, Chryssostomidis C. Enhancing Heat Sink Efficiency in MOSFETs using Physics Informed Neural Networks: A Systematic Study on Coolant Velocity Estimation

Verification on varied experimental conditions

File	Power (W)	Flow Rate (L/min)
A13_4	259.2	1.39
A12_2	259.2	2.34
A13_7	259.2	3.25
A11_1	151.8	1.39
A14_2	151.8	3.25
A13_3	201.4	3.25





Conclusion

- We have formulated a PINNs framework for the effective determination of coolant velocity for heat sink.

- We define a convective boundary loss to infer the heat transfer coefficient for the system and use it along with energy conservation principle to estimate the coolant velocity.

- We introduce a novel layer-wise training strategy that enhances the accuracy and effectiveness of our proposed approach.

- We validate our method based on experimental results.

Thank you

Jack Dirig

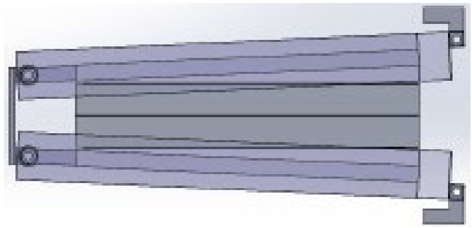
Lever-Actuated PEBB Clamping Mechanism

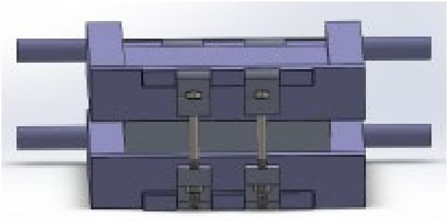
Overview

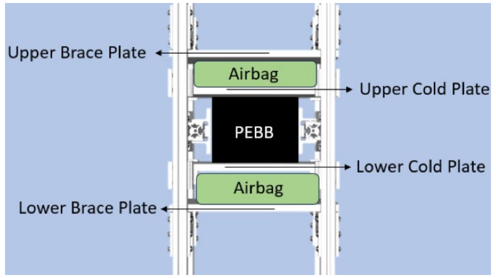
- To stay under 35 lbs, NiPEBBs require indirect water cooling
- NiPEBBs are designed to be frequently moved, installed, and uninstalled by the sailor
- Thermal interface material (TIM) thermal resistance depends heavily on contact pressure
- Our aim is to develop a system to apply and release this pressure as intended while maintaining high power density

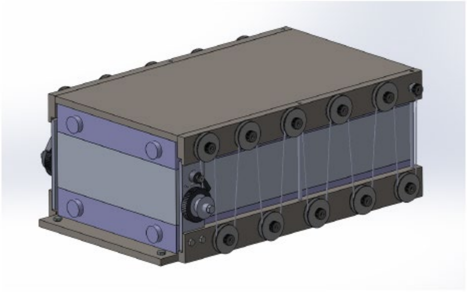
Previous Designs

- Clamshell: Requires tools, not power dense
- Pneumatic: Requires pressurized air support system, power density could be improved
- Block and Tackle Pulley System: Many moving parts, does not allow easy insertion, inexact pressure solution

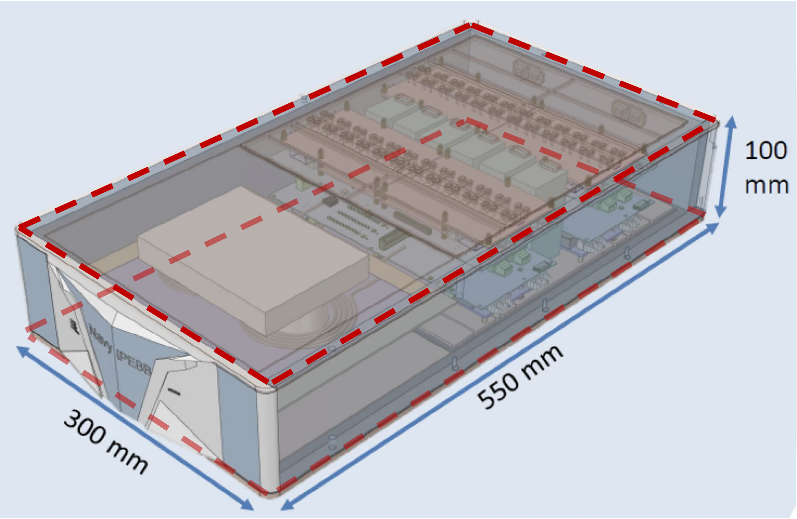








Design Objectives

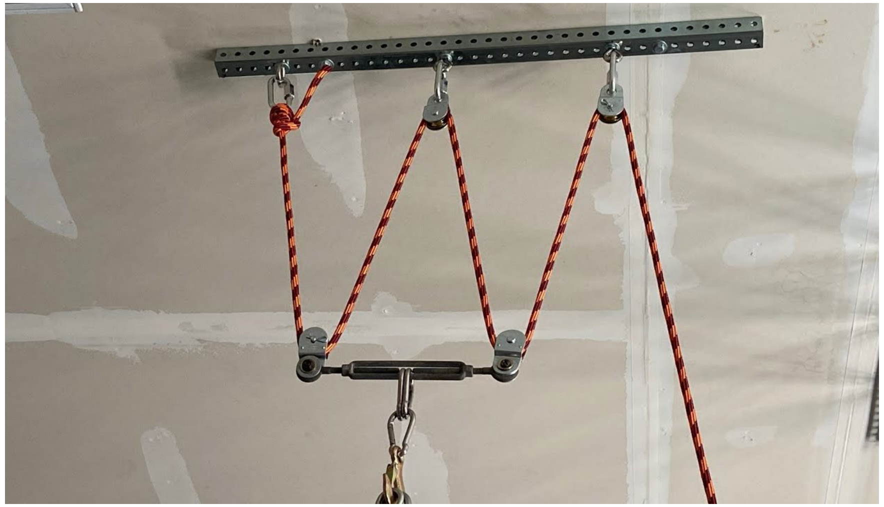


Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation

- Apply 10 psi (2560 lb total) of pressure across the PEBB to ensure sufficient heat transfer to cold plates
- Do so without systems that require additional support (i.e. electrical, air, etc.)
- Make the actuation ergonomic for a sailor
- Maintain high power density (make the system low profile)

Mechanical Concepts

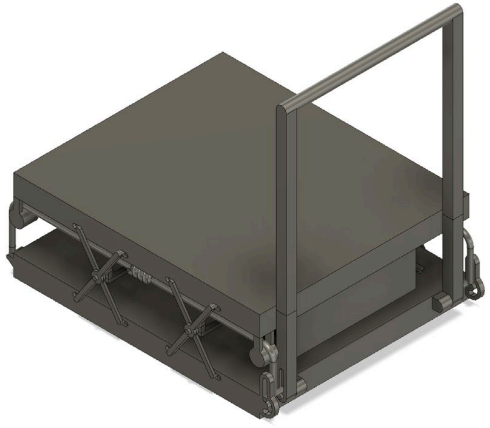
In a typical latch, pulling it causes some spring or elastic material to stretch out, creating tension and storing energy.

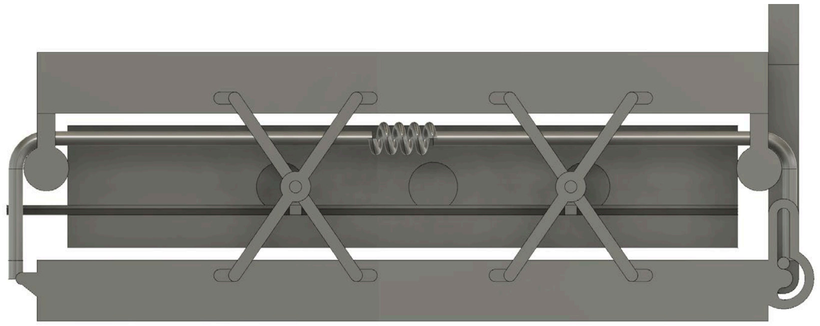


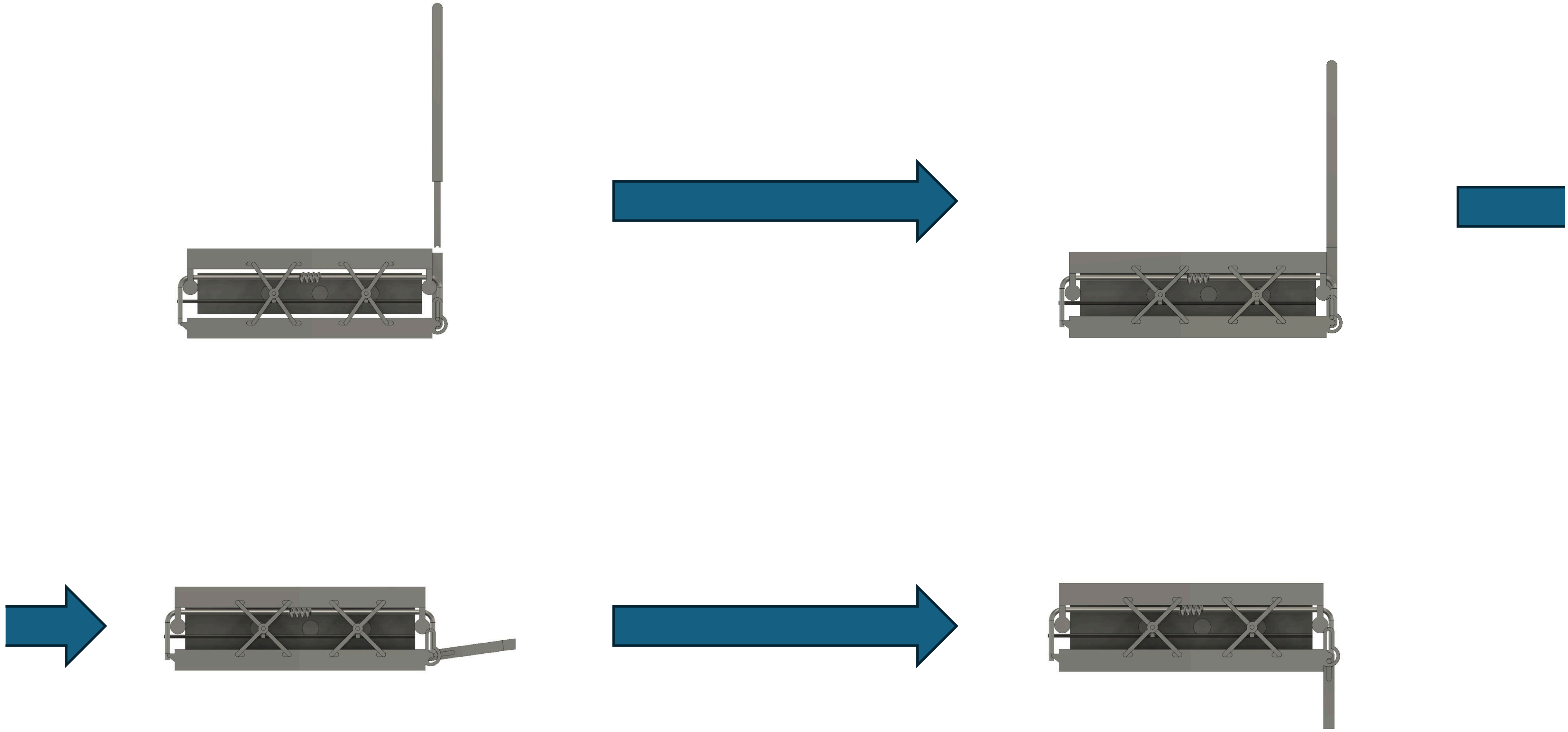
Pulleys can be used in series to create mechanical advantage.

Overall Design

- When stretched, cable pulls cold plates together and applies pressure on PEBB
- Plates are connected via X-brackets and remain in open position without tension
- Lever is removable to improve power density
- Minimal height added to each PEBB (only cold plates and clearance to insert PEBB)

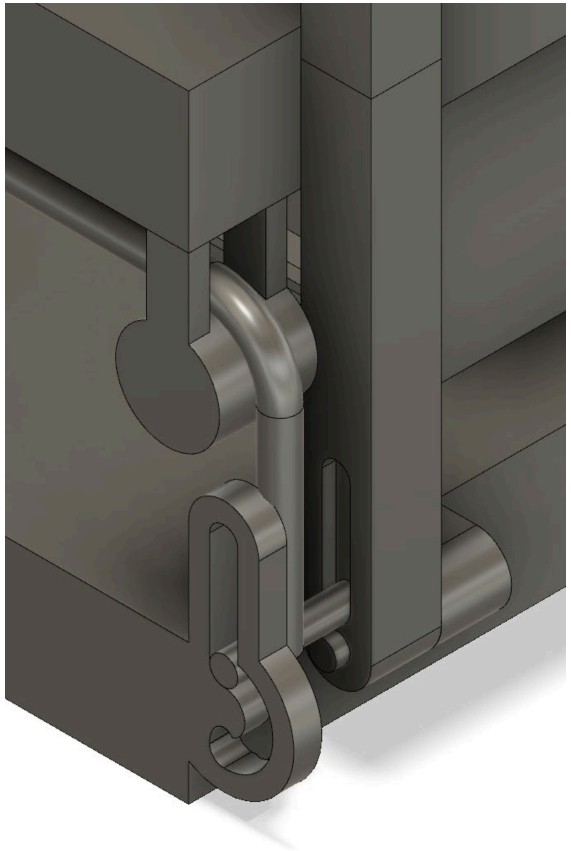






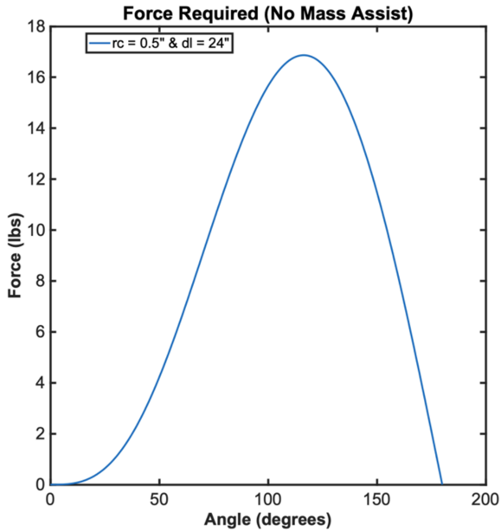
Single Tool/Motion

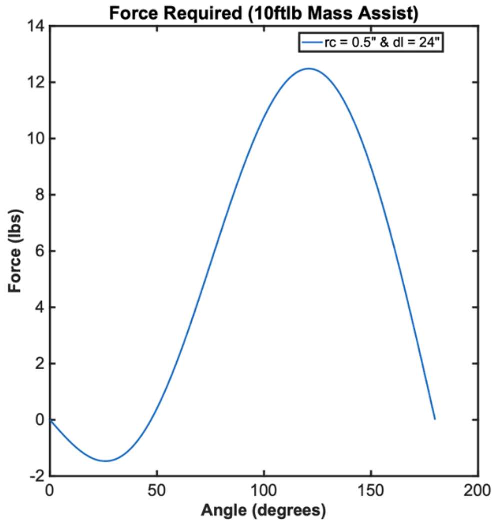
- Inserting the full lever brings plates to the closed position
- Pulling lever around tightens spring
- Pin slides into notch at the bottom to lock position



Easy Actuation

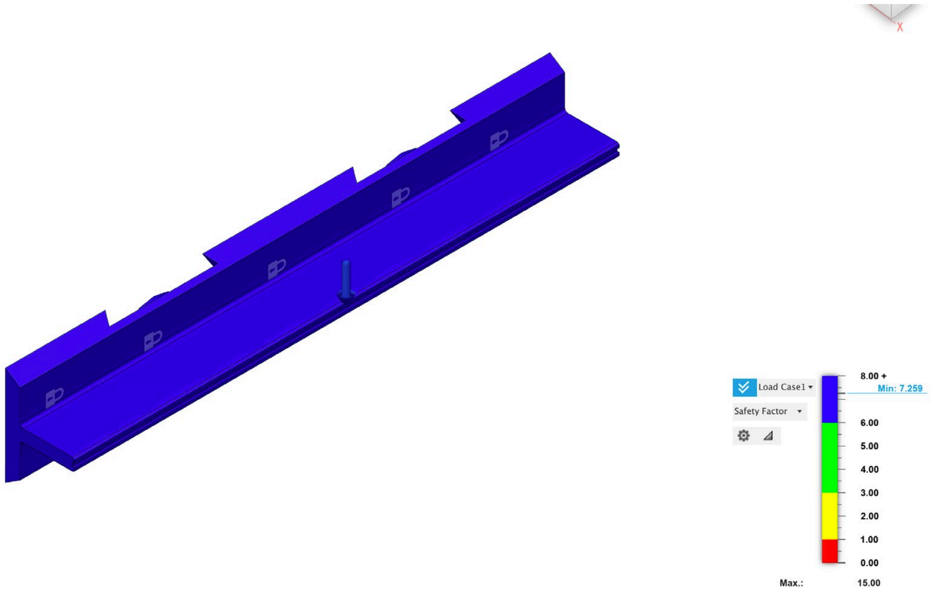
- Single lever motion closes plates and loads spring
- 180º of motion, 2 ft radius
- Maximum force of 13-17 lbf required
- Dampers to slow down lever release





Connections

- PEBB slides into rails fixed to the ship, allowing easy rear electrical connection
- Rails support PEBB and connect to X-brackets; are sufficiently strong to handle additional forces in rough seas
- Flexible liquid cooling connections required for plate movement

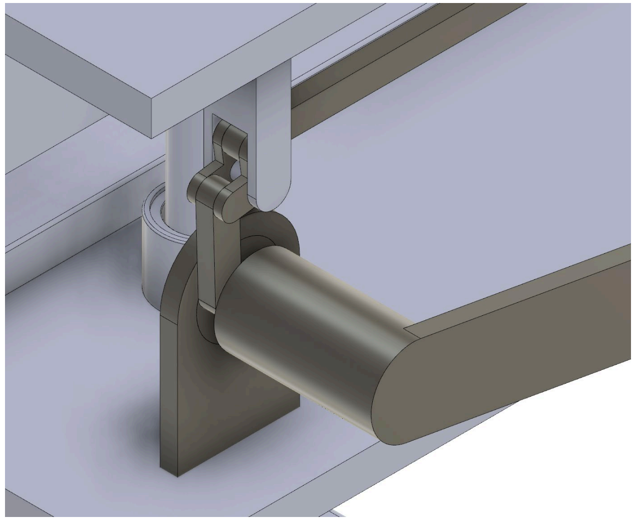


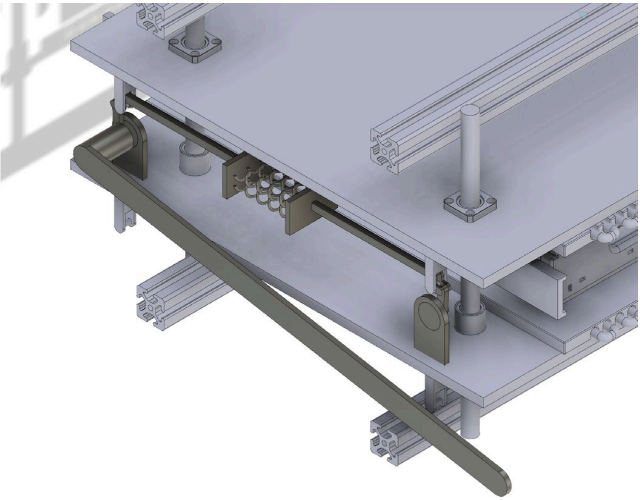
Future Improvements

- No-tool design
- Easier to service
- Smaller inward forces – smaller bending moment on the plate

Future Design

- Design that replaces cables with solid linkages
  - Requires shorter range of motion
  - Removes need for removable lever
  - Less work input by the sailor
  - Improved force transfer at joints reduces bending moment on plate





PEBB Clamping Mechanism Paradigm Shift

MIT Sea Grant Design Lab

Presented by Jacob Film

Presentation Date: 5/21/25

Revisions: 5/23/25

Massachusetts Institute of Technology

Motivation Review – Why are we clamping the PEBB?

"Plug & Play" PEBB

- Quick & hassle-free insertion/removal
- Indirect Liquid Cooling → Poor heat transfer at boundary

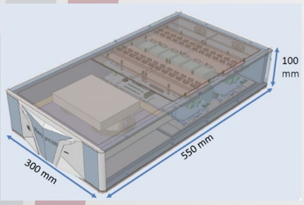
Interface Requirements

Non-permanent installation

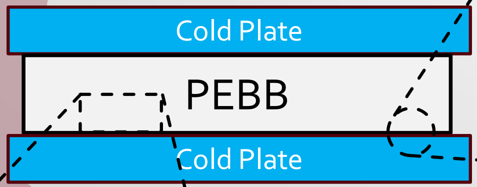
Reduce thermal resistance → Use a Thermal Interface Material → Apply sufficient pressure

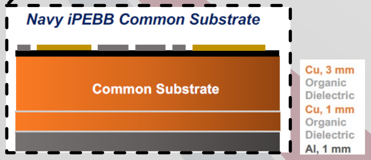
Motivation Review – Why are we clamping the PEBB?

Apply sufficient pressure to reduce thermal resistance



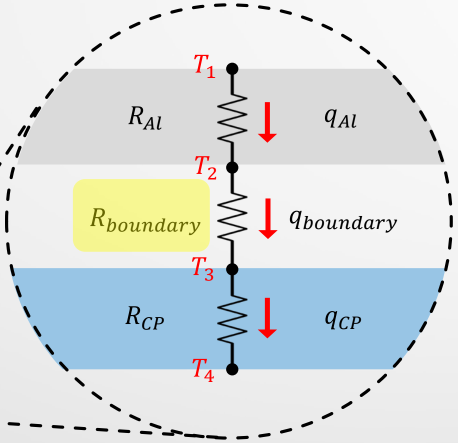
Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation



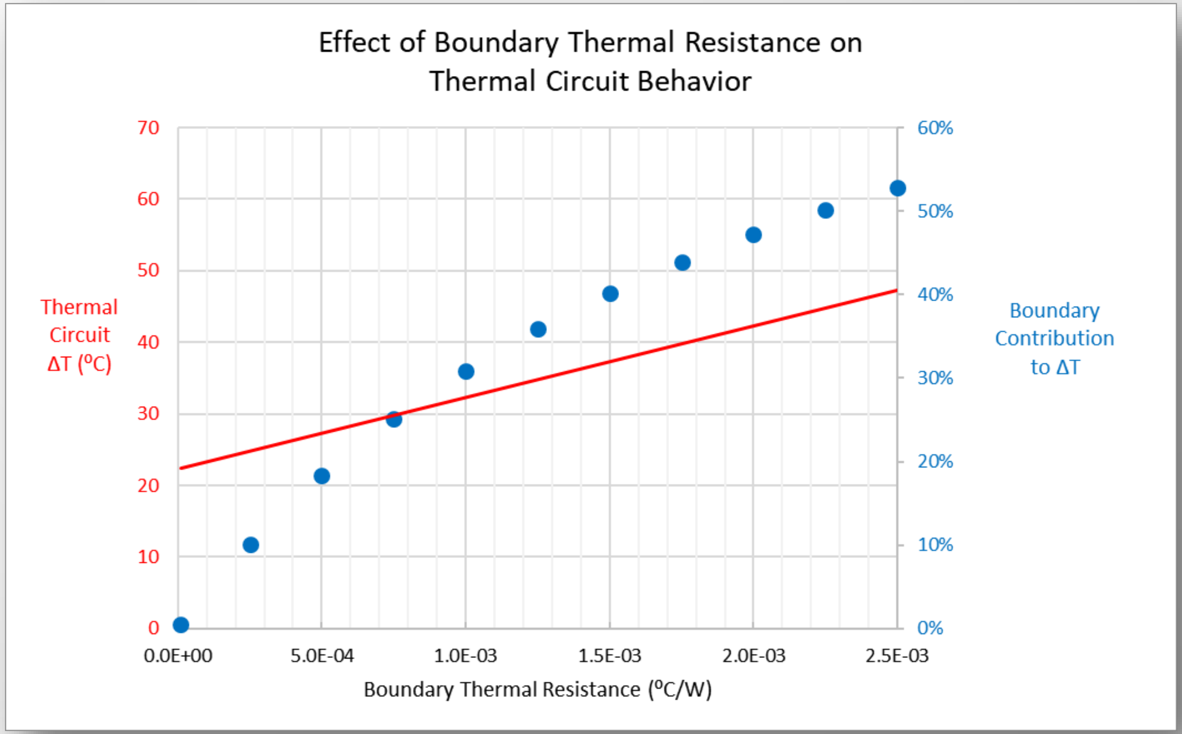


Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation

Simplified Thermal Circuit

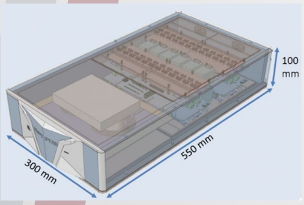


R_{CP} based on Wakefield-Vette 6-Pass Buried Bottom Source 24" Cold Plate @ 0.75 gpm with engaged contact area adjustment



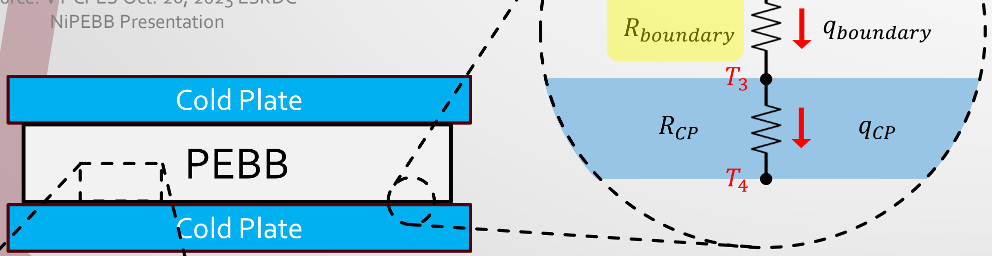
Motivation Review – Why are we clamping the PEBB?

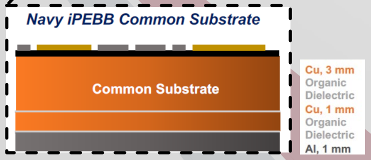
Apply sufficient pressure to reduce thermal resistance



Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation

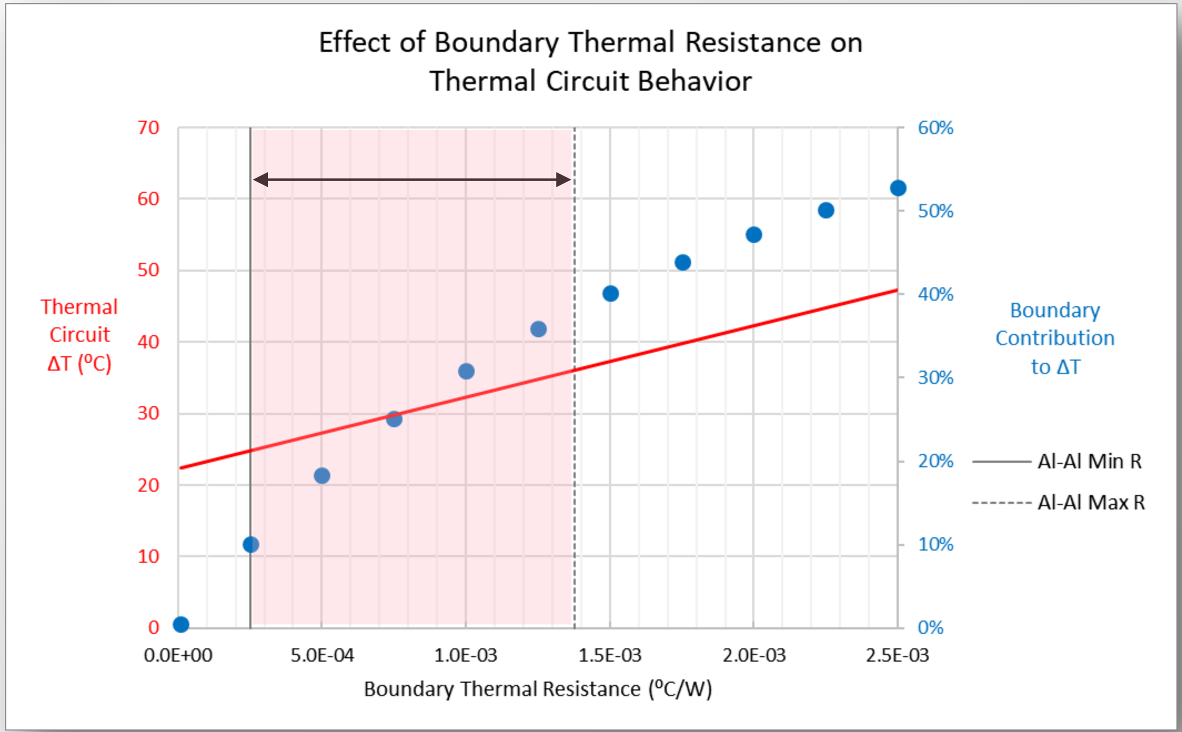
Simplified Thermal Circuit





Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation

R_{CP} based on Wakefield-Vette 6-Pass Buried Bottom Source 24" Cold Plate @ 0.75 gpm with engaged contact area adjustment



Motivation Review – Why are we clamping the PEBB?

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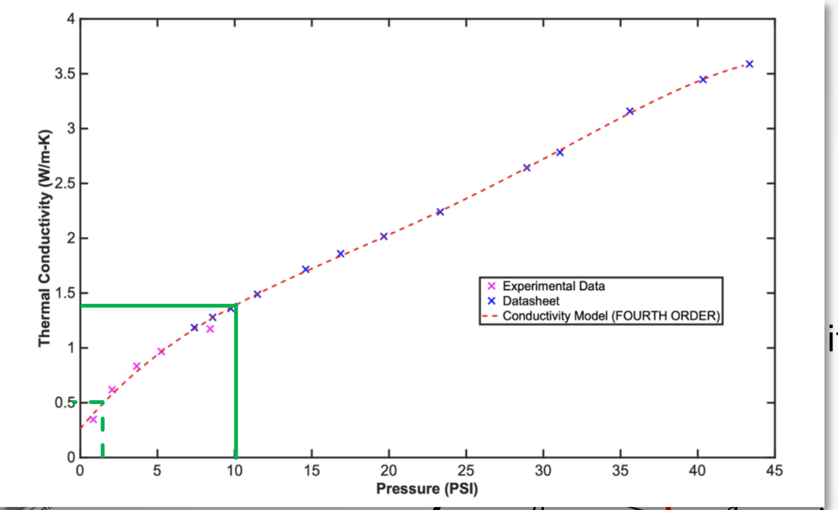
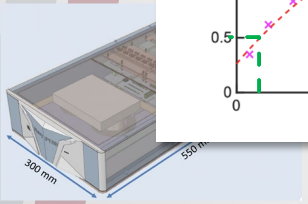
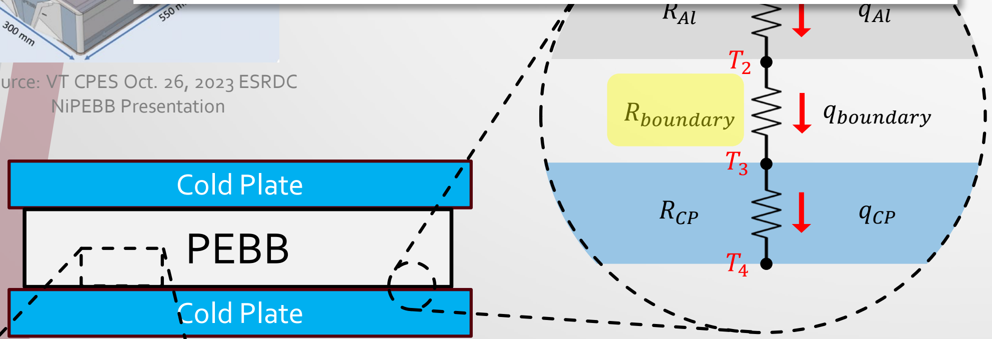
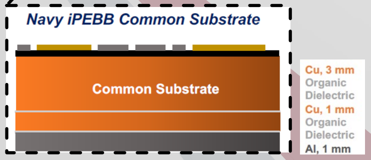




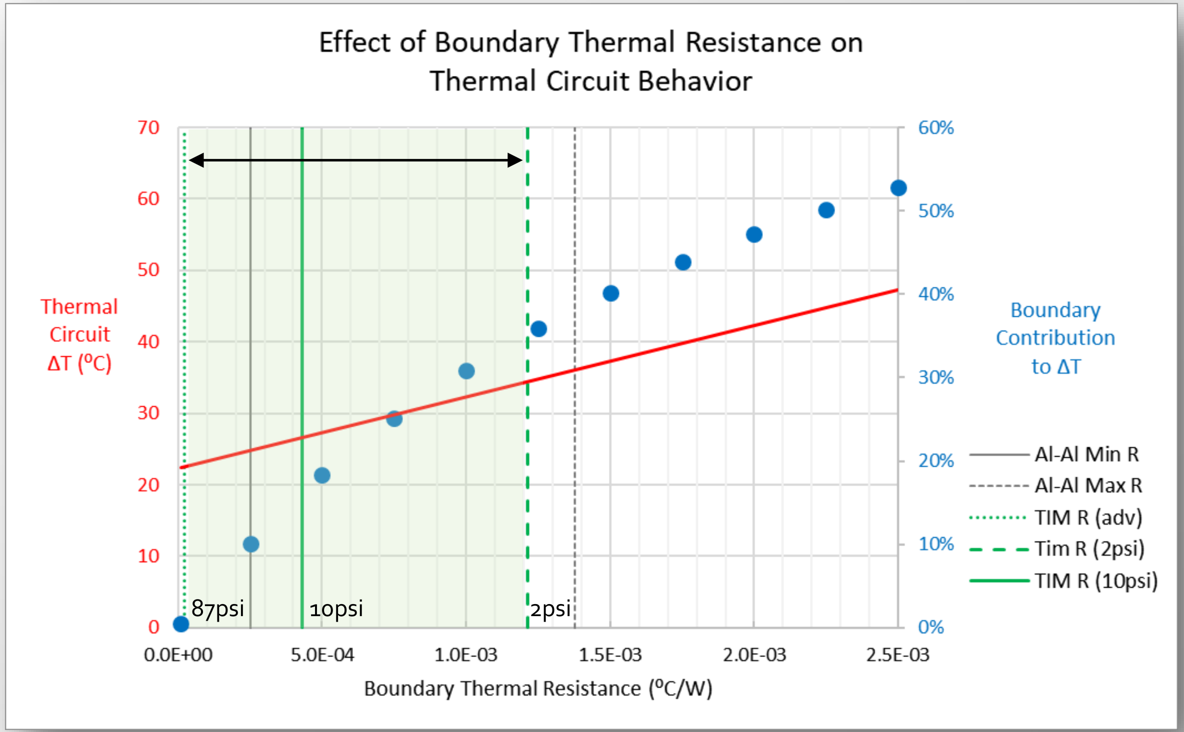
Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation





Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation

R_{CP} based on Wakefield-Vette 6-Pass Buried Bottom Source 24" Cold Plate @ 0.75 gpm with engaged contact area adjustment



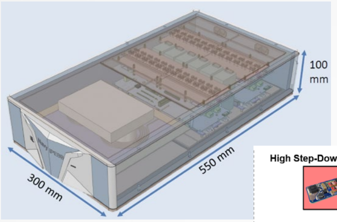
More Contact Pressure = Less Thermal Resistance

- → Reduced impact on ship cooling system
- → Enables PEBB operation at higher power

Clamping Pressure Applied via Clamping Force

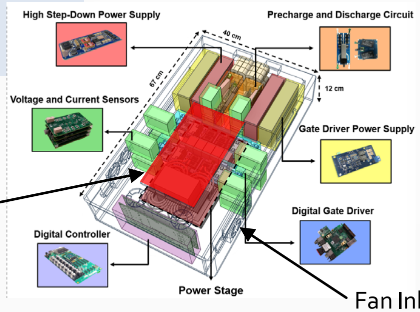
Apply sufficient pressure to reduce thermal resistance

Design Development Note



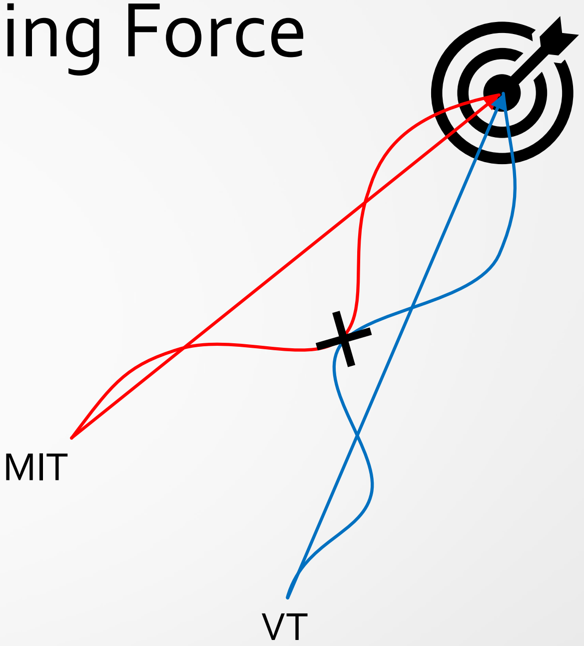
Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation

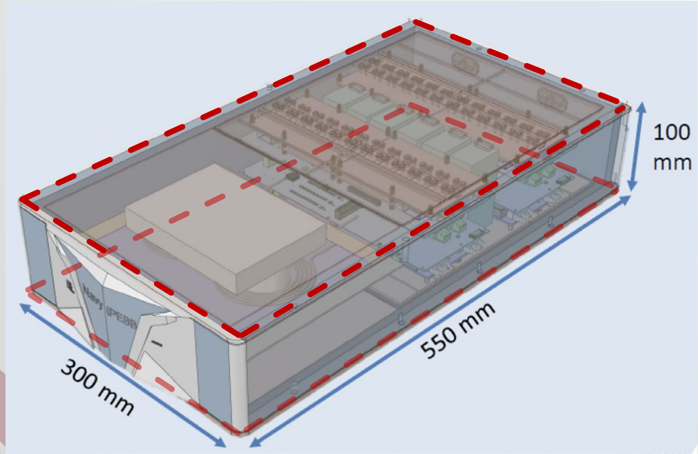
Source: Most recent VT CPES NiPEBB Information Exchange with MIT



6.5”x12” Common Substrate

Fan Inlets for Transf. cooling





Source: VT CPES Oct. 26, 2023 ESRDC NiPEBB Presentation

NiPEBB Top/Bottom Face Area:

550mm x 300mm = 0.165m^2 [$255.75in^2$]

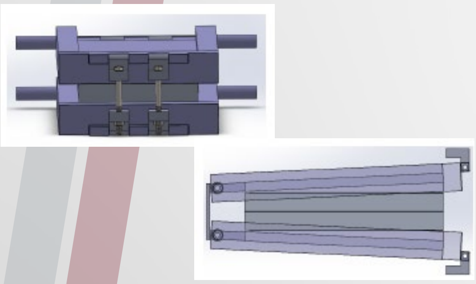
Required Force:

$255.75in^2 \cdot 10psi$ = 2,557.5lbs

Clamping Force Generation

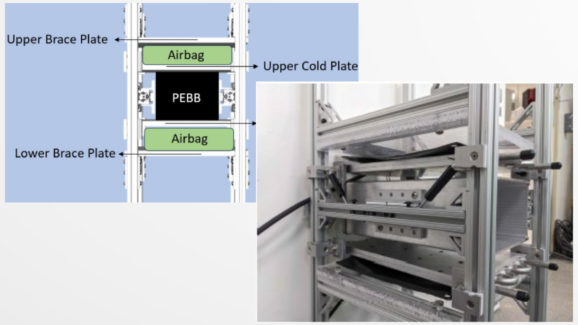
All of our designs so far have sought to <u>generate</u> the required clamping force by storing *potential energy* and *starting from equilibrium*

Hinged Clamp (Clamshell)



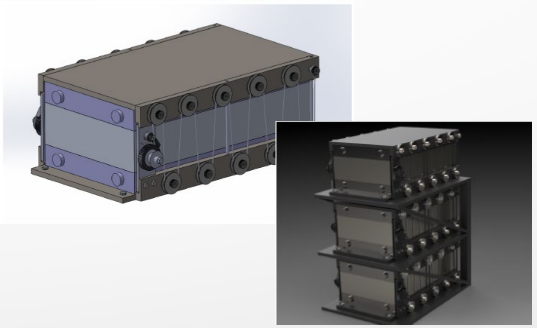
- Energy Storage: Bolt Tension
- Input: Torque via hand tools

Pneumatic Mechanism



- Energy Storage: Air Pressure
- Input: Compressed Air System

"Block and Tackle" Pulley System (UMASS Student Group)



- Energy Storage: Elastic Potential – Cable Tension
- Input: Torque via hand tools

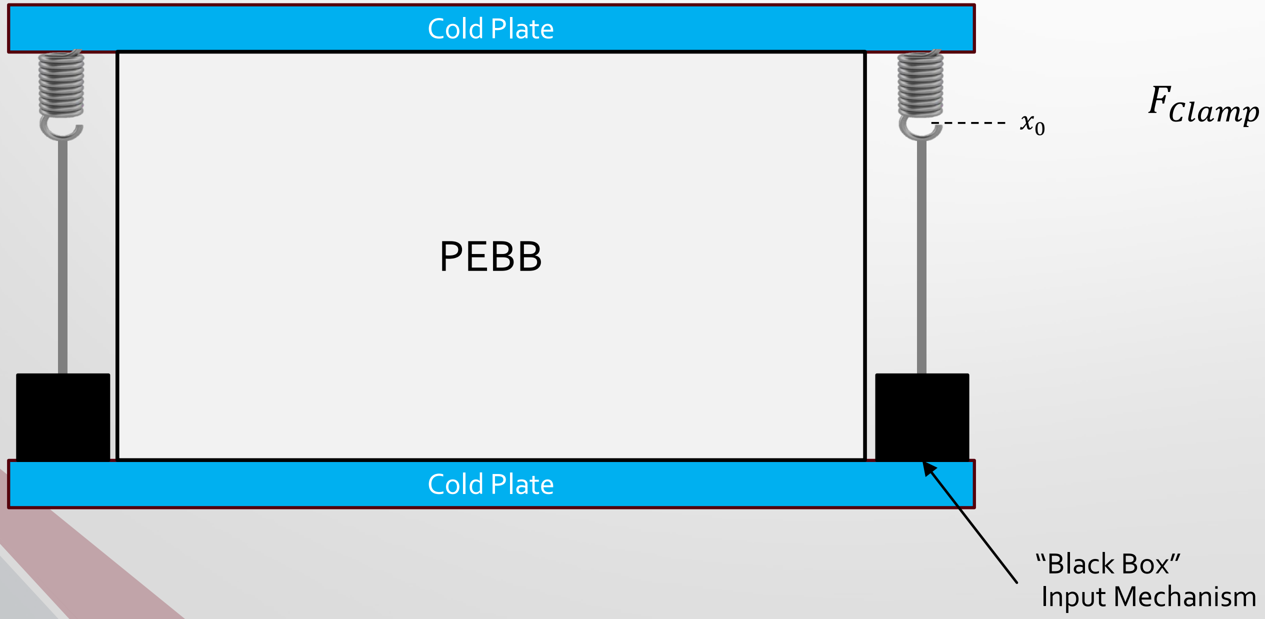
Spring Cable and Lever System

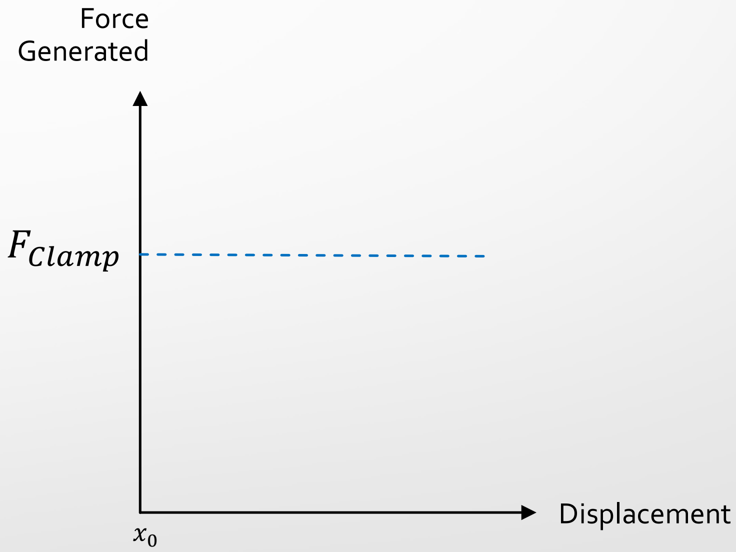
- Energy Storage: Elastic Spring Energy
- Input: Torque via built-in lever arm

Clamping Force Generation

From an energy standpoint, this requires our Input Mechanism, and consequently the operator, to input all of the mechanical work required

Example: Spring Cable System

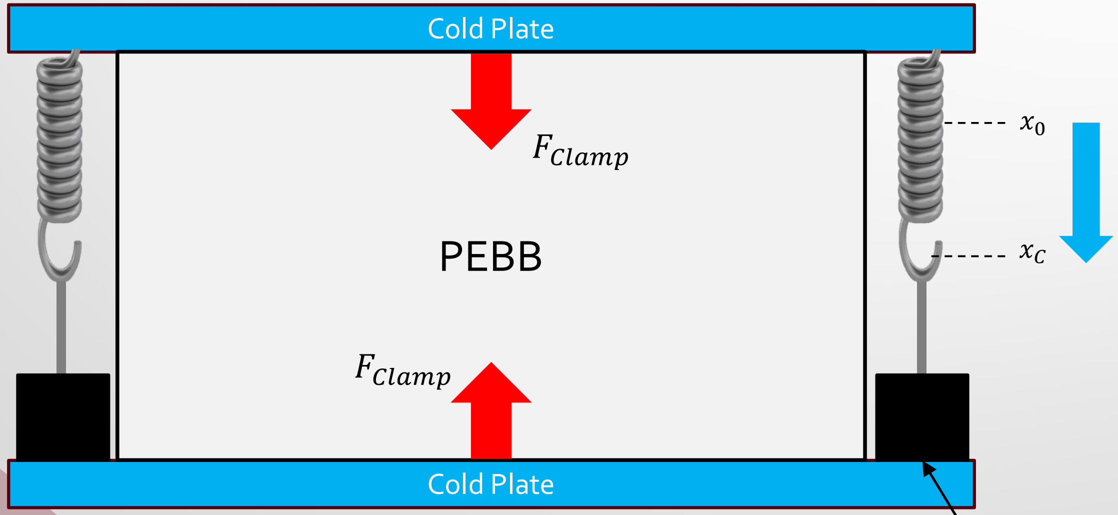




Clamping Force Generation

From an energy standpoint, this requires our Input Mechanism, and consequently the operator, to input all of the mechanical work required

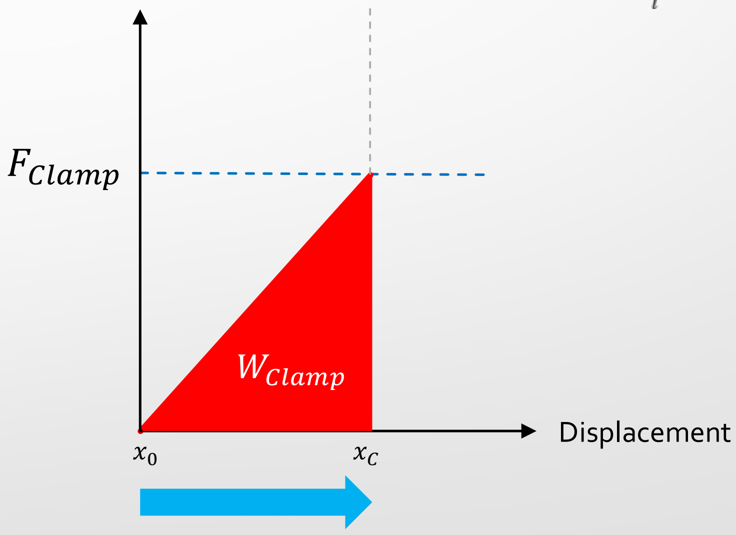
Example: Spring Cable System



Parallel spring displacement shown for visual intuition
Forces in this scenario would be $2 \cdot F_{Clamp}$

"Black Box"
Input Mechanism

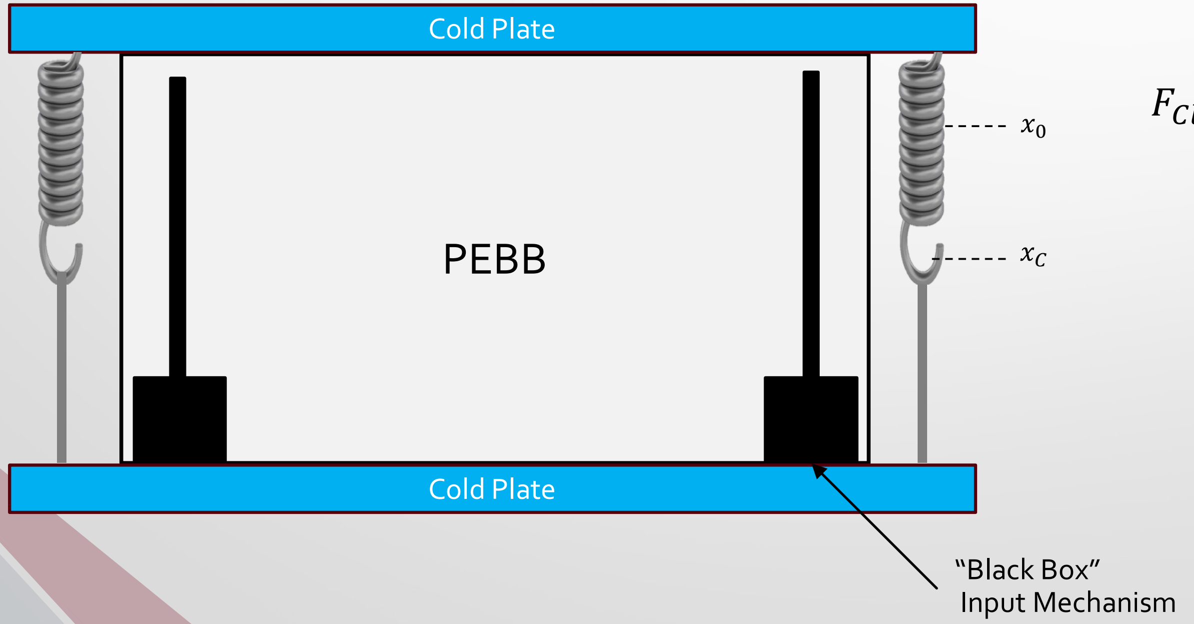
$$W_{\text{Spring}} = \int_{x_i}^{x_f} F_S \cdot \text{dx}$$



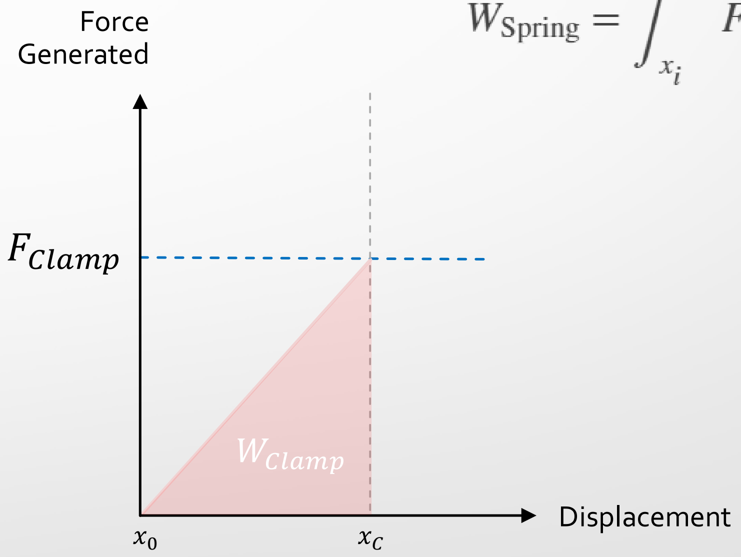
Clamping Force Preload & Release

If instead we preload the clamping force by storing potential energy ahead of time, the only work required by our Input Mechanism / the operator is the work necessary to release the PEBB

Example: Spring Cable System



$$W_{\text{Spring}} = \int_{x_i}^{x_f} F_S \cdot \mathrm{dx}$$

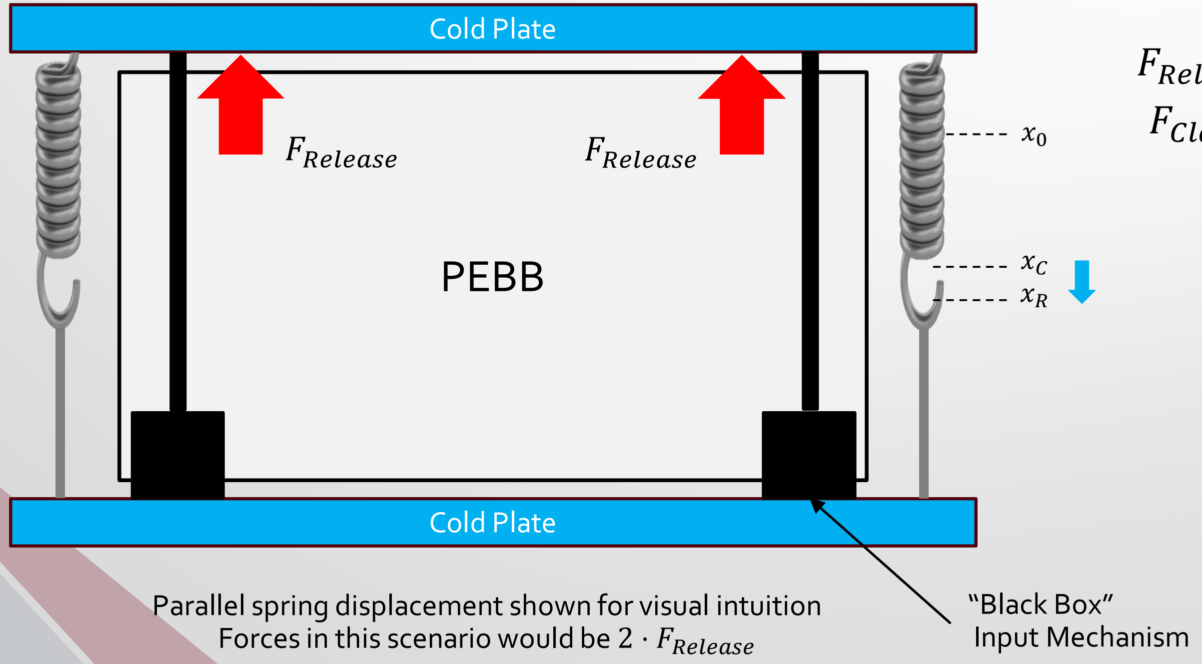


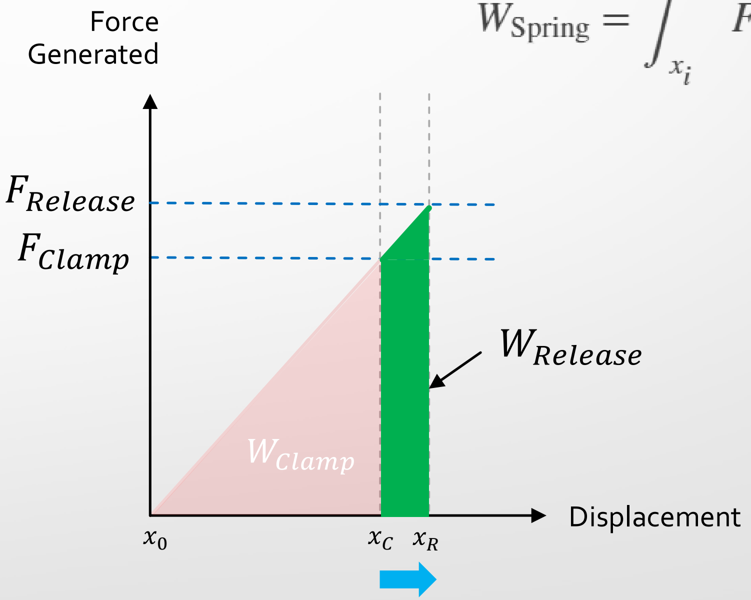
Clamping Force Preload & Release

If instead we <u>preload</u> the clamping force by storing potential energy ahead of time, the only work required by our Input Mechanism / the operator is the work necessary to <u>release</u> the PEBB

Example: <u>Spring Cable System</u>

$$W_{\text{Spring}} = \int_{x_i}^{x_f} F_S \cdot \mathrm{dx}$$





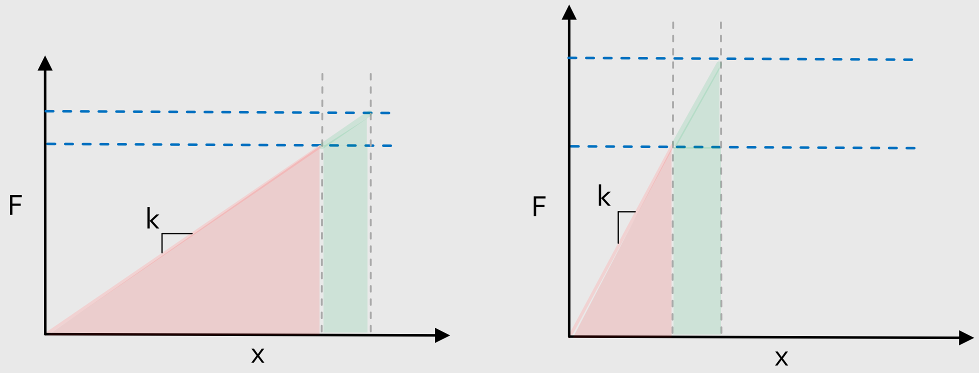
How helpful is this?

It depends...

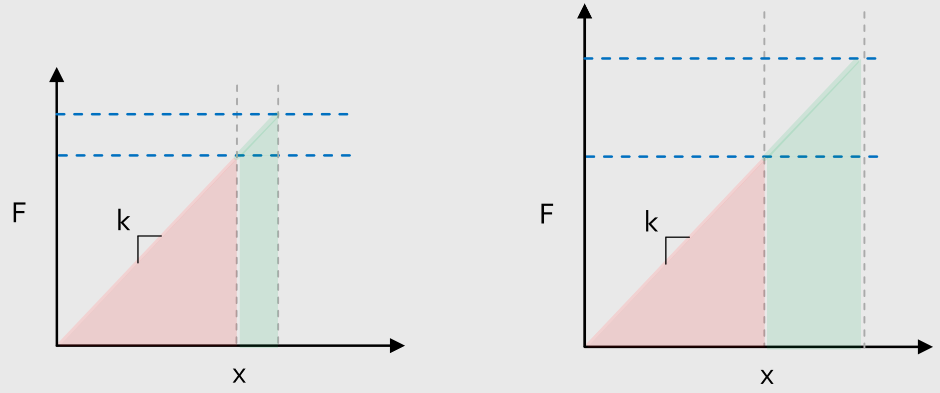
Spring Stiffness

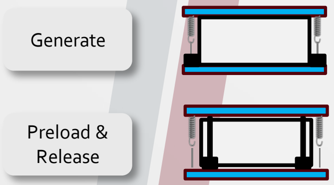
Clearance Gap

Stiffness: Low vs. High

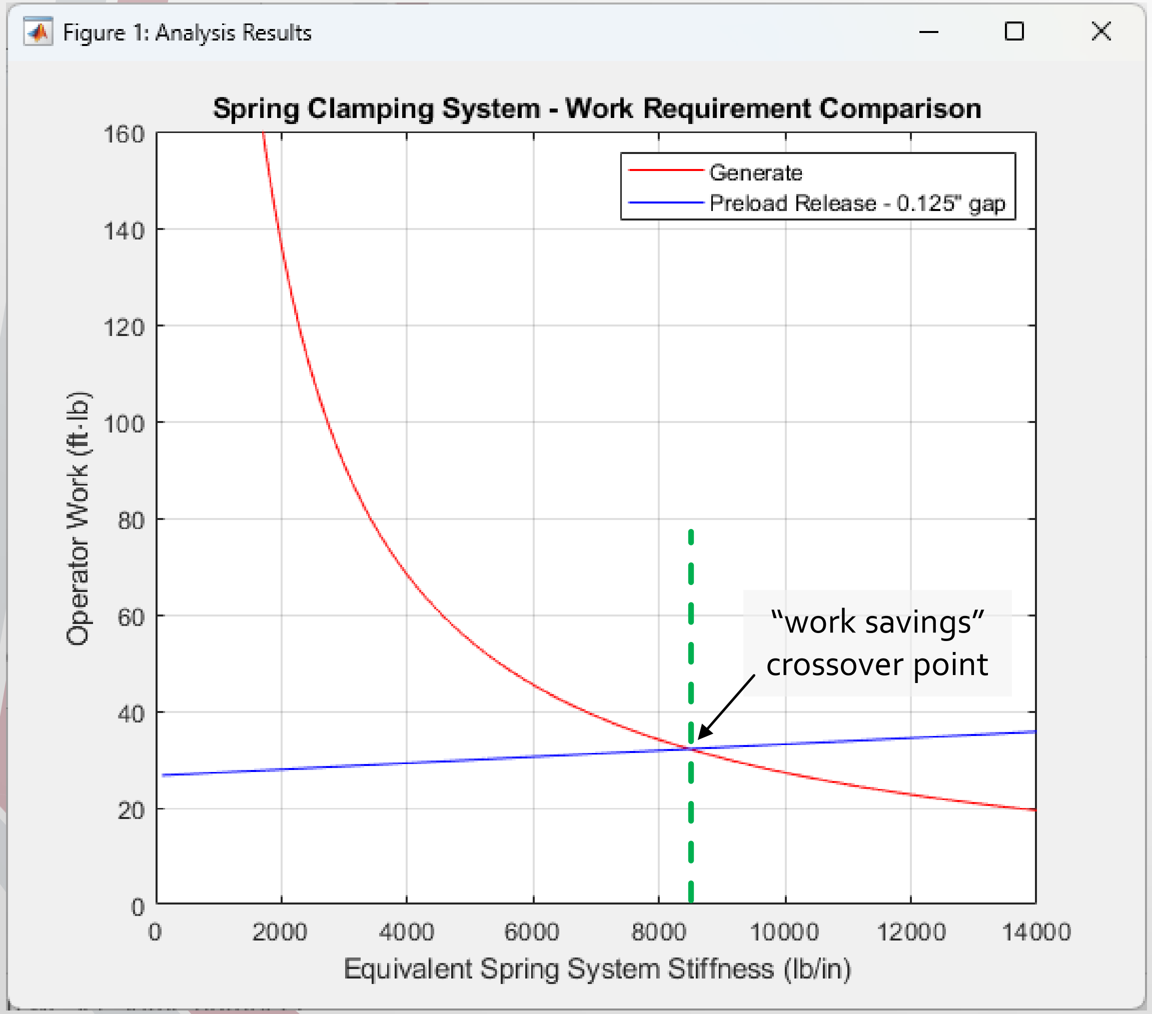


Clearance Gap: Low vs. High





How helpful is this?

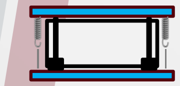


Trends

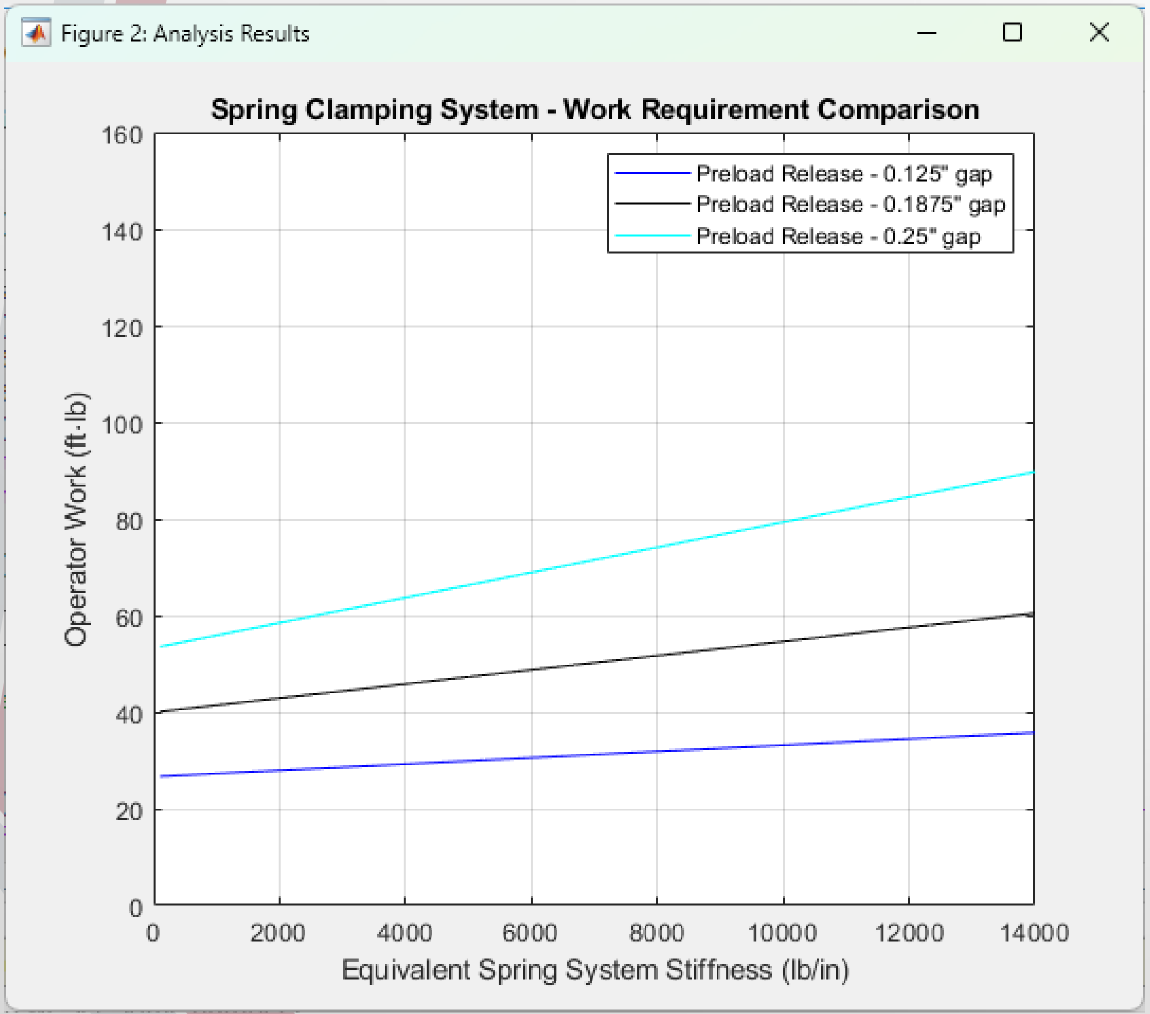
- Lower Spring System Stiffness equates to higher "work savings" for the operator
  - Note: Preload & Release is not decoupled from Generate - we still have to do this work in 'Preloading' the system during assembly

Generate

Preload & Release



How helpful is this?



Trends

- Lower Spring System Stiffness equates to higher "work savings" for the operator
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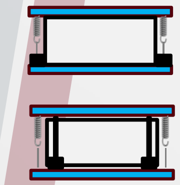
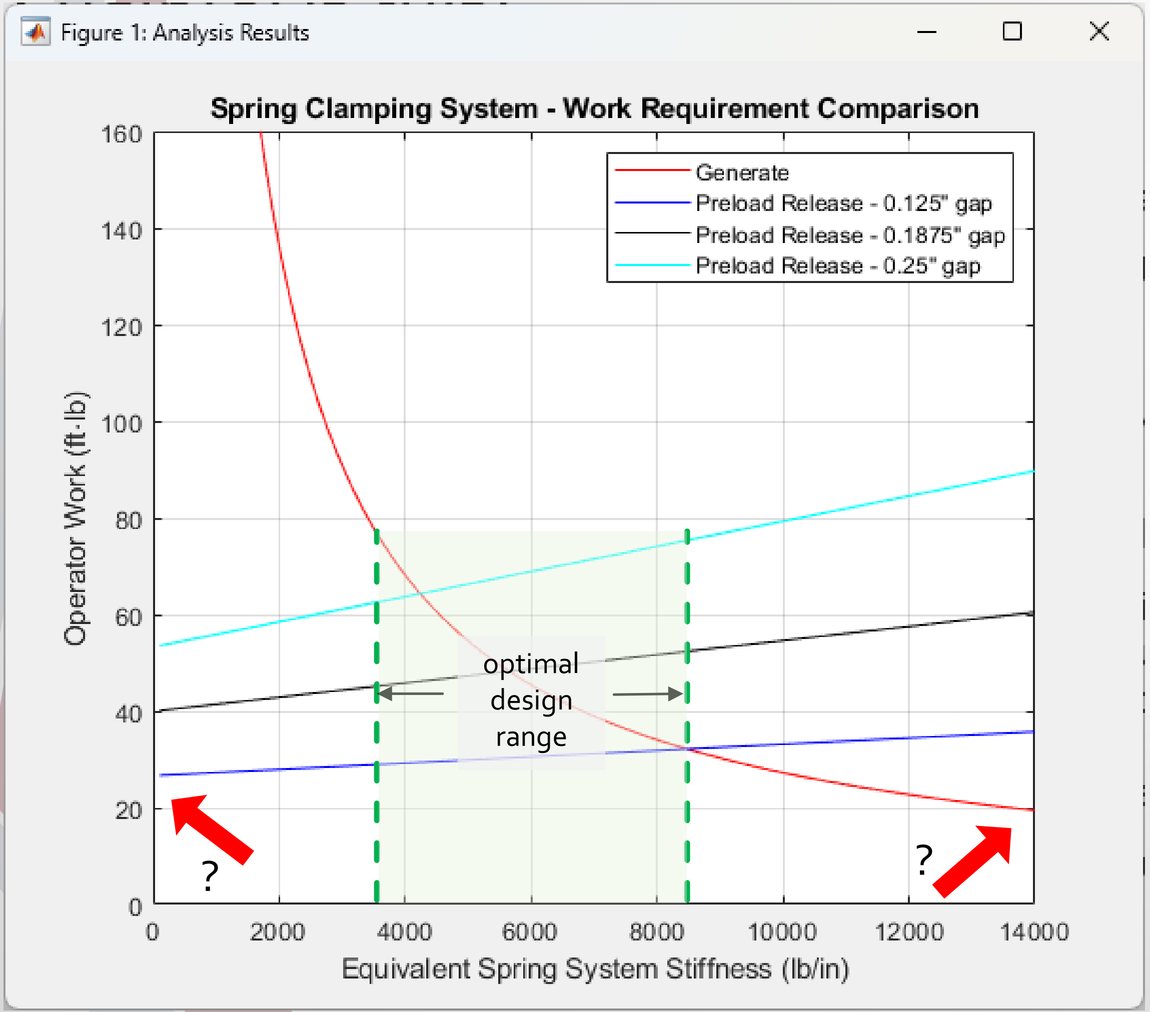
- Minimizing the required clearance gap reduces the overall work required

Generate

Preload & Release



How helpful is this?



Trends

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  - Note: Preload & Release is not decoupled from Generate - we still have to do this work in 'Preloading' the system during assembly
- Minimizing the required clearance gap reduces the overall work required

Both stiffness extremes come with certain design penalties

- High stiffness → bulkier/heavier spring array and performance is highly sensitive to tighter movement tolerances
- Low stiffness → large preload displacement reduces potential power density savings due to minimum solid spring heights

The Paradigm Shift - What else changes?

	Generate	Preload & Release
User Input Mechanism	Forces cold plates *together*	Forces cold plates *apart*

The Paradigm Shift - What else changes?

	Generate	Preload & Release
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User Input Energy	Clamping Energy * Mech. Efficiency	< Clamping E * Mech. Eff.
Total Energy Storage	Minimum required for clamping	> than min. req.

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Reliability of P Application	Relies on input mechanism	Relies on energy storage method
Input Mechanism Failure	Fails “open” → loss of clamping force causes cooling performance issues	Fails “closed” → loss of release force causes PEBB insertion/removal issues

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	Generate	Preload & Release
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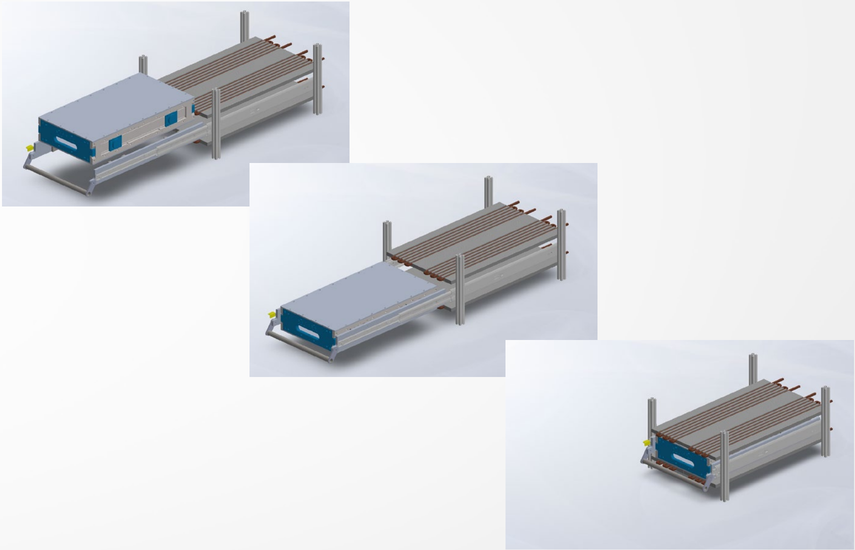
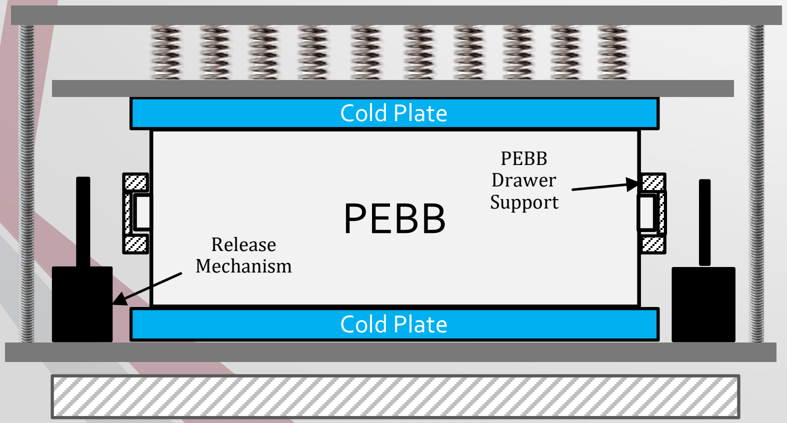
Interface Size/Weight	…	…

Clamping Design - Moving Forward

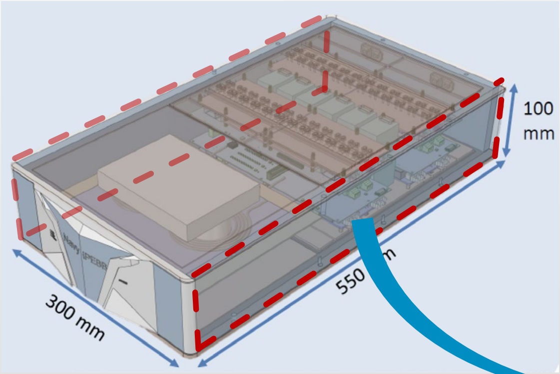


Preload & Release Paradigm

- Interaction with Insertion / Alignment of PEBB with Electrical Connection
- Exploration of different Spring System Configurations
- Optimization of the balance between operator effort, power density, cooling performance, interface complexity, etc...



Distributed Spring Array



Source: VT CPES Oct. 26, 2023
ESRDC NiPEBB Presentation

Accuride 3608-5 Drawer Slides

Clamping Design - Moving Forward

More generally…

- Structural & Thermal Coordination with VT
  - NiPEBB design to withstand anticipated pressure
  - Understand expected deflection impacts on pressure distribution and thermal behavior
  - More granular understanding of PEBB surface heat flux distribution
- Design Evaluation & Selection
  - We are pushing a decision point via evaluation metrics for Interface Performance, Use, and Design

Metrics for PEBB Latching & Clamping Mechanism

Performance (P)

1. Pressure application on PEBB top/bottom surface
   - Target: 10psi & evenly distributed
   - Benchmark: Target is required
2. Power density (kW/Volume)
   - Target: Maximize (aka minimize volume required / PEBB (250kW))
   - Benchmark: 6 PEBBs vertically stacked in 64"H x 24"W x 36"D cabinet
3. Interface Weight
   - Target: Minimize
   - Benchmark: None established yet
4. Securing PEBB to Ship
   - Target: Withstand dynamic loading (~2.1 x gravity in Z-direction)
   - Benchmark: Target is required
5. Ease of connection with Electrical System
   - Target: Automatic system mate upon PEBB insertion
   - Benchmark: Target is required
6. Ease of connection with Cooling System
   - Target: Automatic system mate upon PEBB insertion
   - Benchmark: Tool free & accessible quick-connects

Use Factors (U)

1. Total work required from user input (ft-lb)
   - Target: Minimize
   - Benchmark: None established yet
2. Maximum force required from user input (lb)
   - Target: Minimize
   - Benchmark: 35lb – confirm with Navy prescribed Ergonomic ranges
3. Insertion Equipment Requirements
   - Target: tool-free
   - Benchmark: Target is required
4. Duration/complexity/intuitiveness of user input
   - Target: Minimize
   - Benchmark: None established yet
5. Impact of PEBB height on user input
   - Target: Minimize
   - Benchmark: None established – confirm with Navy prescribed Ergonomic ranges

Design Factors (D)

1. Complexity & number of moving parts/joints
   - Target: Minimize
   - Benchmark: None established yet
2. Preventative Maintenance required
   - Target: Maintenance Free
   - Benchmark: None established – compare with Navy expectations for similar equipment
3. Anticipated Cost
   - Target: Minimize
   - Benchmark: None established yet

Thanks!

Further Questions / Discussion?

Shipboard Power Systems

The Grainger Energy Machines Facility, MIT

Steven B. Leeb and Team

THANK YOU.

- Doubly-Fed Machine (DFM) and modeling

- Non-Intrusive Voltage Sensing

- PEBB Interface and Stabilization

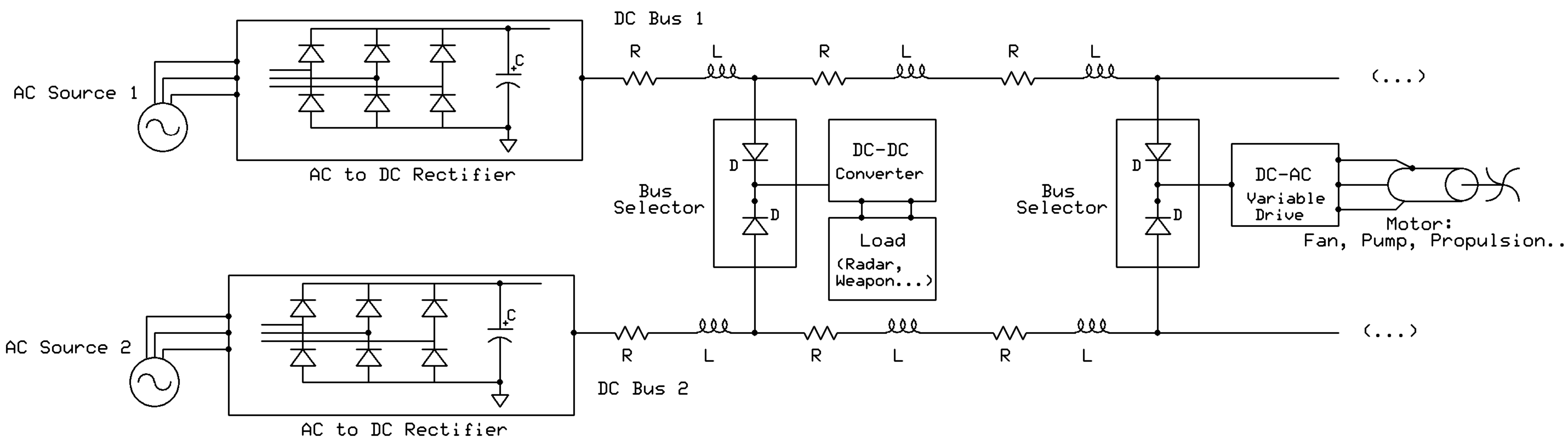
- Doubly-Fed Machine (DFM) and modeling

- Non-Intrusive Voltage Sensing

- PEBB Interface and Stabilization

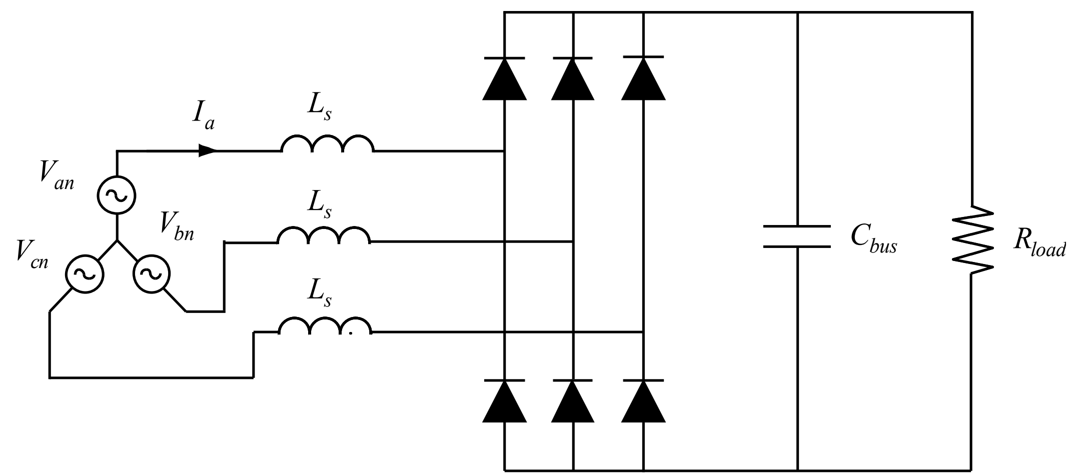
MVDC Architecture

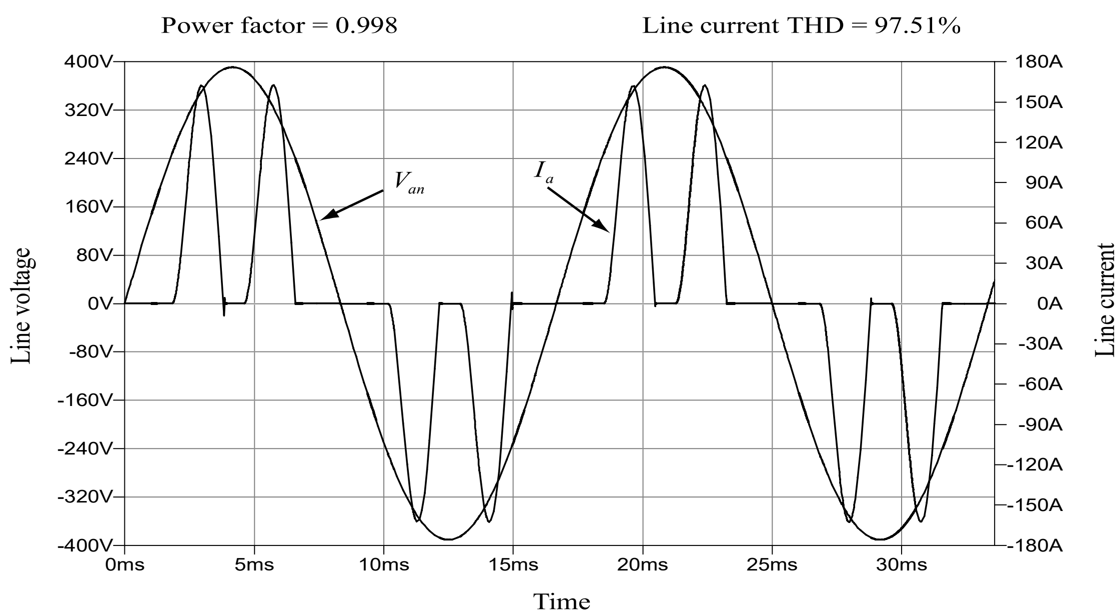
Cartoon:



Power Electronics

This:

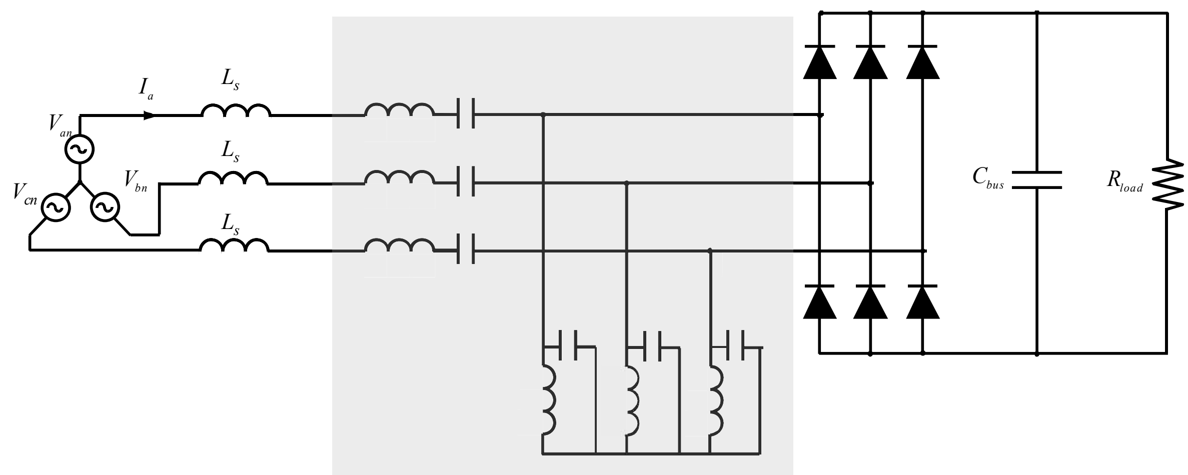


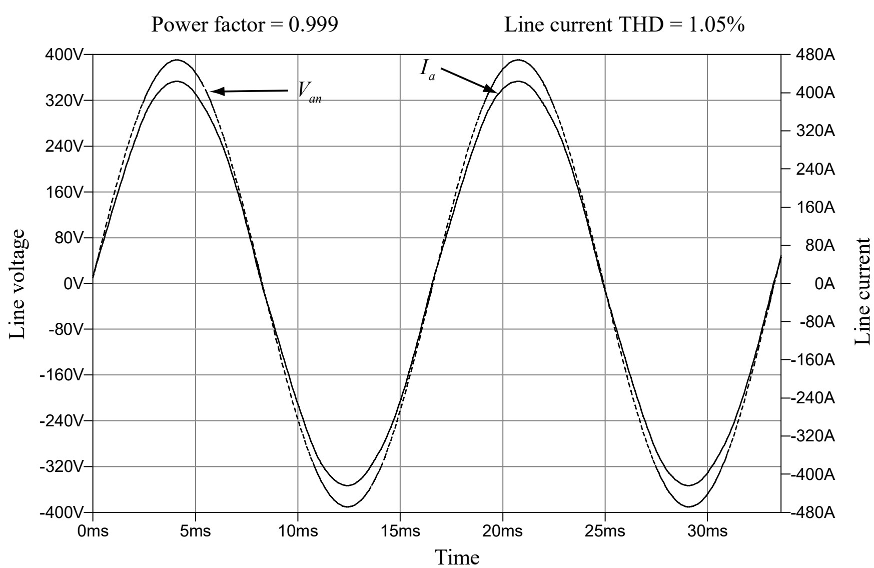


…creates this.

Passive Rectification

This may weigh more:

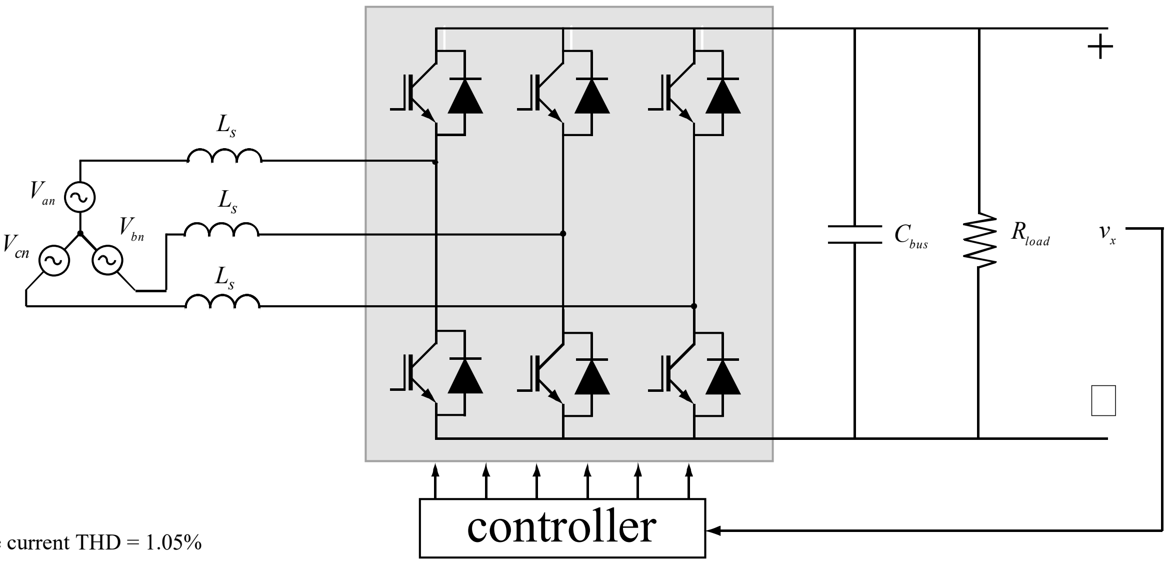


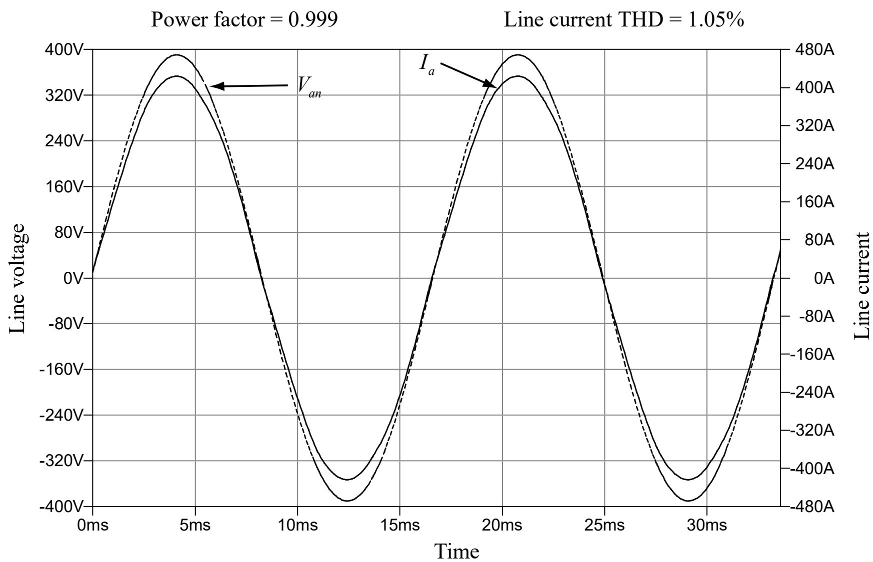


but it also works, and it may be repairable to some level in the field…

Active Power Electronics

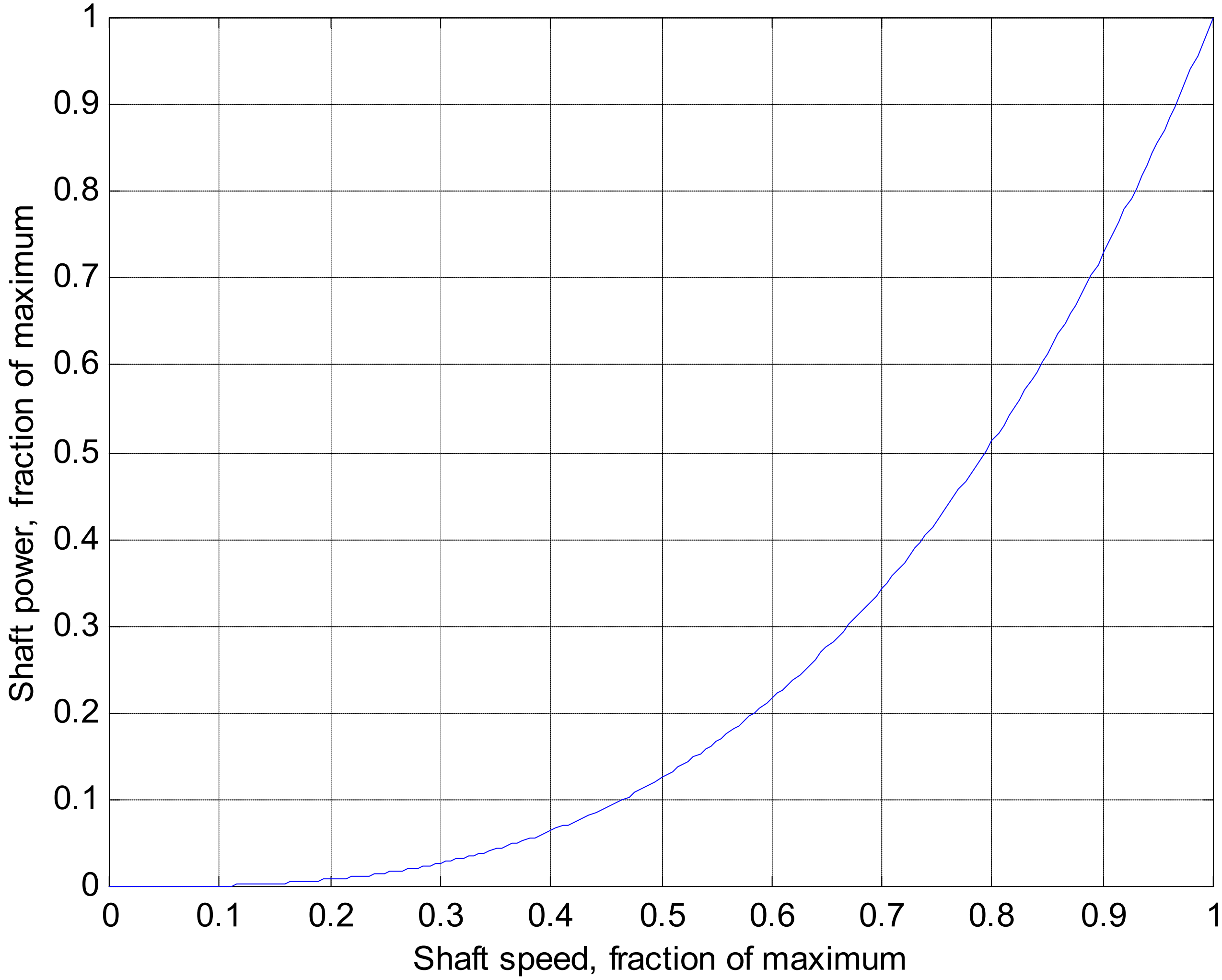
This:



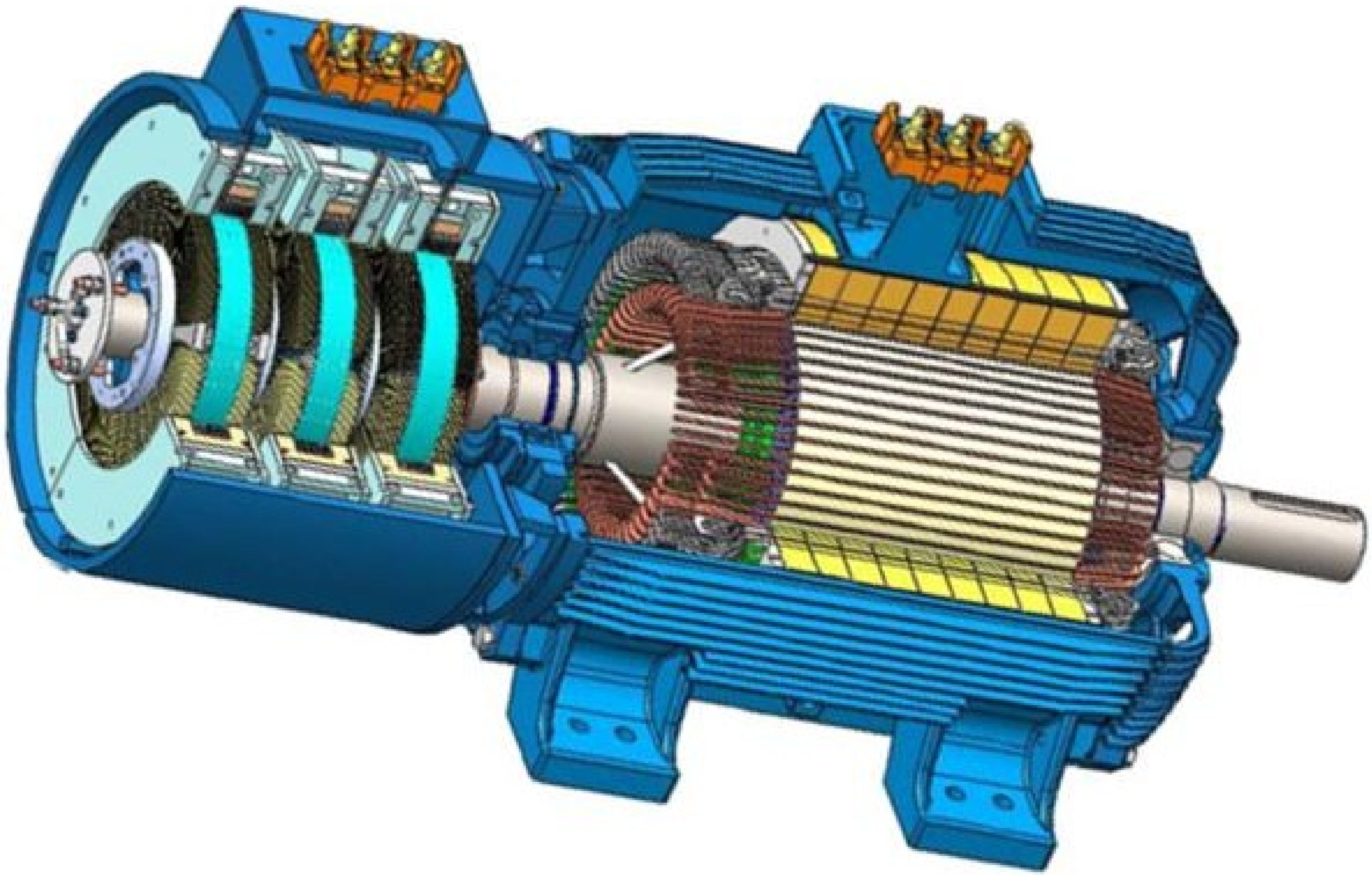


Fixes the problem, but may not "repair" easily…

Ship Propulsion Power

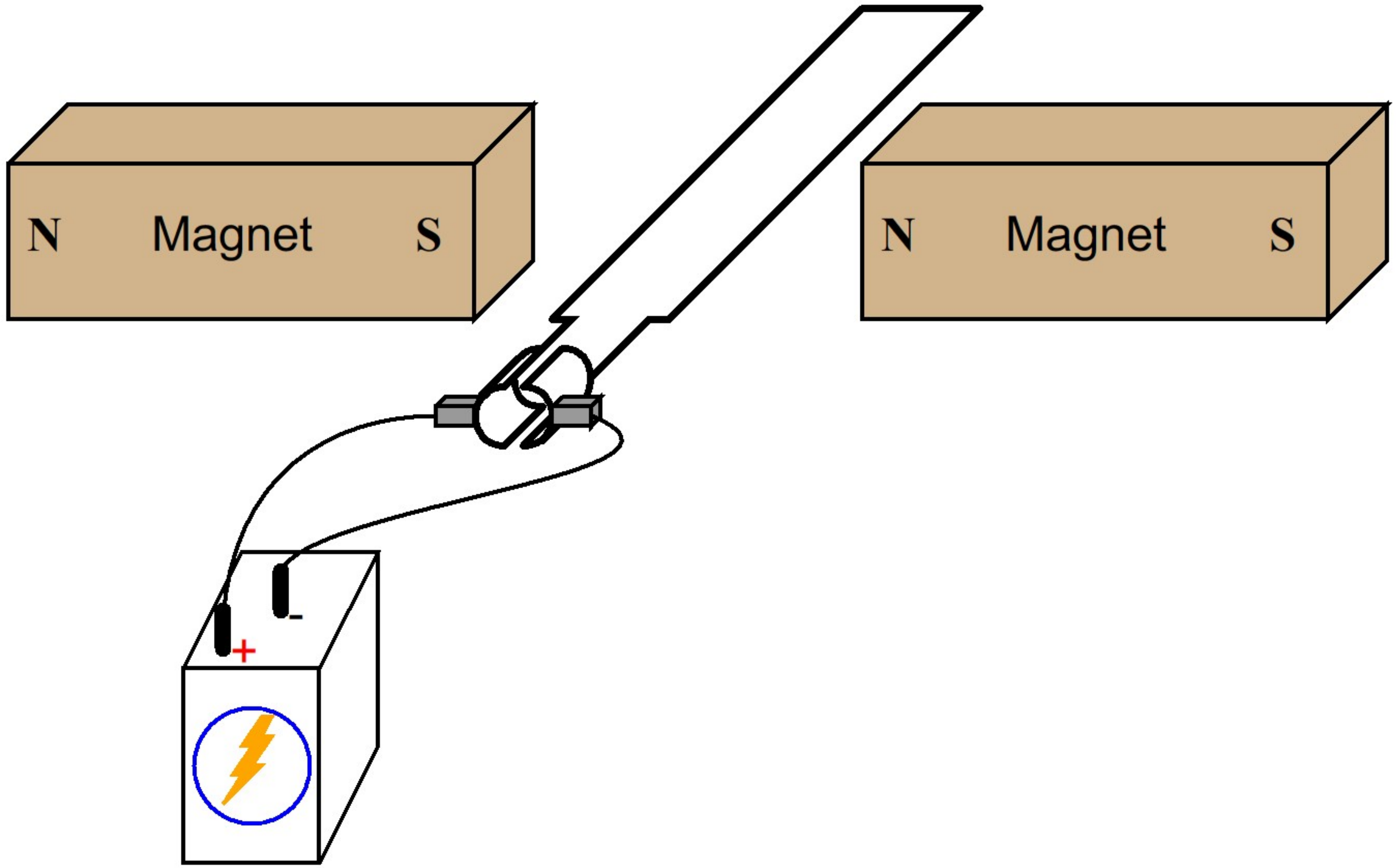


Doubly-Fed Machine



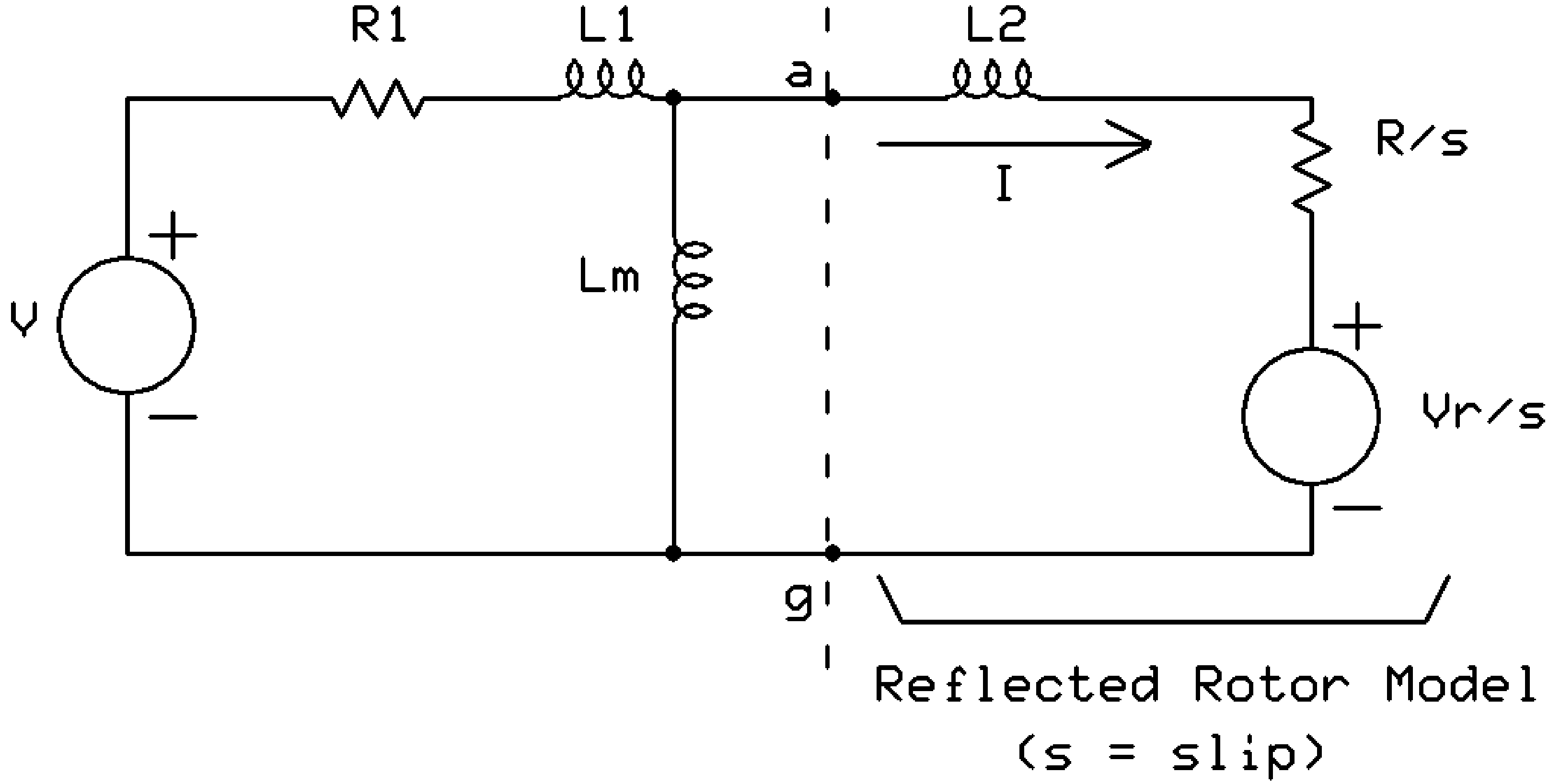
Two Modes

In "DC-mode" (low speed), like a brushed machine, with an electronic commutator!

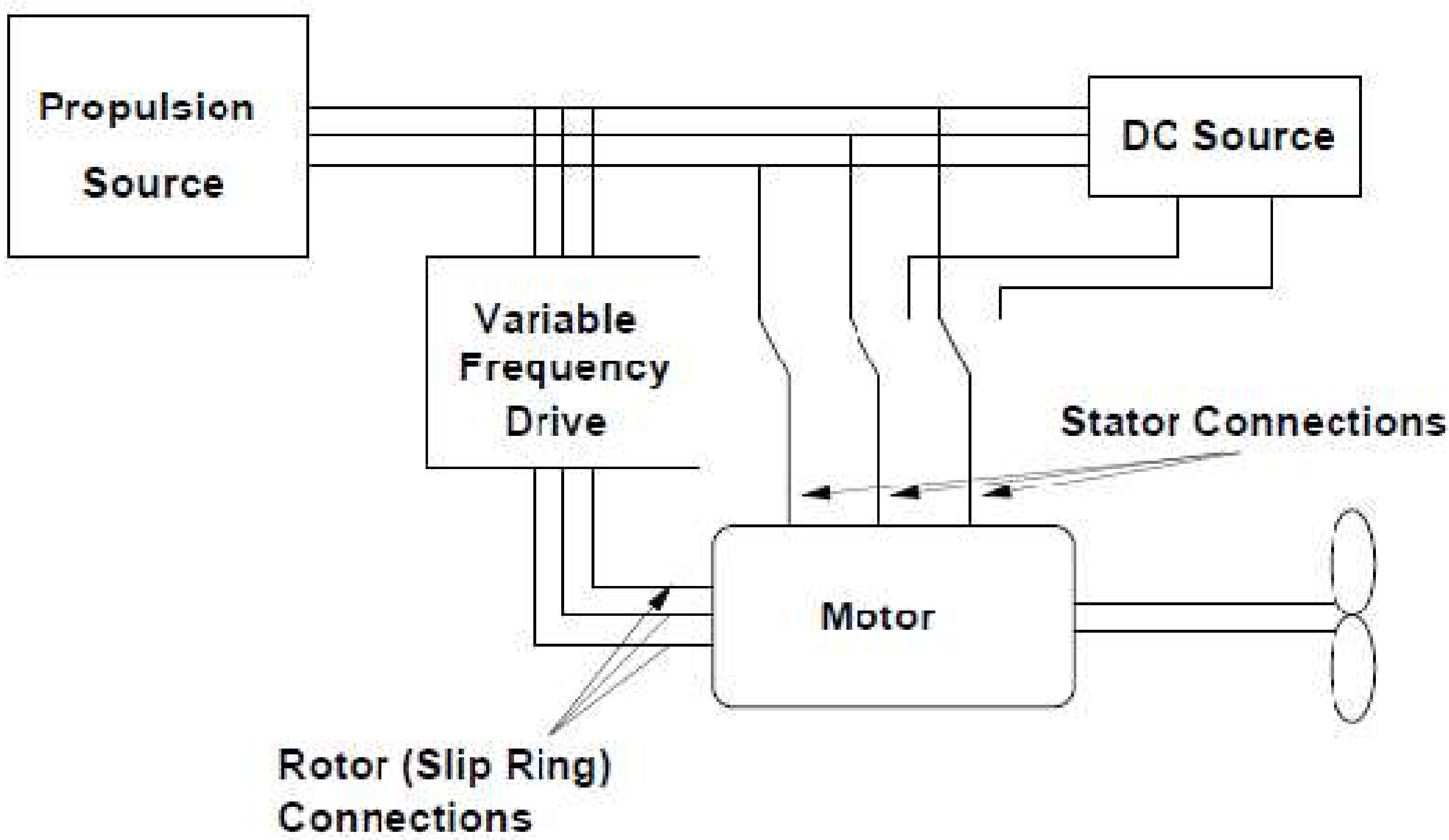


Doubly-Fed Machine

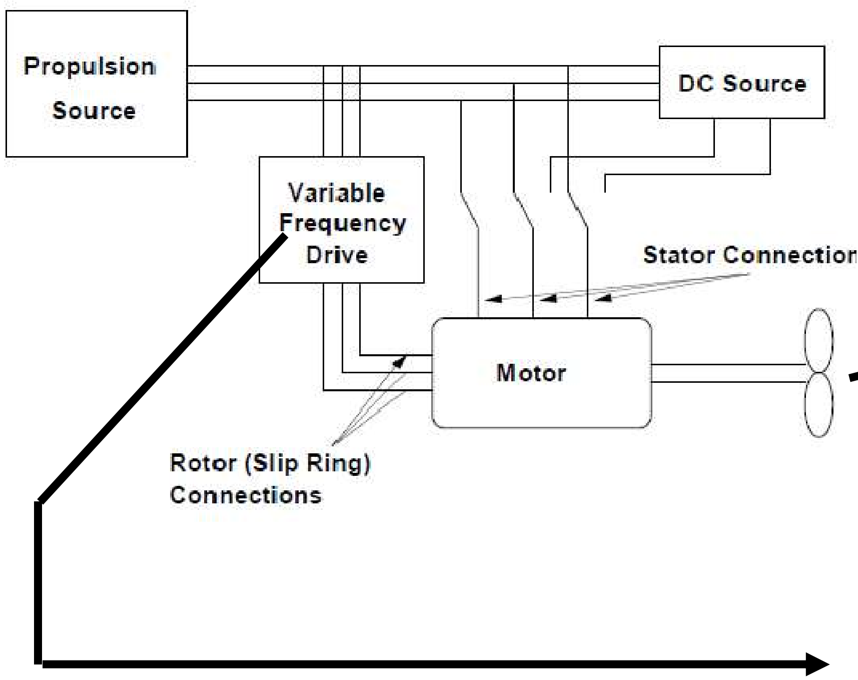
In “AC-mode” (high speed), like an induction machine, with access to the rotor voltage!

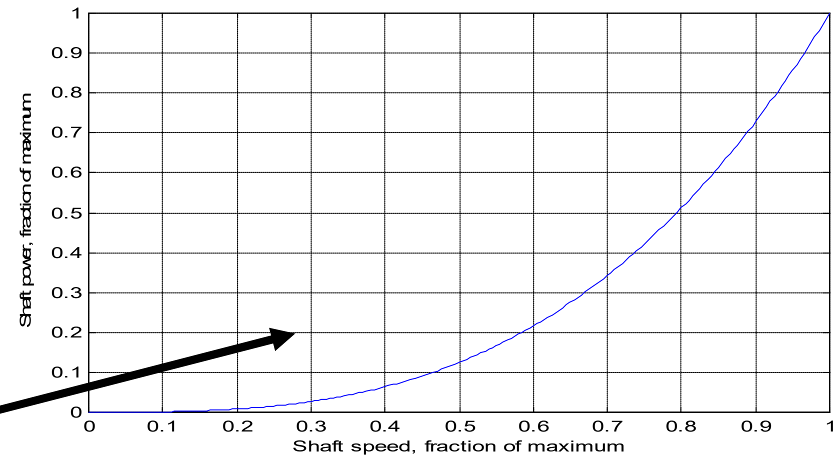


DFM Propulsion

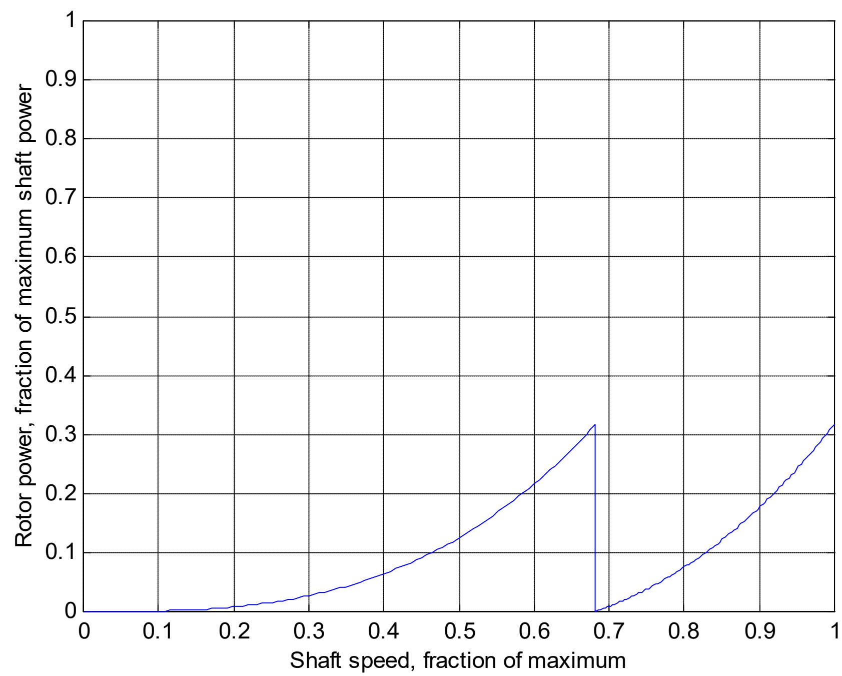


DFM Propulsion





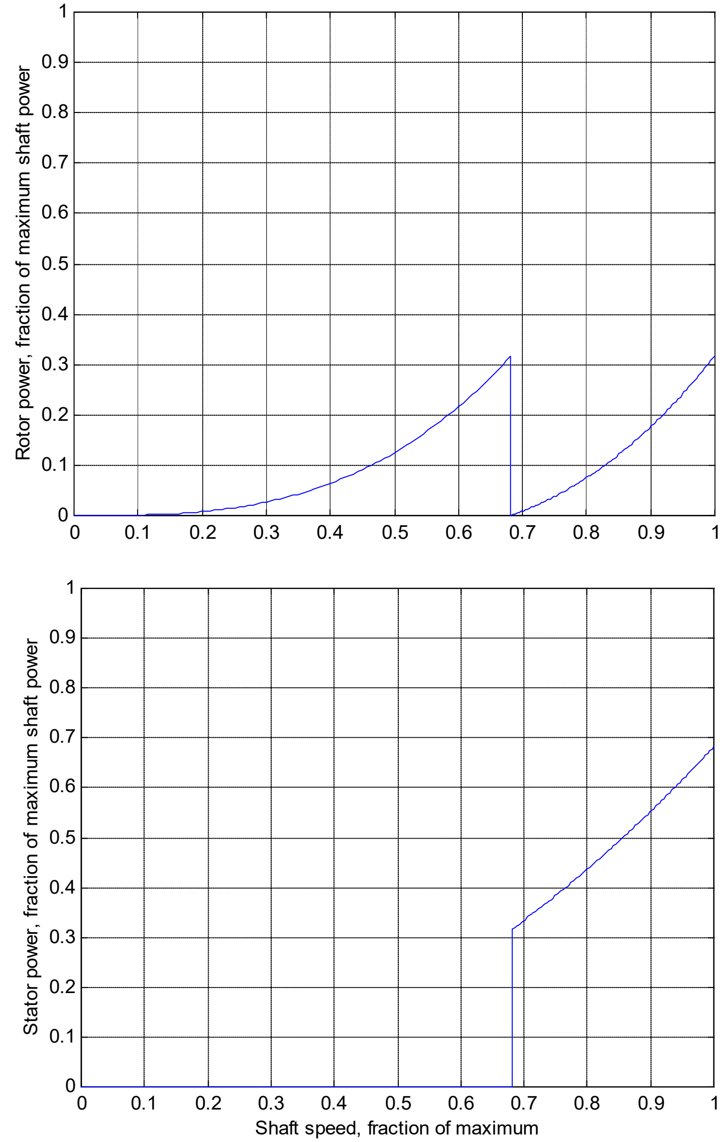
Rotor drive power profile:



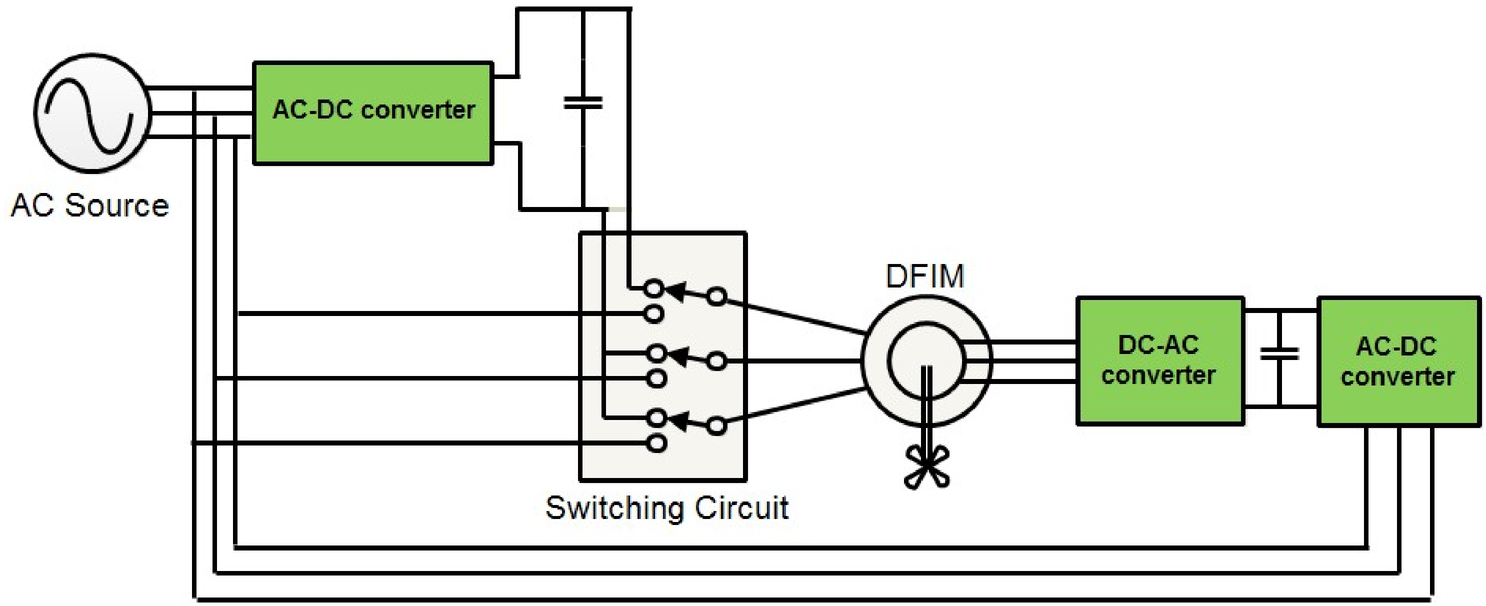
DFM Power

Rotor Power:

Stator Power:
(from AC service!)



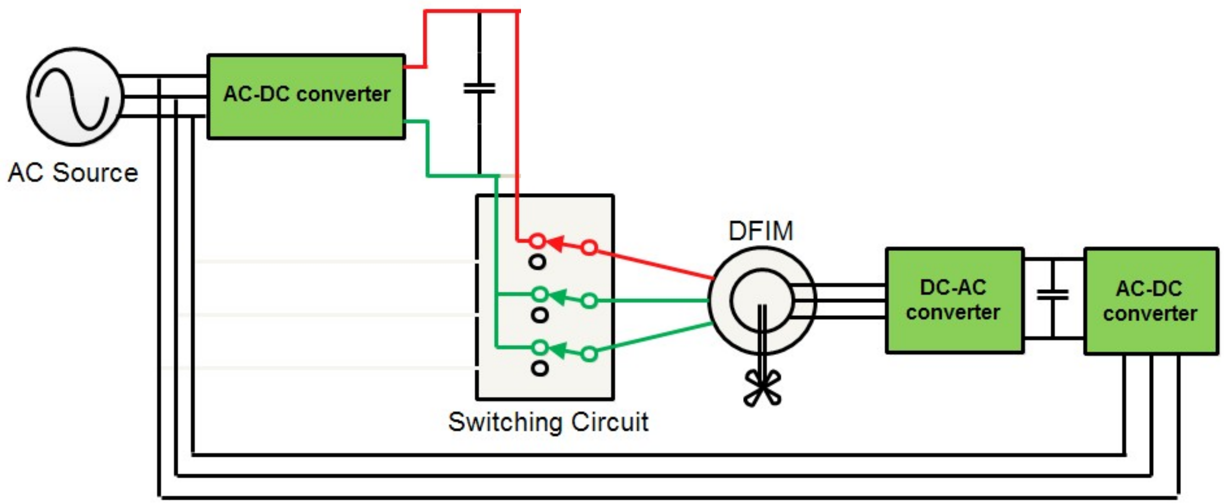
DFM drive



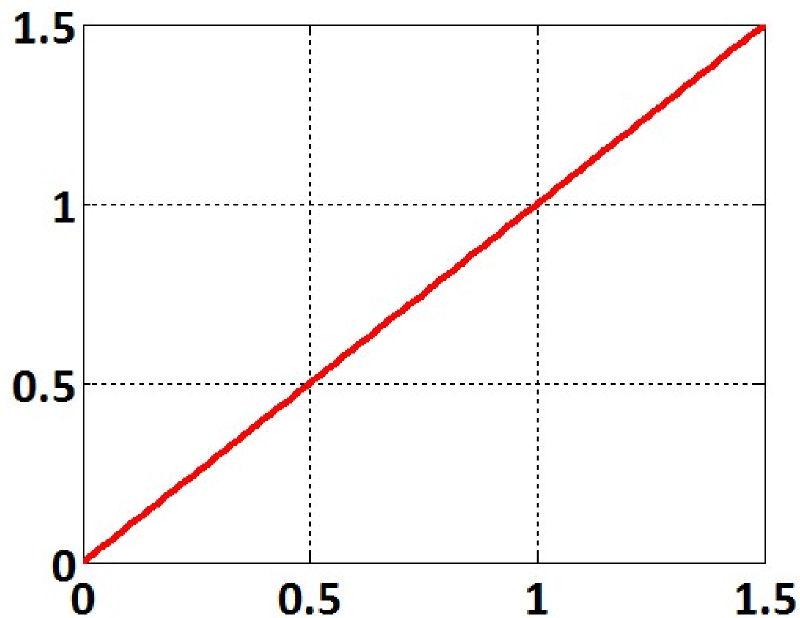
Assumption: "Ideal DFM"

- Zero resistance
- Zero leakage inductance
- Zero magnetizing current
- Rotor current rating is identical to stator current rating

DC Mode

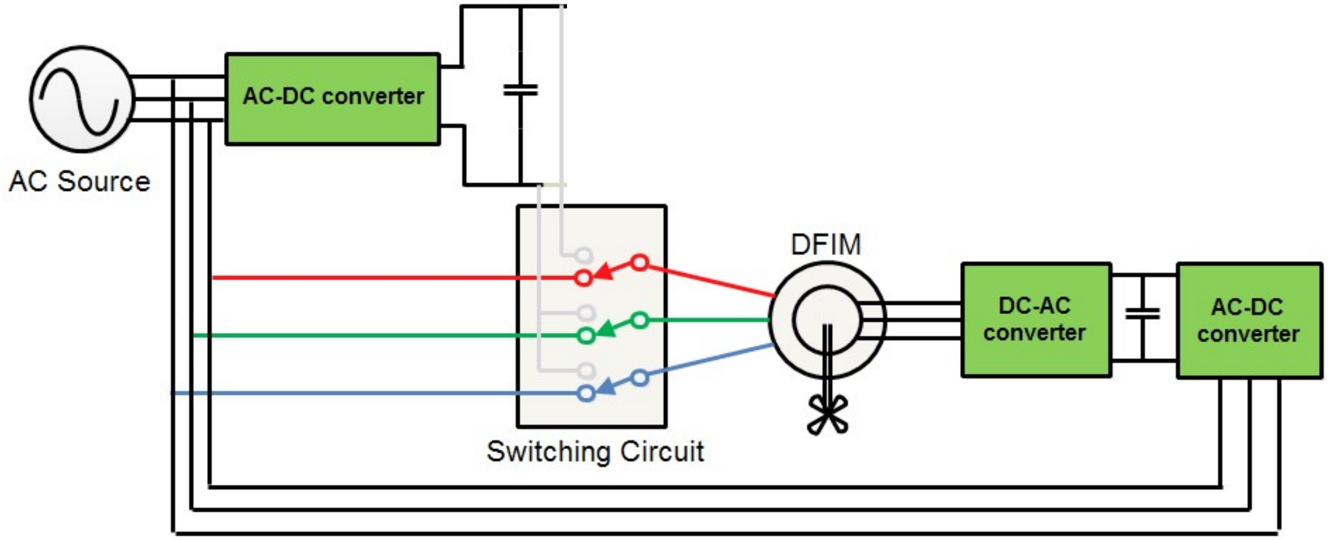


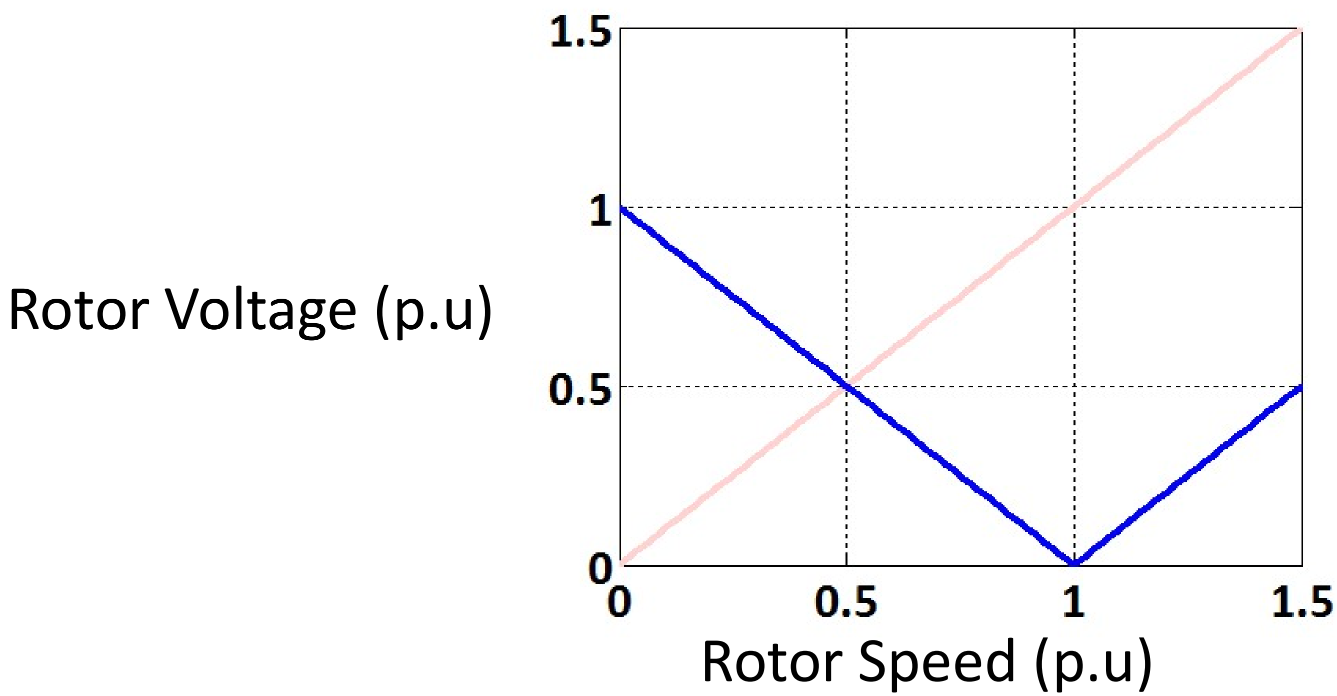
Rotor Voltage (p.u)



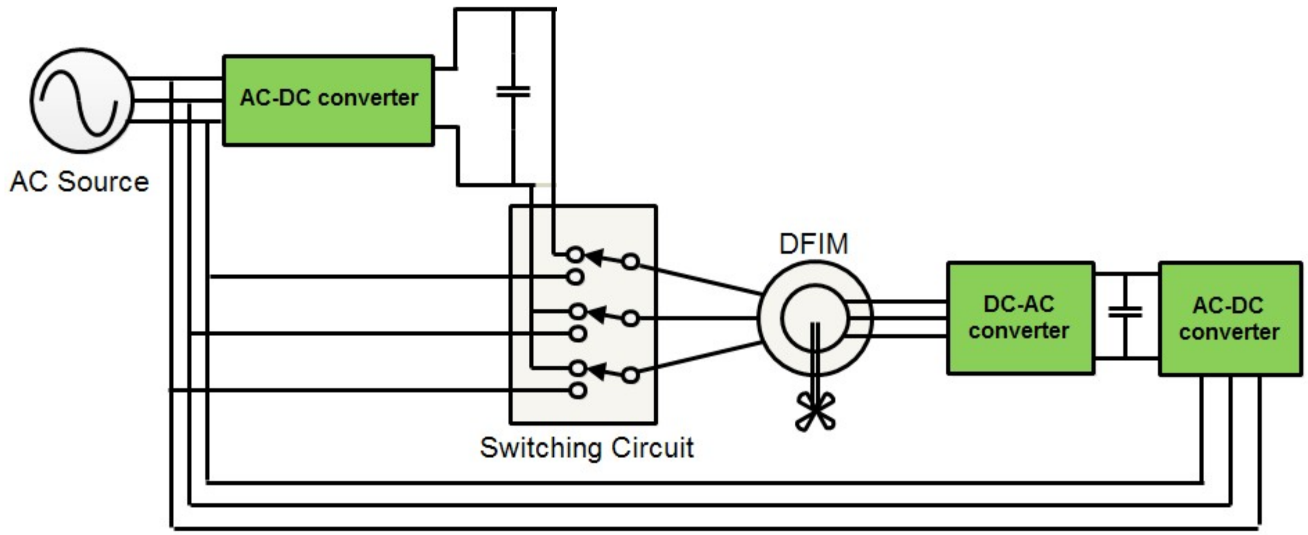
Rotor Speed (p.u)

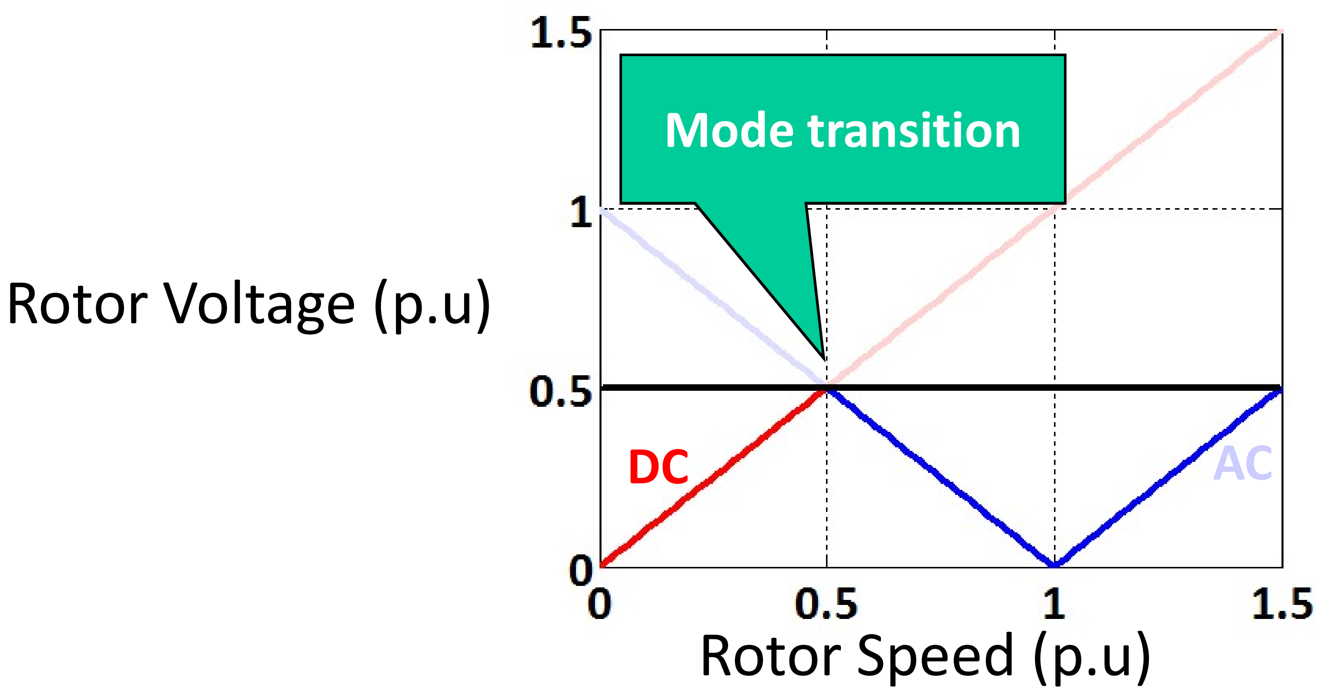
AC Mode


AC-DC converter
AC Source
Switching Circuit
DFIM
DC-AC converter
AC-DC converter


Rotor Voltage (p.u)
1.5
1
0.5
0
0
0.5
1
1.5
Rotor Speed (p.u)

Mode Transition





Control: Transition between AC-DC Modes

DC mode

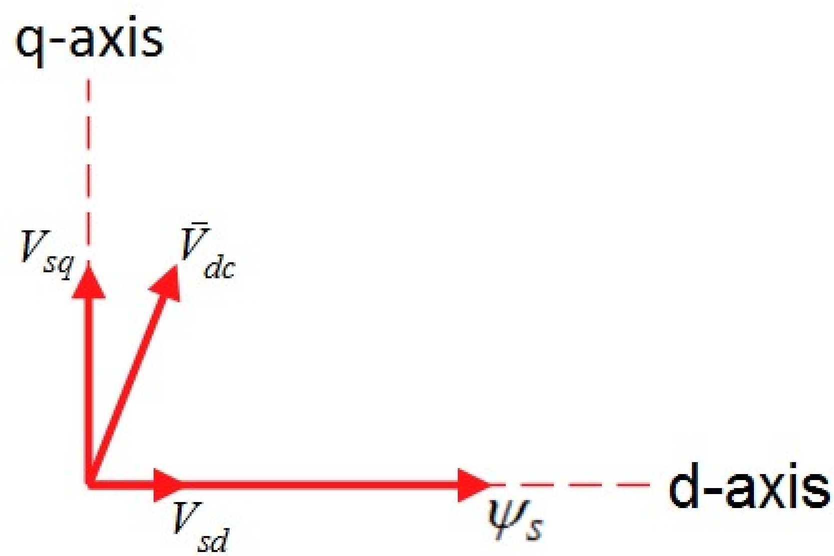
Stationary stator flux & voltage

$\Longleftrightarrow$

AC mode

Rotating stator flux & voltage

Space vector in DC Mode (Stator Flux Orientation)



Zero @ steadystate

$$\boxed{\frac{d}{dt}\psi_s} = V_{sd} - R_s I_{sd}$$

$$\omega_s \psi_s = V_{sq} - R_s I_{sq}$$

Transition between Modes

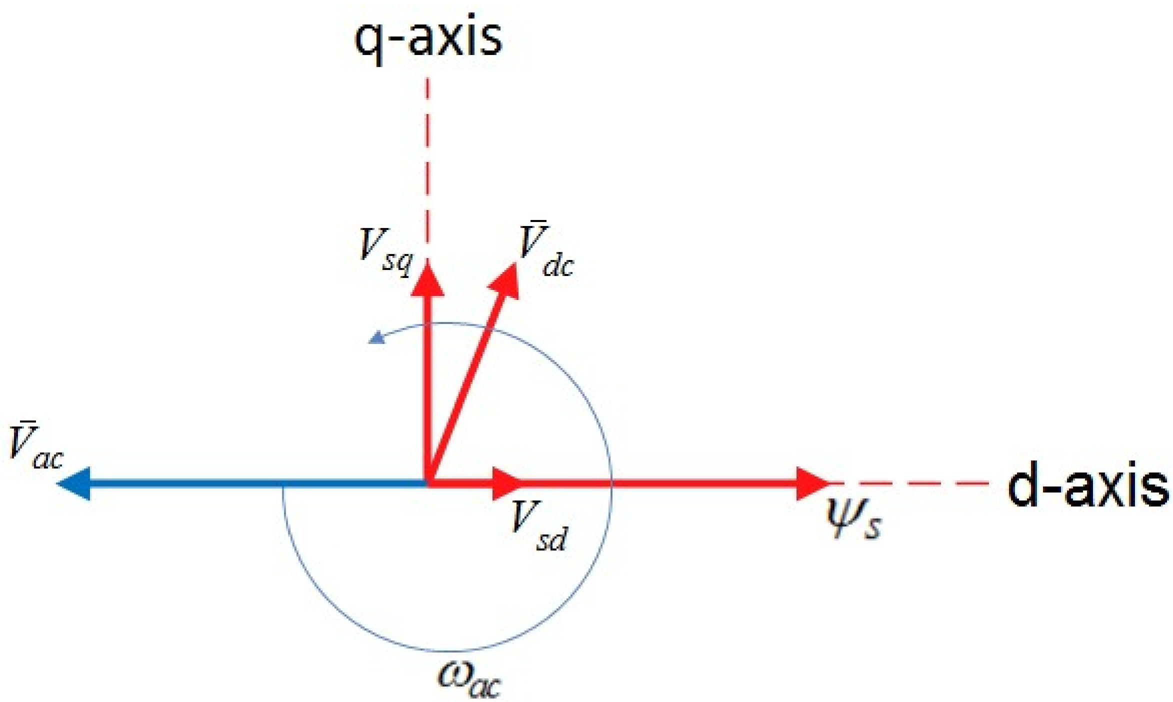
DC mode

Stationary stator flux & voltage

AC mode

Rotating stator flux & voltage

Target: To switch to AC Mode



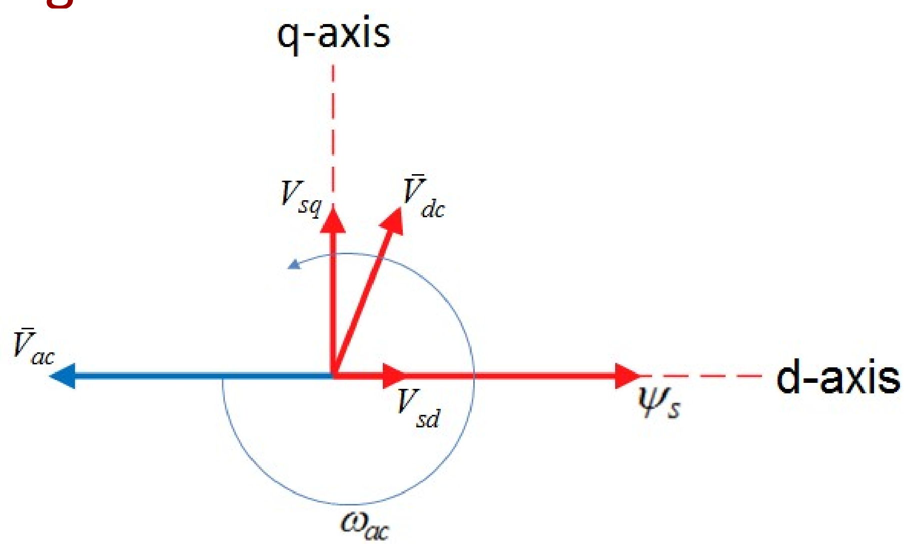
$$\frac{d}{dt}\psi_s = V_{sd} - R_s I_{sd}$$

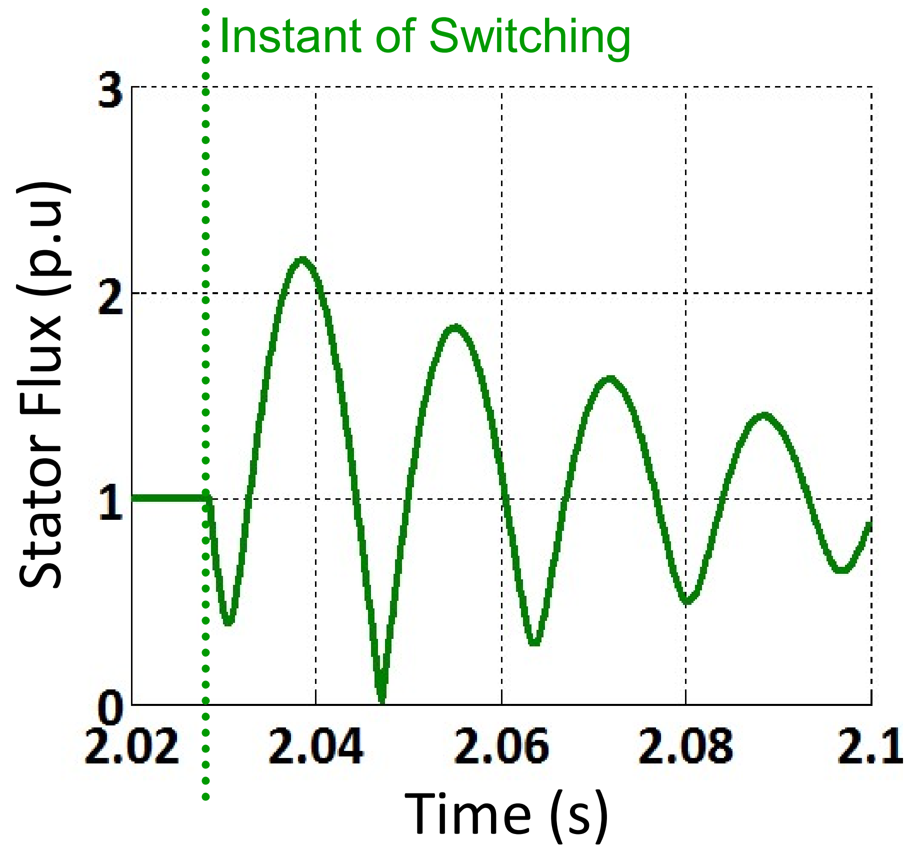
$$\psi_s \frac{d\delta}{dt} = V_{sq} - R_s I_{sq}$$

Transition between AC-DC Modes

DC mode	AC mode
Stationary stator flux & voltage	Rotating stator flux & voltage

Target: To switch to AC Mode





"Bump-less" transition

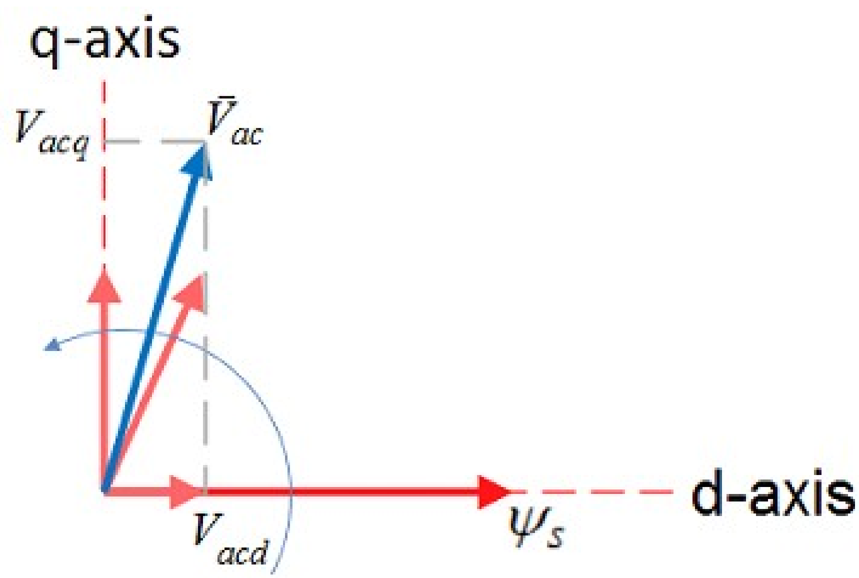
DC mode

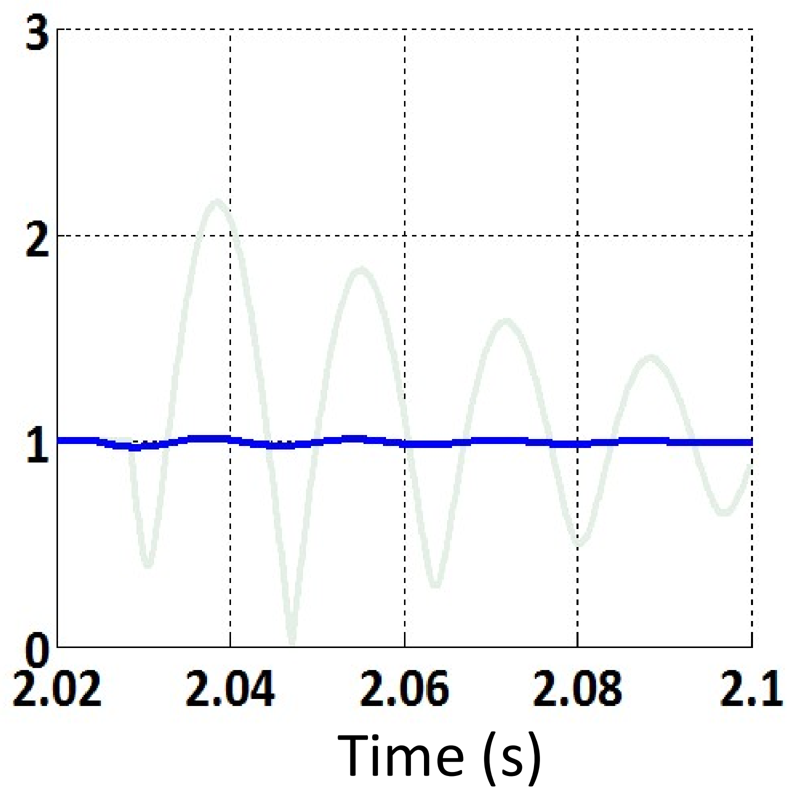
Stationary stator flux & voltage

AC mode

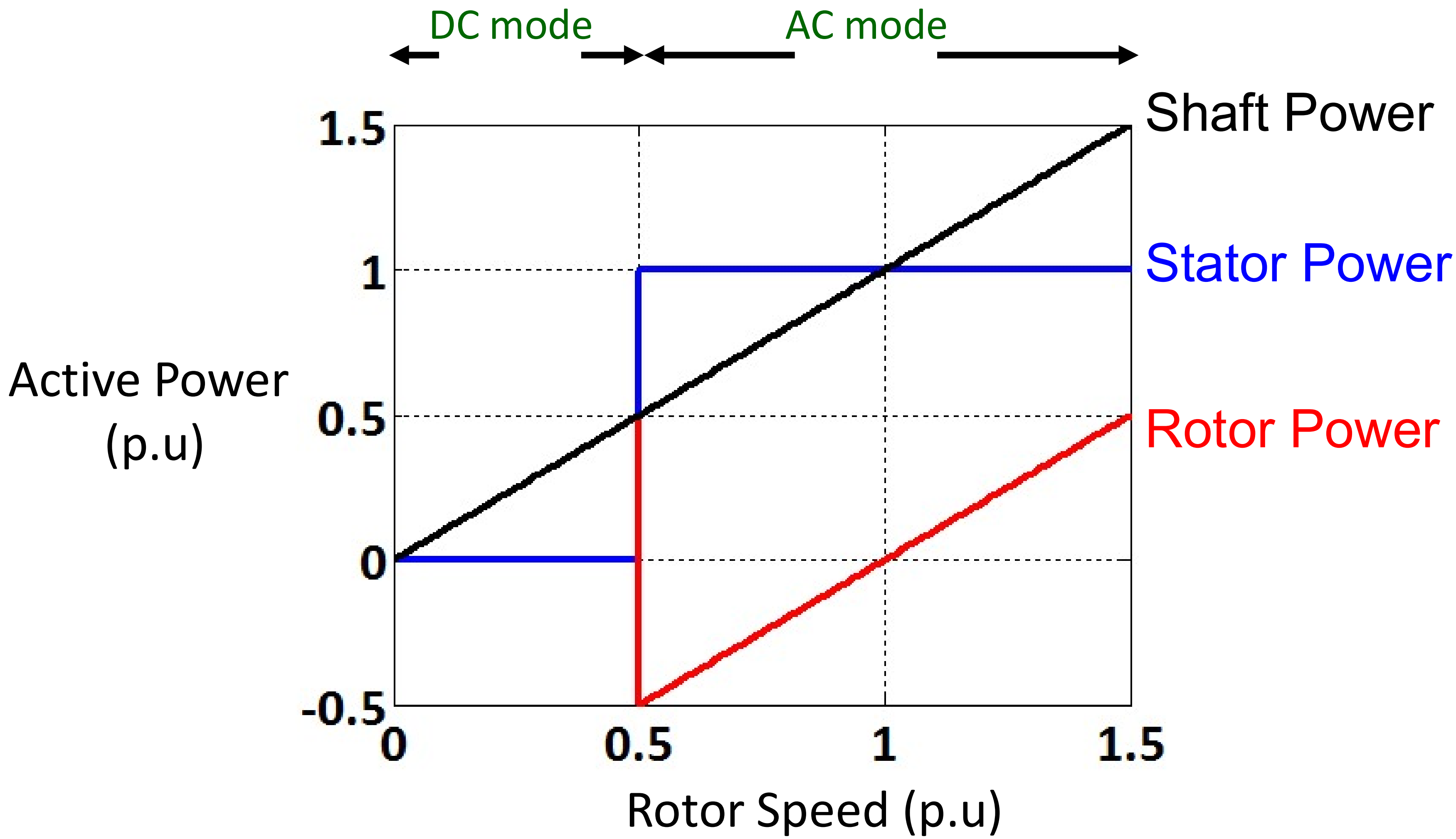
Rotating stator flux & voltage

Space vector @ transition





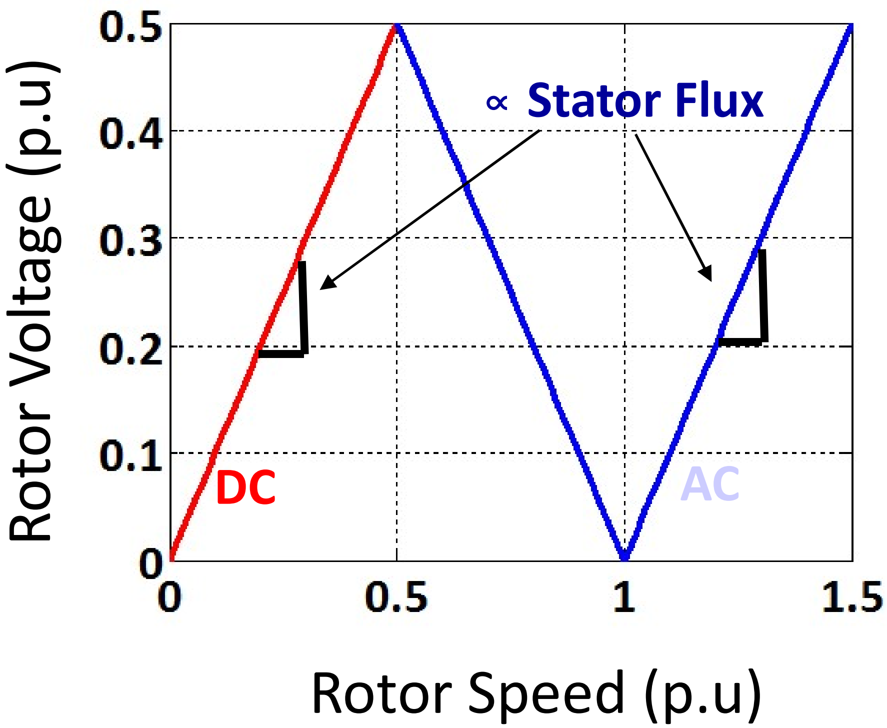
Wide speed range with reduced power electronics

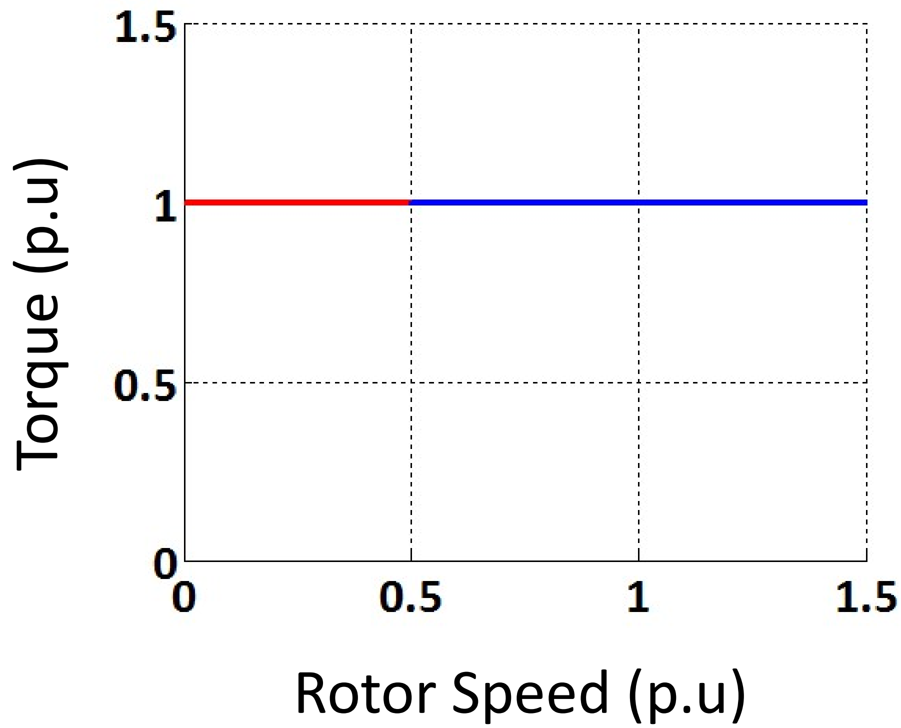


$$\frac{\text{Max. Rotor Power}}{\text{Max. Shaft Power}} = \frac{0.5}{1.5}$$

Torque speed characteristic

dc mode stator flux = ac mode stator flux

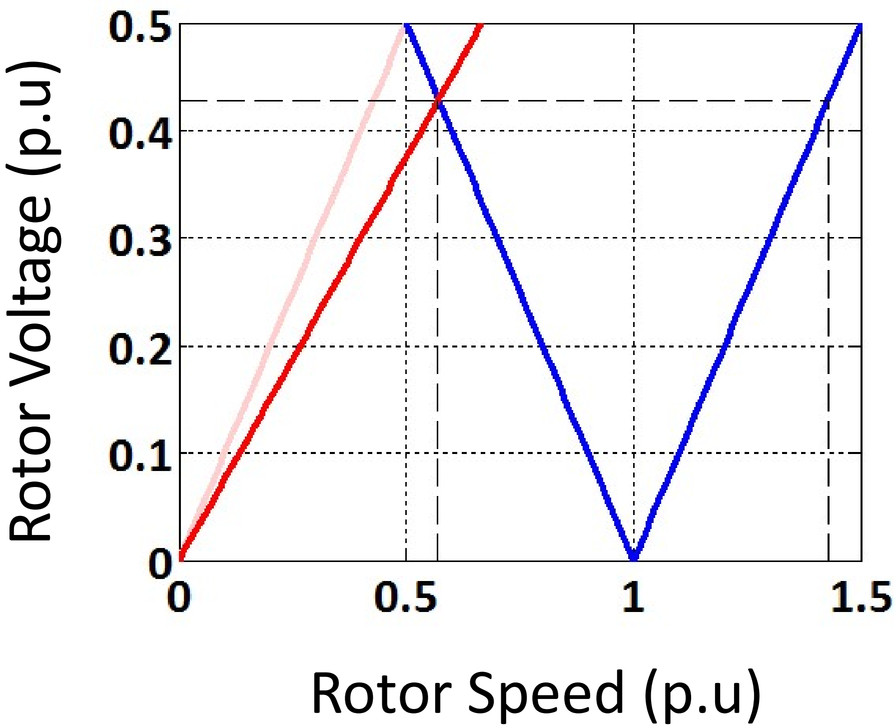


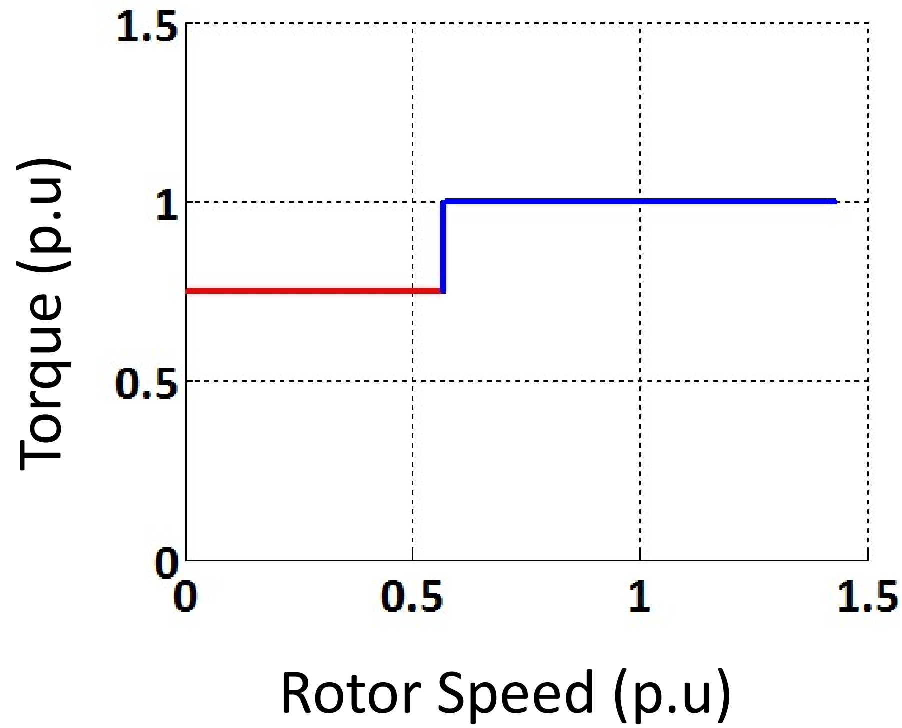


Rotor power electronics “**current rating**” driven by ac mode torque

Torque speed characteristic

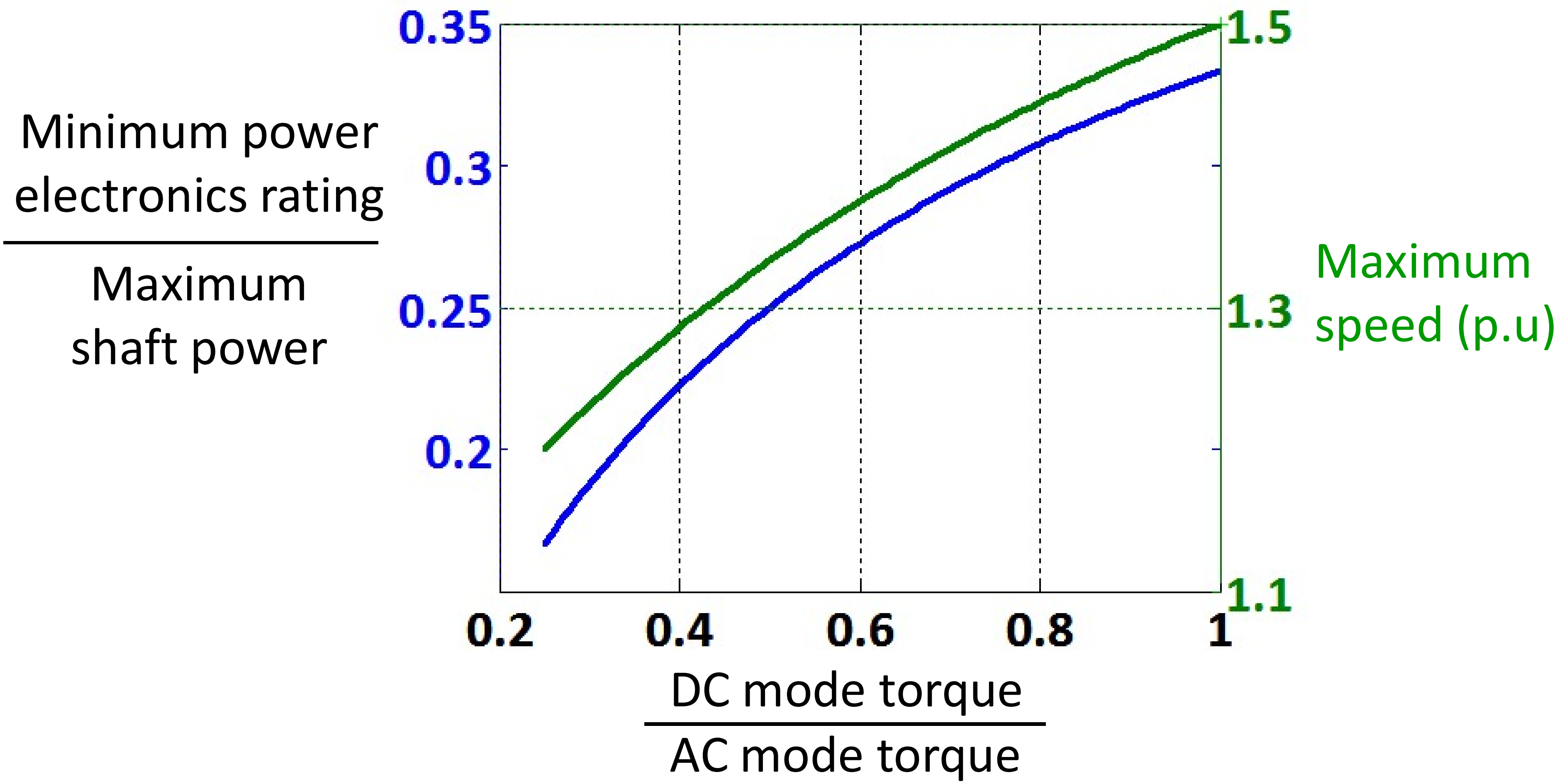
dc mode stator flux = 0.75 * ac mode stator flux





Rotor power electronics **“voltage rating”** driven by dc mode torque

Power electronics size

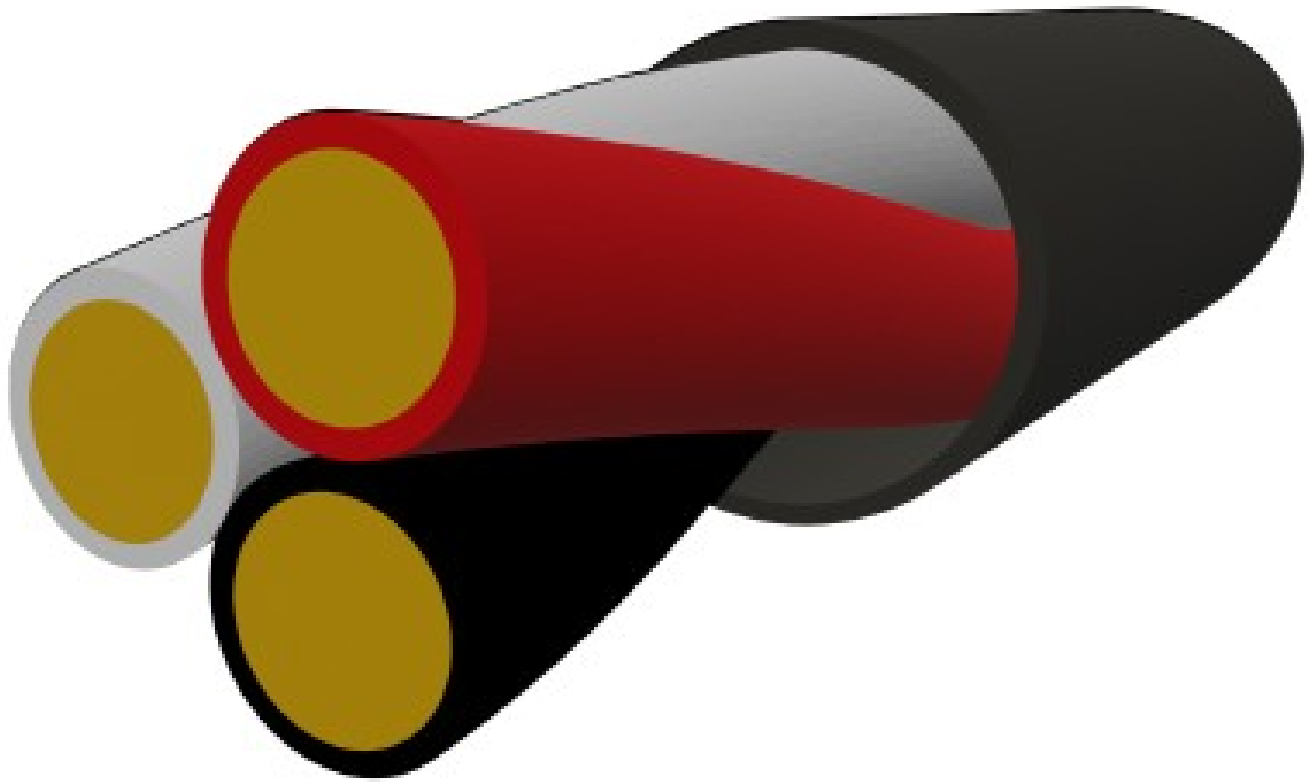


- Doubly-Fed Machine (DFM) and modeling

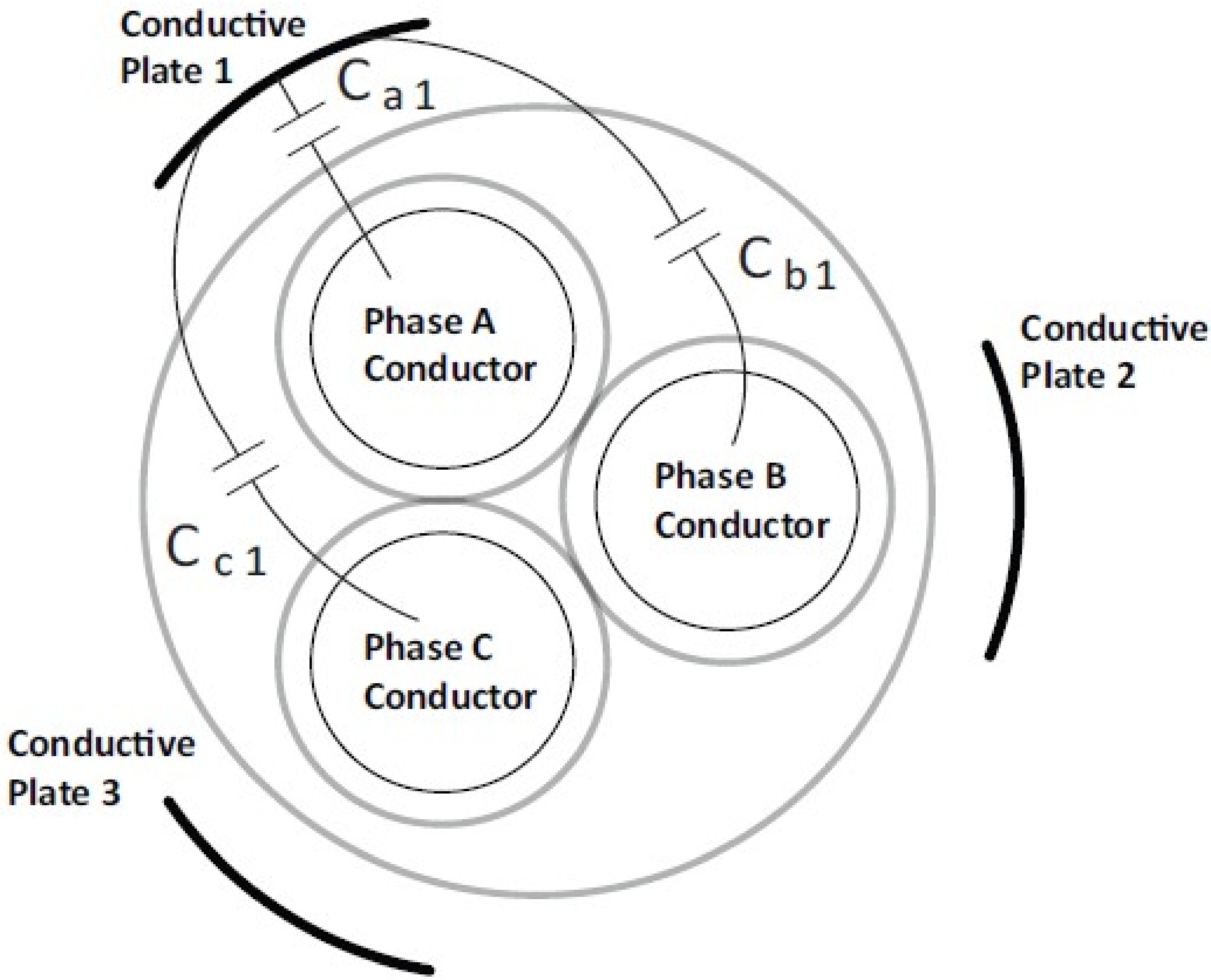
- Non-Intrusive Voltage Sensing

- PEBB Interface and Stabilization

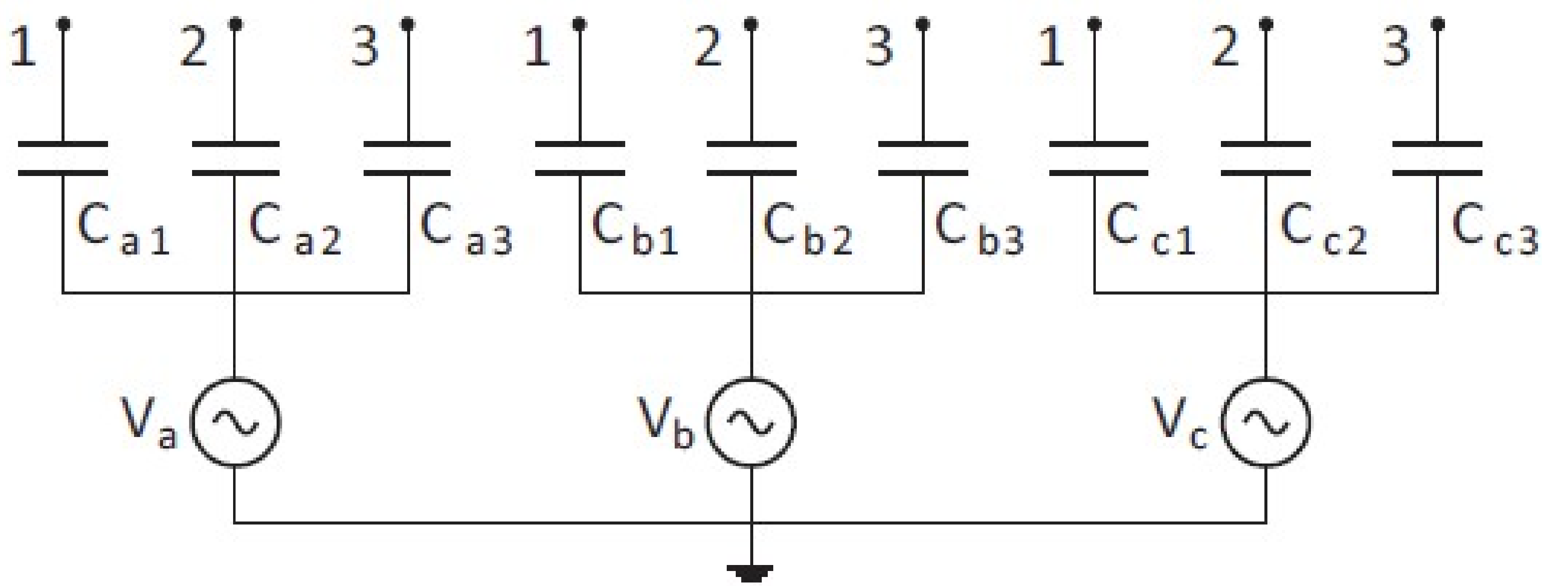
Shipboard Power Cable



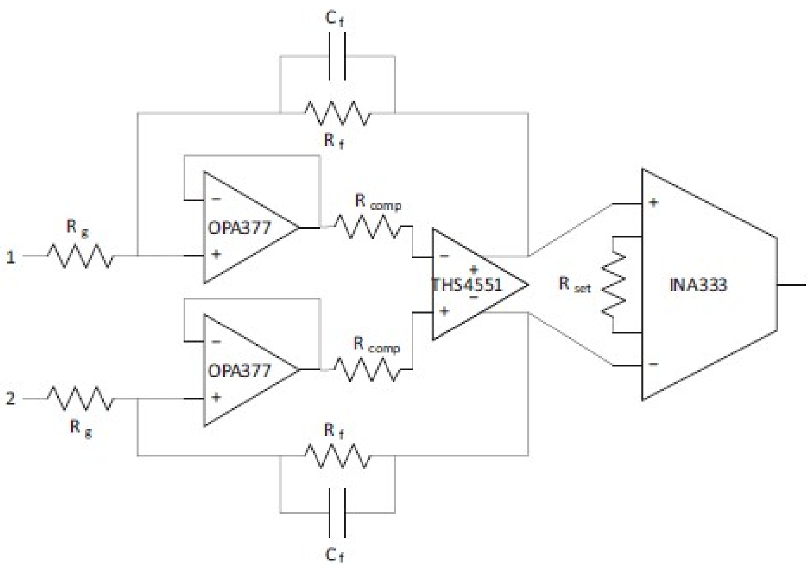
Sensor Approach

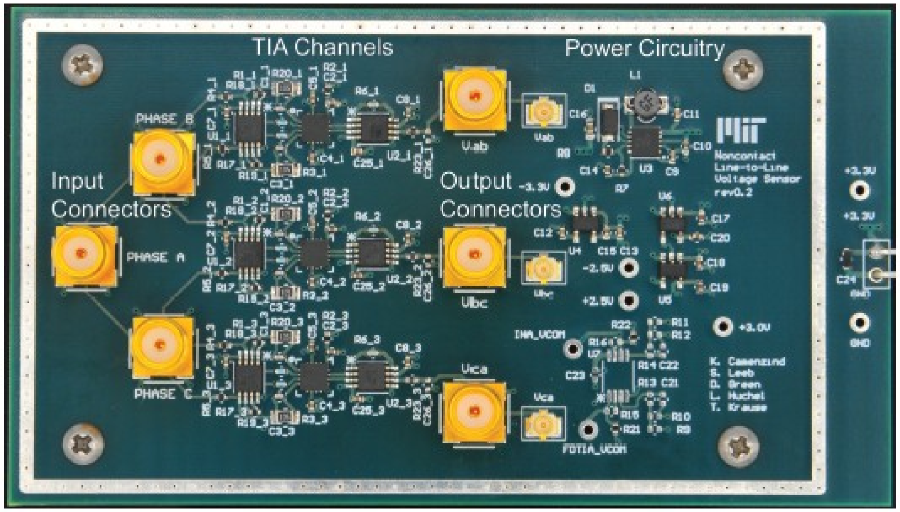


Sensor Circuit Model

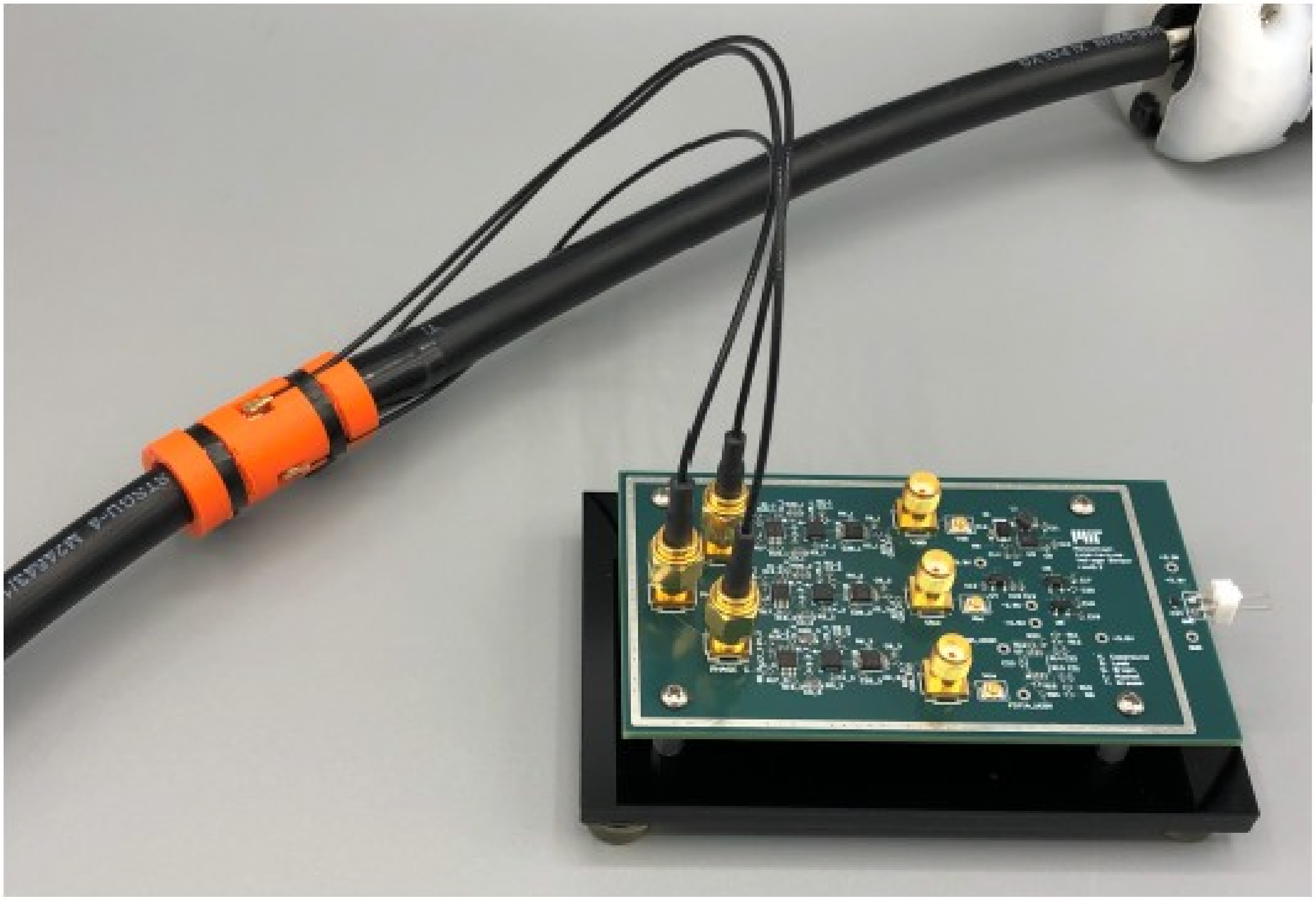


Nonintrusive Voltage Sensing

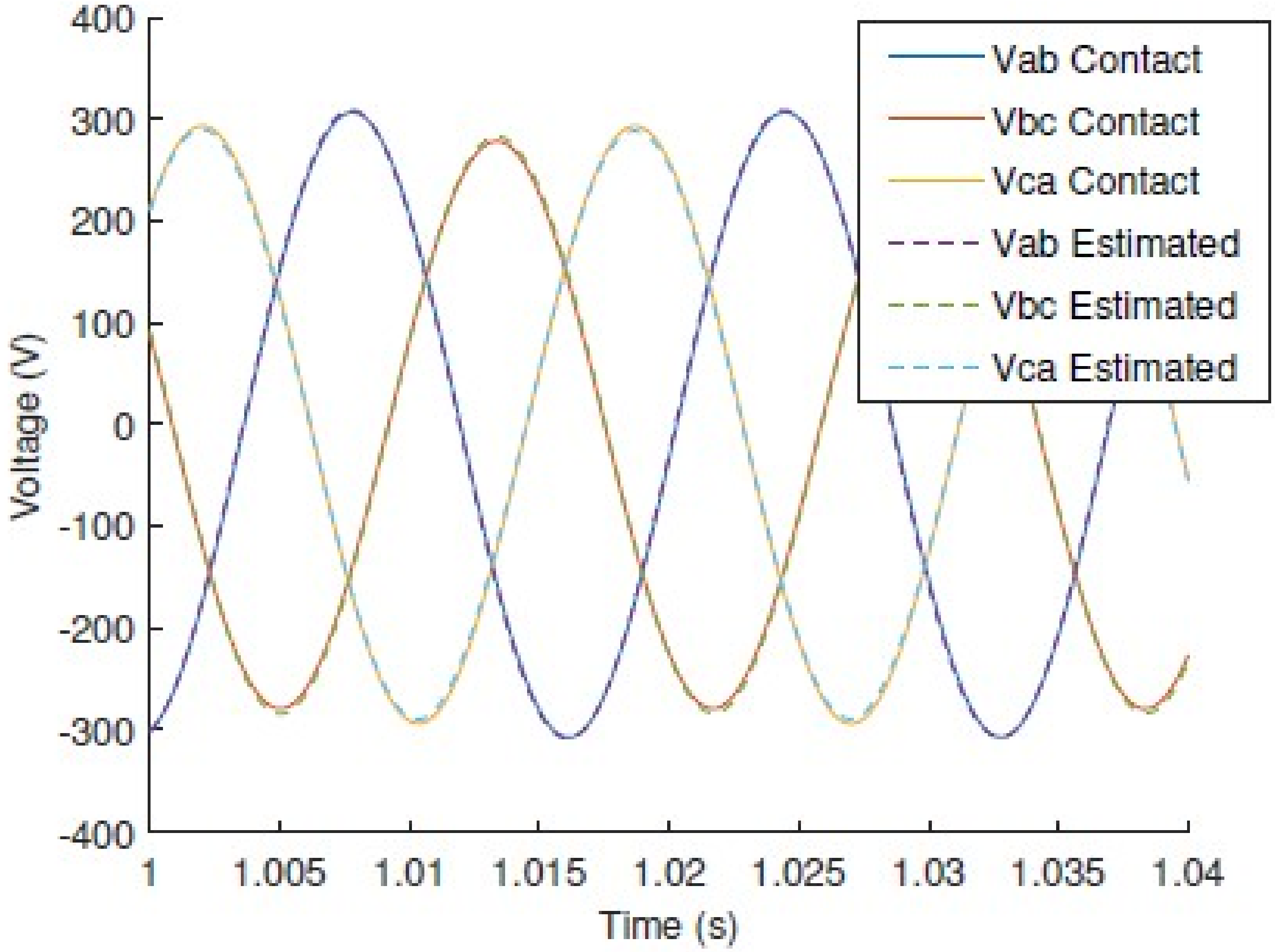




Test Prototype



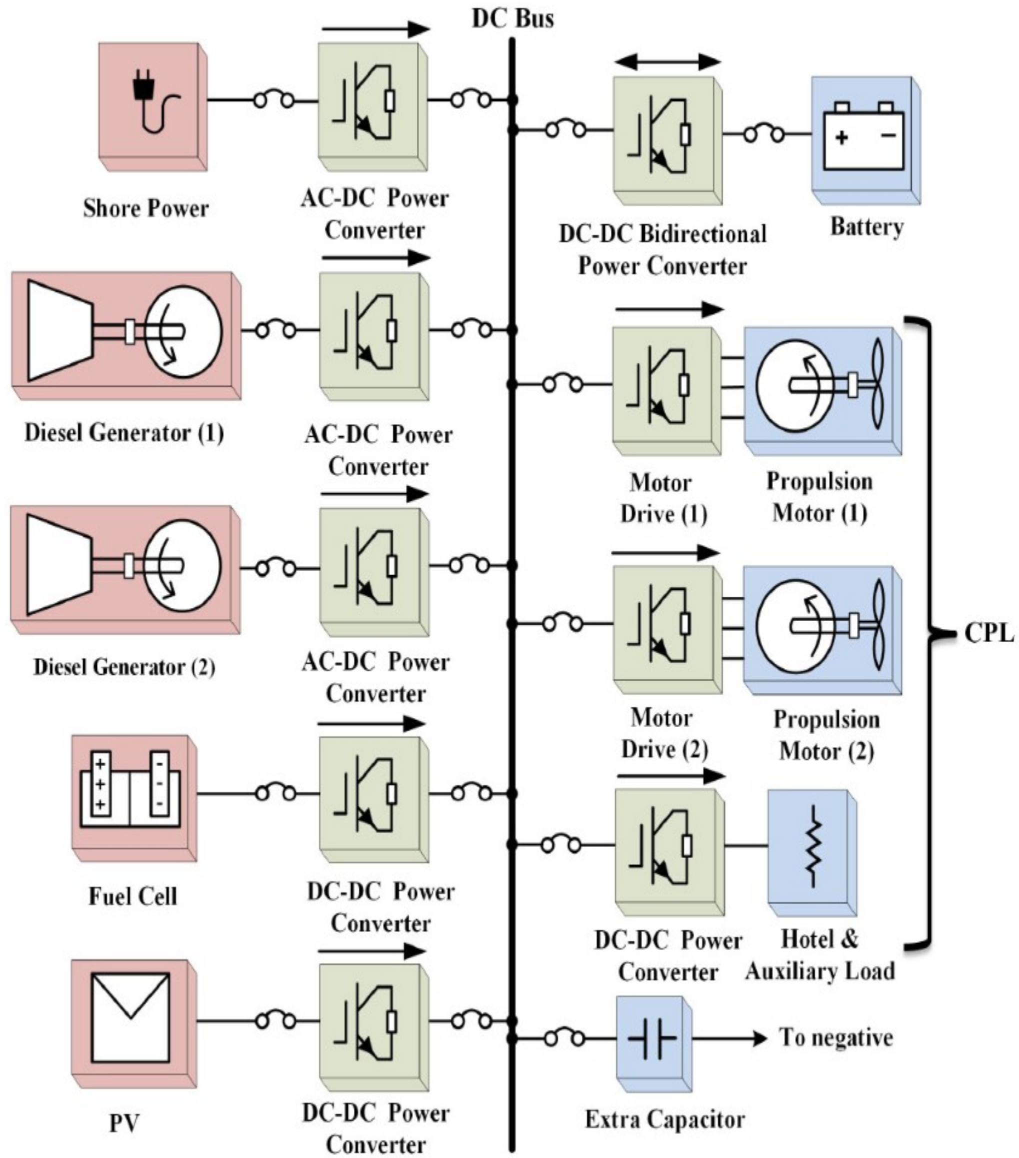
Results!


Vab Contact
Vbc Contact
Vca Contact
Vab Estimated
Vbc Estimated
Vca Estimated
Voltage (V)
Time (s)
400
300
200
100
0
-100
-200
-300
-400
1
1.005
1.01
1.015
1.02
1.025
1.03
1.035
1.04

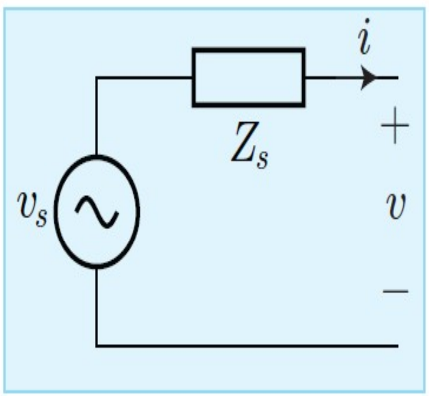
- Doubly-Fed Machine (DFM) and modeling
- Non-Intrusive Voltage Sensing
- PEBB Interface and Stabilization

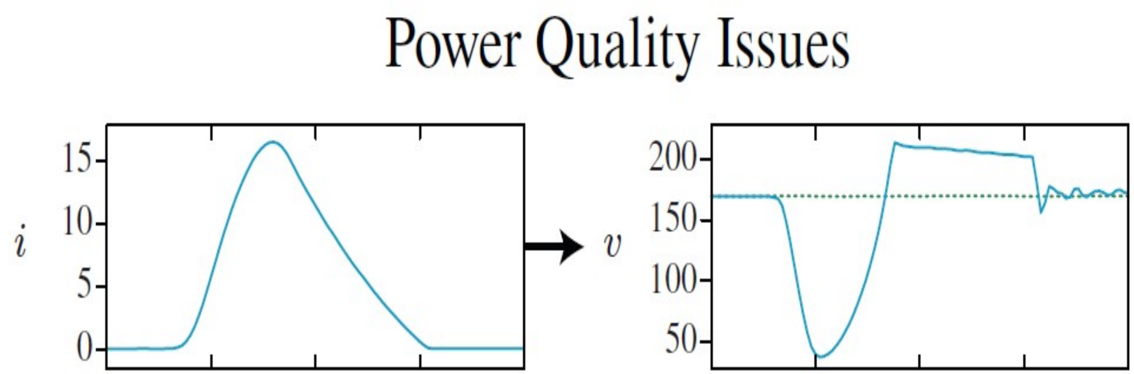
Motivation

- Loads connected to either DC or AC grid through PEBBs act as constant power loads (CPL)
- CPLs are destabilizing, particularly in DC systems



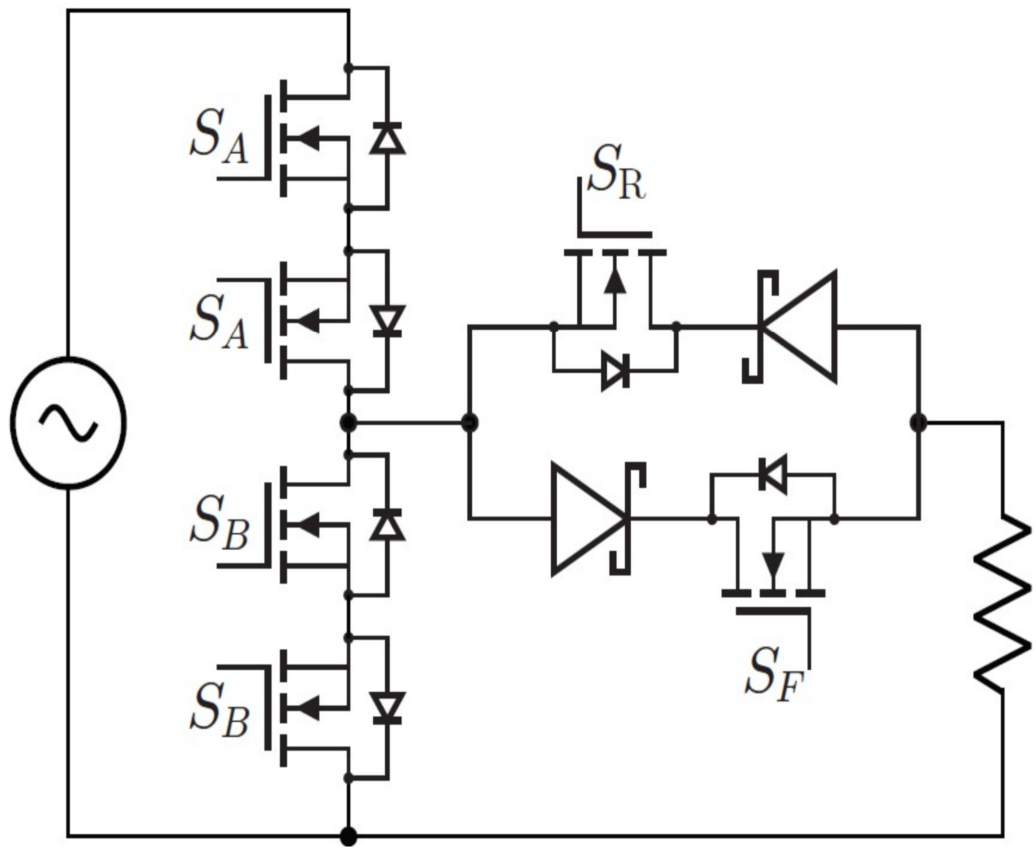
Source Impedance



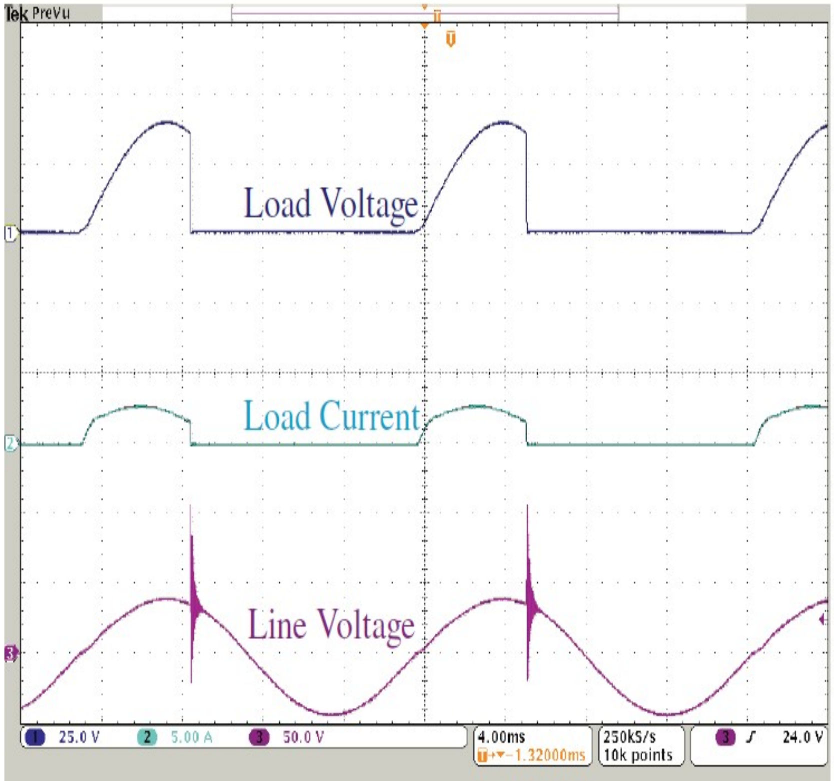


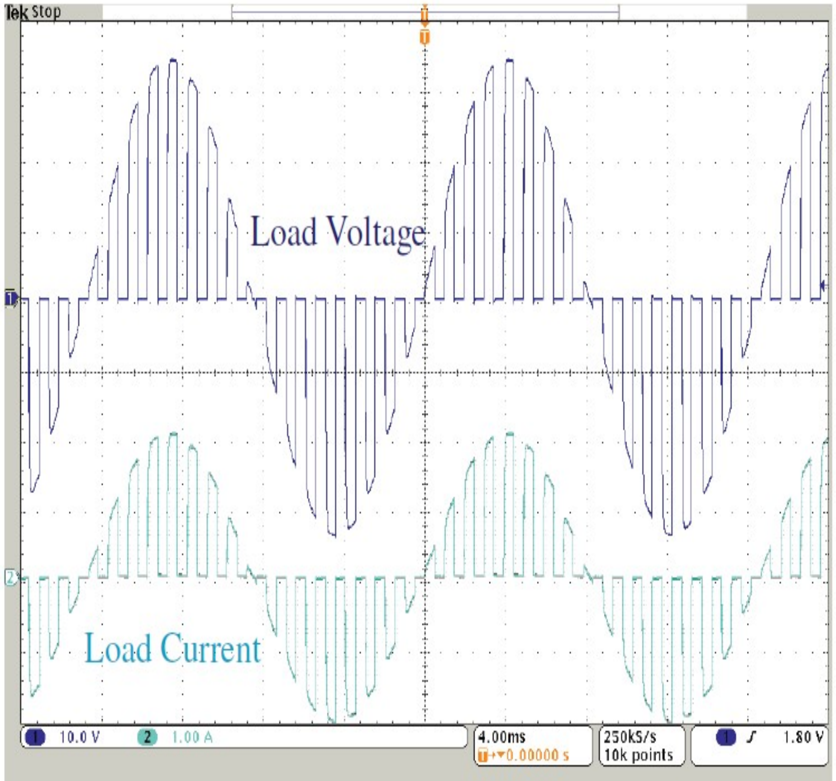
PEBB Interface for Control, Protection, and Sys Id

- Use four-quadrant switches for enhanced switching behavior

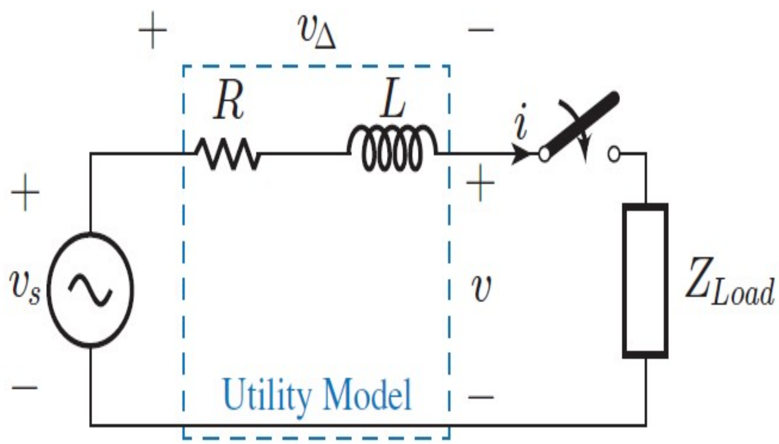


Complete Control over Load/Grid Interaction



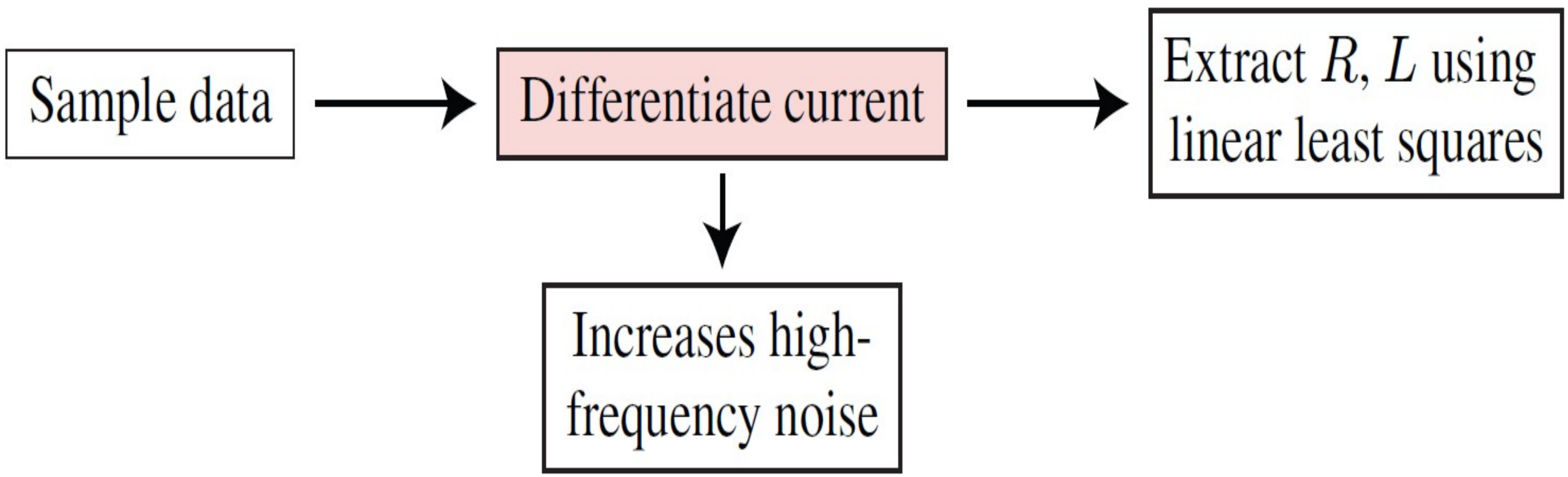


One Approach: Parameteric Identification



$$v_s - v = v_\Delta = (R + sL)i$$

$$s \Rightarrow \frac{d}{dt}$$



Source/Line Parameter Identification

- Find governing circuit equation $\rightarrow$ $v_s - v = v_\Delta = (R + sL)i$
- Suggest a differentiation operator based on a low-pass filter $\rightarrow$ $\lambda_k = \dfrac{1}{s\tau_k + 1} \Rightarrow s = \dfrac{1-\lambda_k}{\lambda_k \tau_k}$
- Perform operator substitution $\rightarrow$ $-\dfrac{R}{L}[\lambda_k i](t) + \dfrac{1}{L}[\lambda_k v_\Delta](t) = \dfrac{1}{\tau_k}\Big(i(t) - [\lambda i](t)\Big)$
- Constrcut matricies with sampled data $\rightarrow$

$$\psi = \begin{bmatrix} -[\lambda_k i](t_1) & [\lambda_k v_\Delta](t_1) \\ -[\lambda_k i](t_2) & [\lambda_k v_\Delta](t_2) \\ \vdots & \vdots \\ -[\lambda_k i](t_N) & [\lambda_k v_\Delta](t_N) \end{bmatrix} \quad \hat{\theta} = \begin{bmatrix} \widehat{\frac{R}{L}} \\ \widehat{\frac{1}{L}} \end{bmatrix} \quad y = \begin{bmatrix} \frac{1}{\tau_k}\Big(i(t_1) - [\lambda_k i](t_1)\Big) \\ \frac{1}{\tau_k}\Big(i(t_2) - [\lambda_k i](t_2)\Big) \\ \vdots \\ \frac{1}{\tau_k}\Big(i(t_N) - [\lambda_k i](t_N)\Big) \end{bmatrix}$$

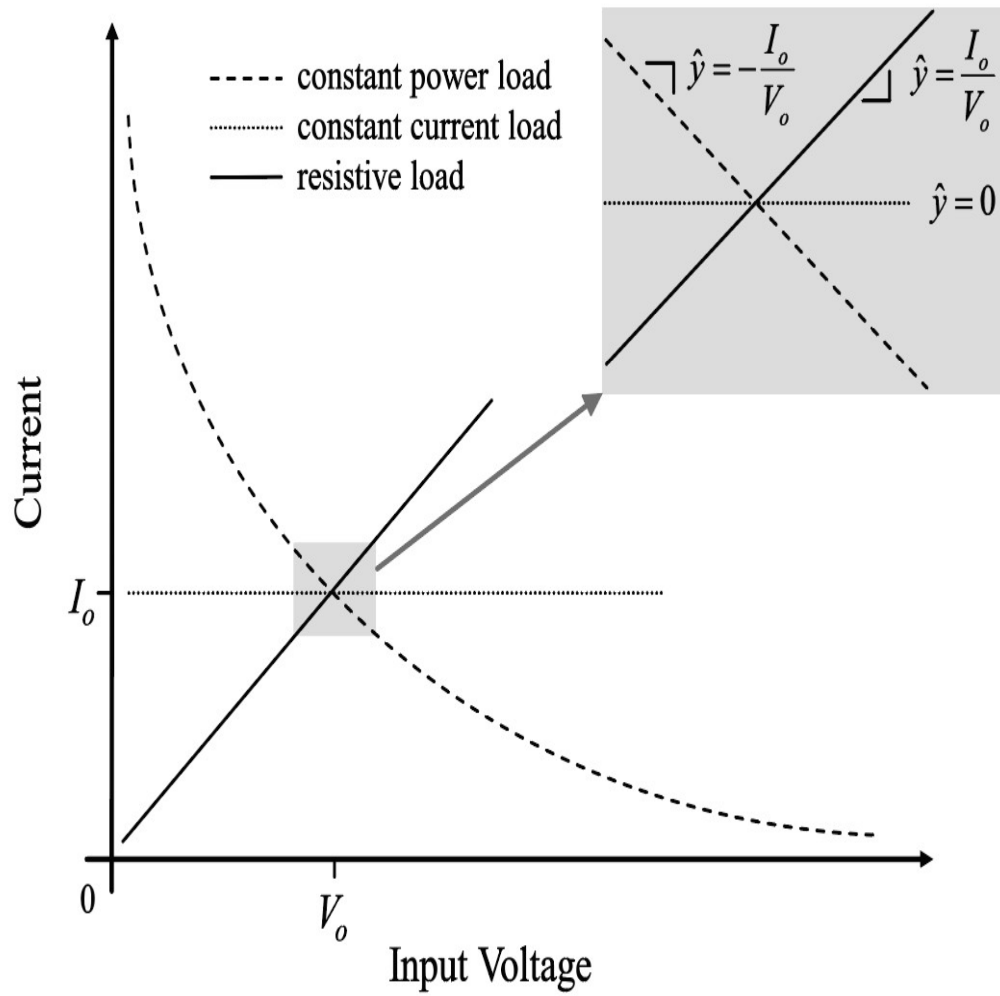
- Perform LLS to obtain parameters $\rightarrow$ $\psi\hat{\theta} = y$

Extracted R, L values

CPL Behavior

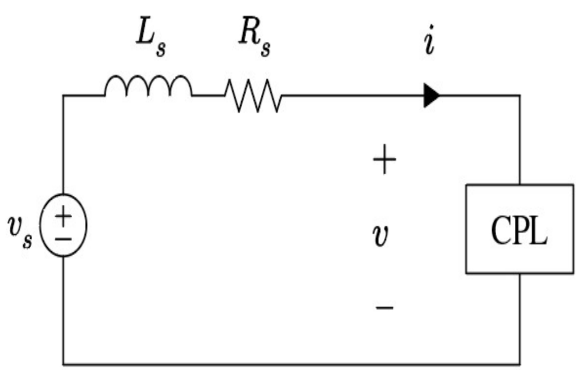
- CPLs decrease input current when input voltage increases to maintain constant power

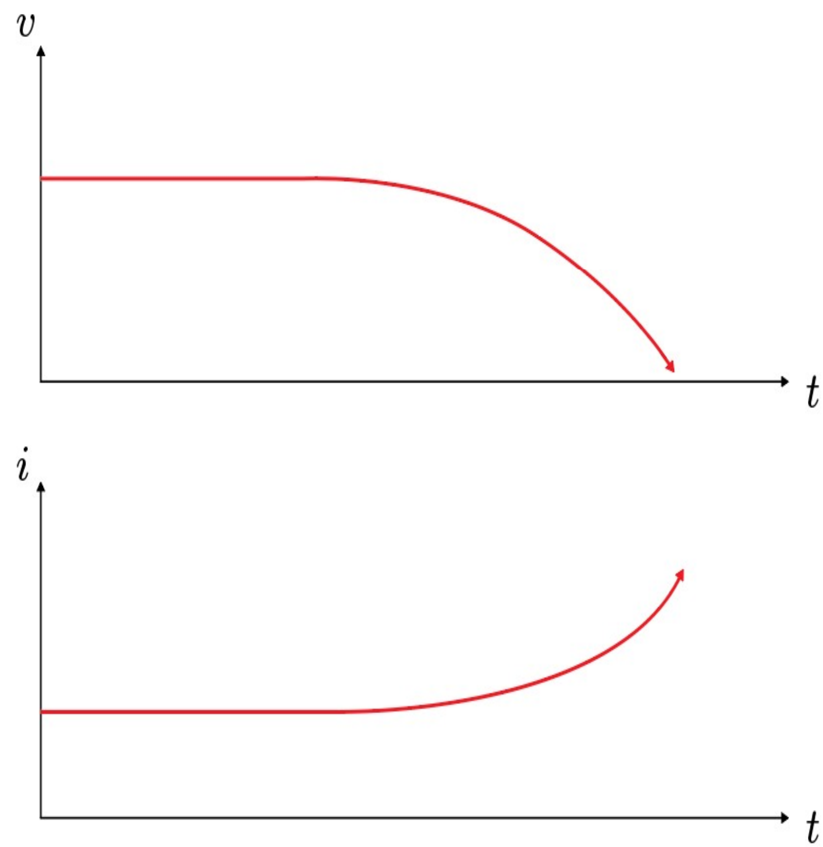
- Presents negative incremental impedance to the bus



CPL Behavior

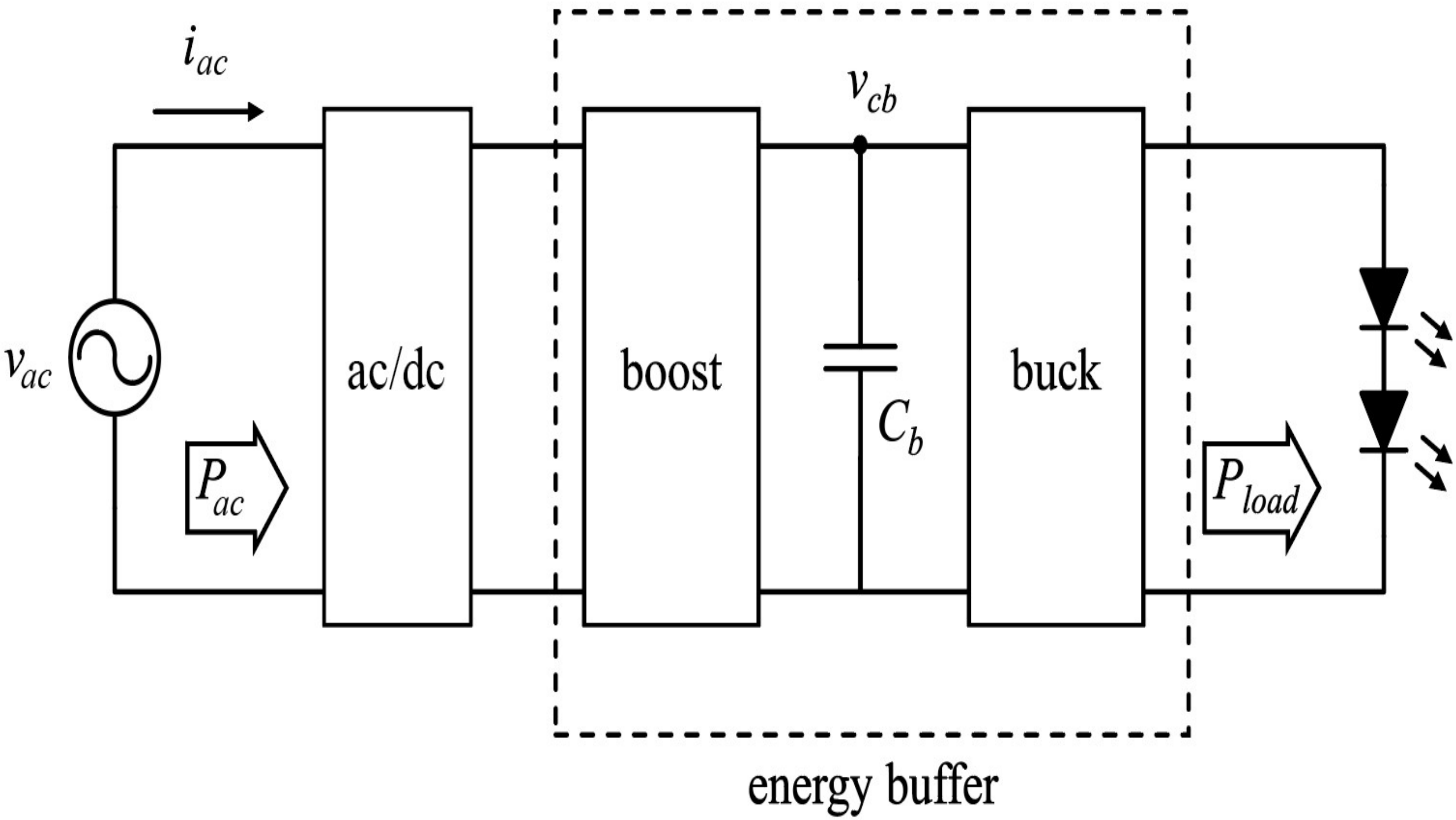
- Without proper care, CPLs can *crash* the DC bus:





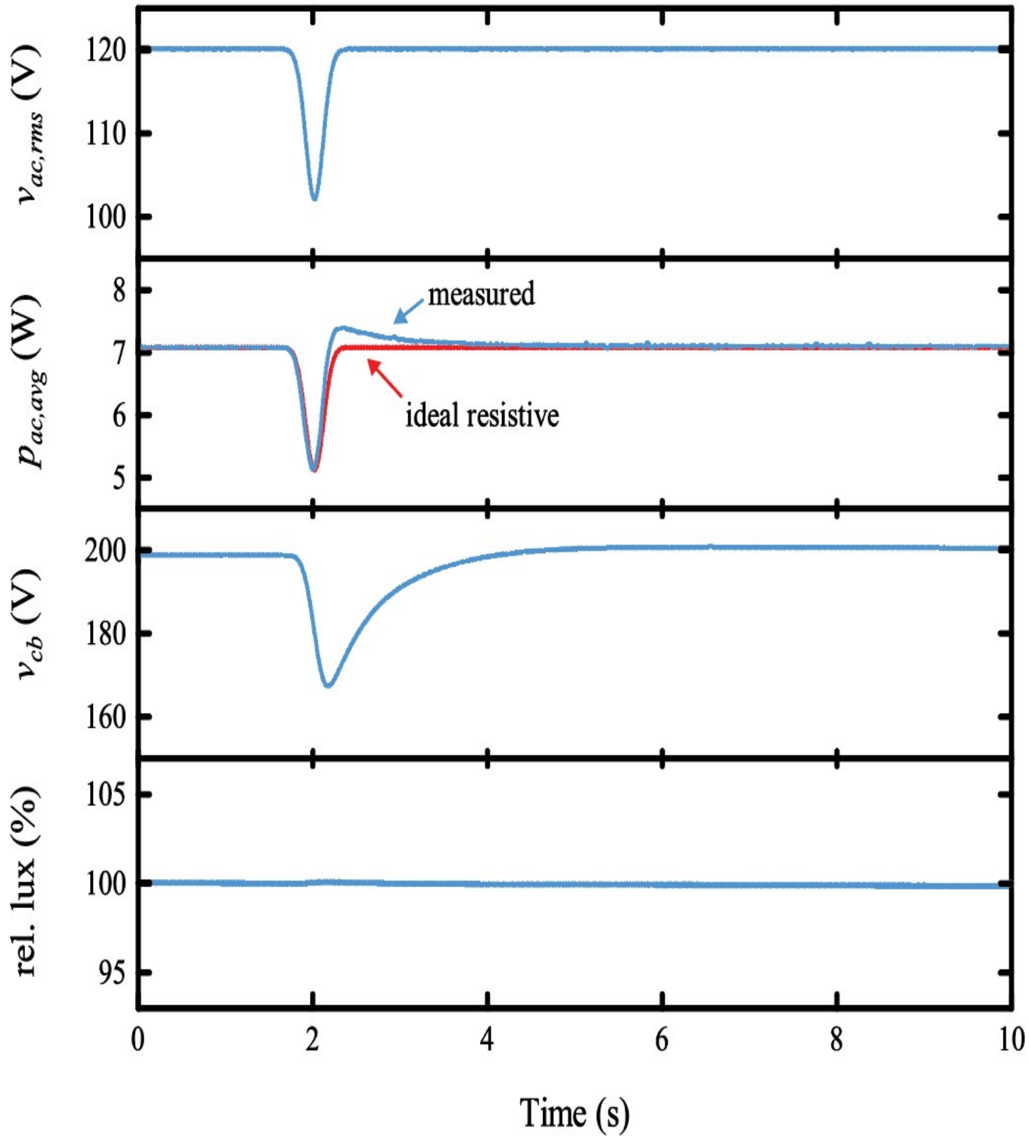
Energy Buffered PEBB

Addition of an energy buffer allows the PEBB to deliver constant power but present an input impedance that is stabilizing



Energy Buffered PEBB Transient Response

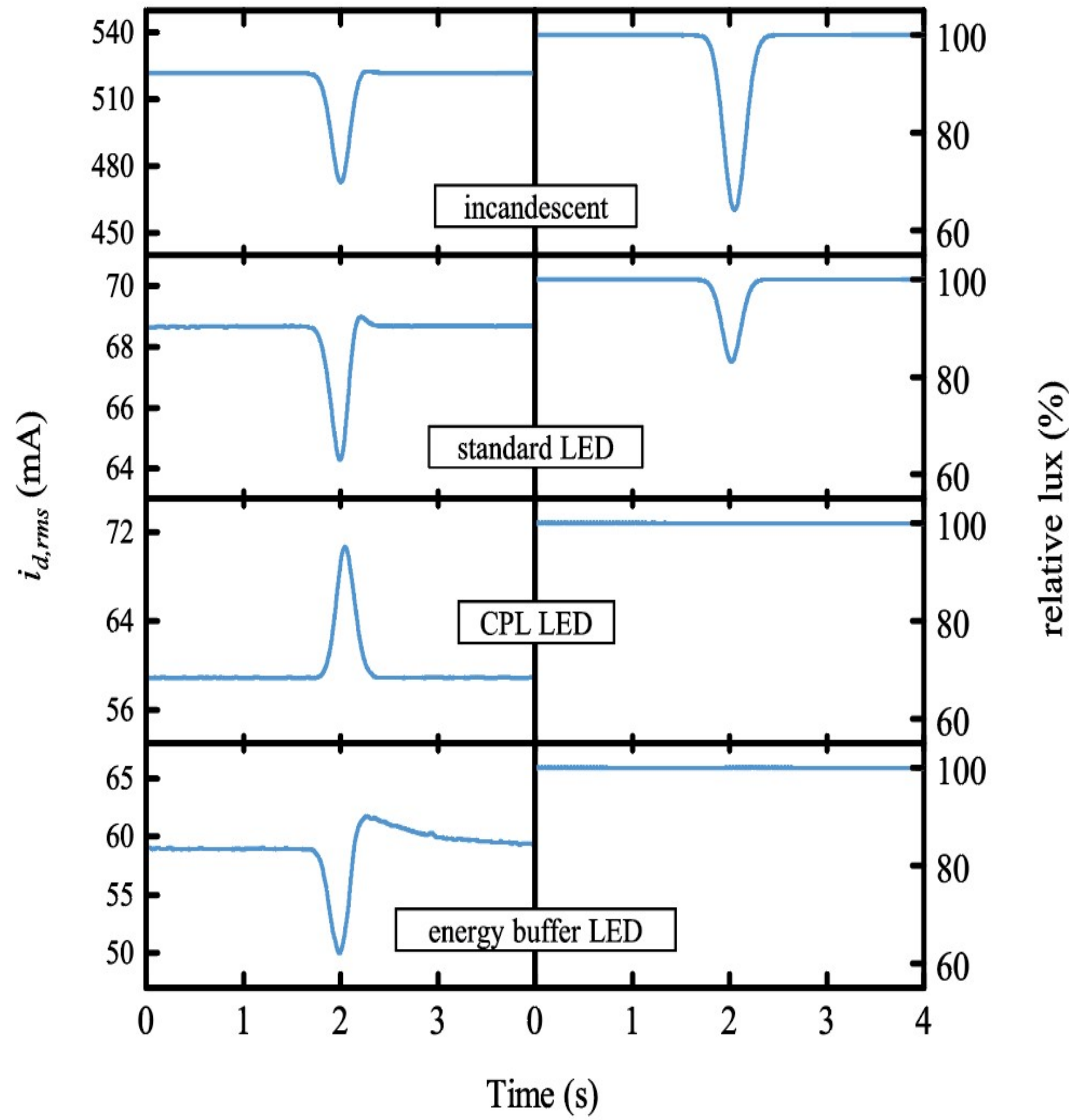
- Input current drops with input voltage initially, and current is gently increased to recovered energy deficit in buffer
- Input stage resembles a resistive load
- Example: for lighting applications, this converter provides constant light output



Technology Comparison

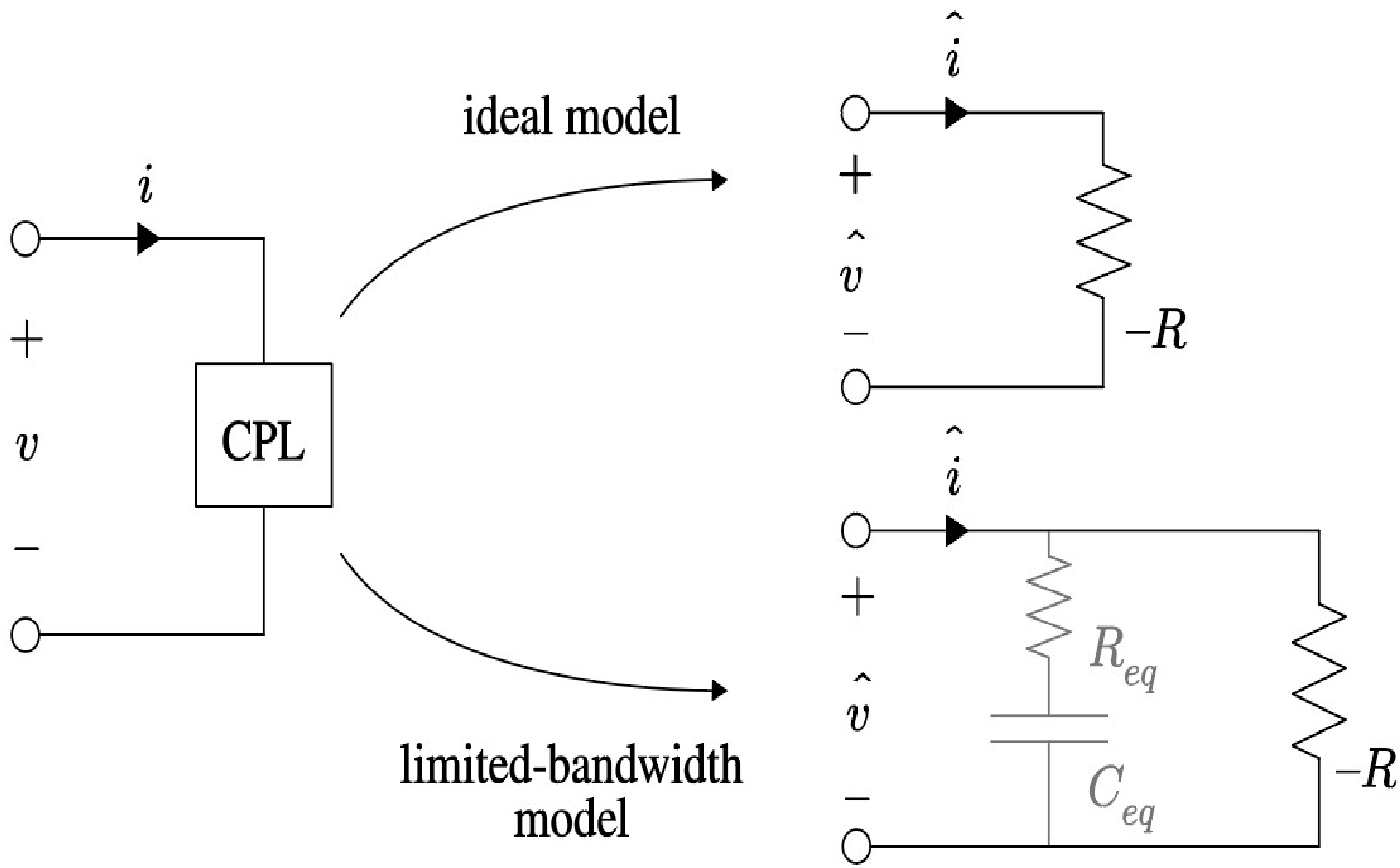
- Energy-buffered PEBB provides constant power with the most resistive input impedance

- Translates to other loads including motors, computers, etc.



Load Impedance Modeling

Our technique adds an equivalent branch to the input model:

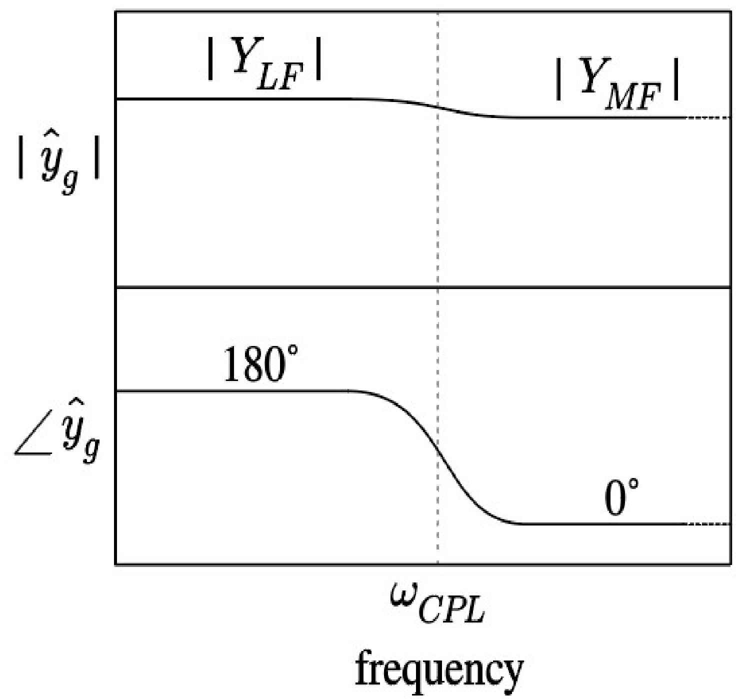


Load Impedance Modeling

- Input admittance is negative at low frequency to achieve constant input power on a slow time scale

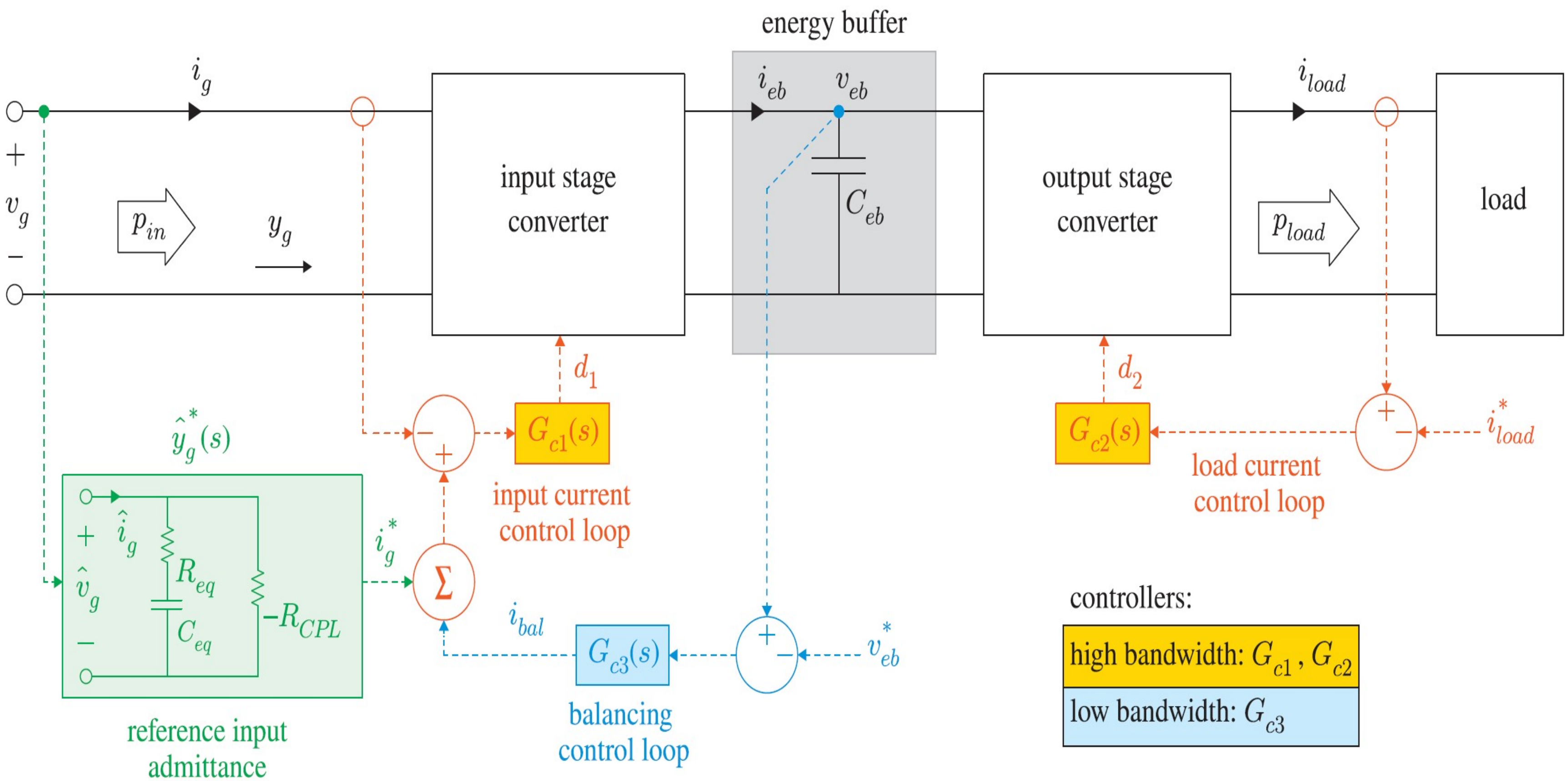
- Input admittance is positive (resistive) at high frequency to present stabilizing impedance in frequency range on interest

- CPL bandwidth can be modified on the fly to handle stability issues that arise



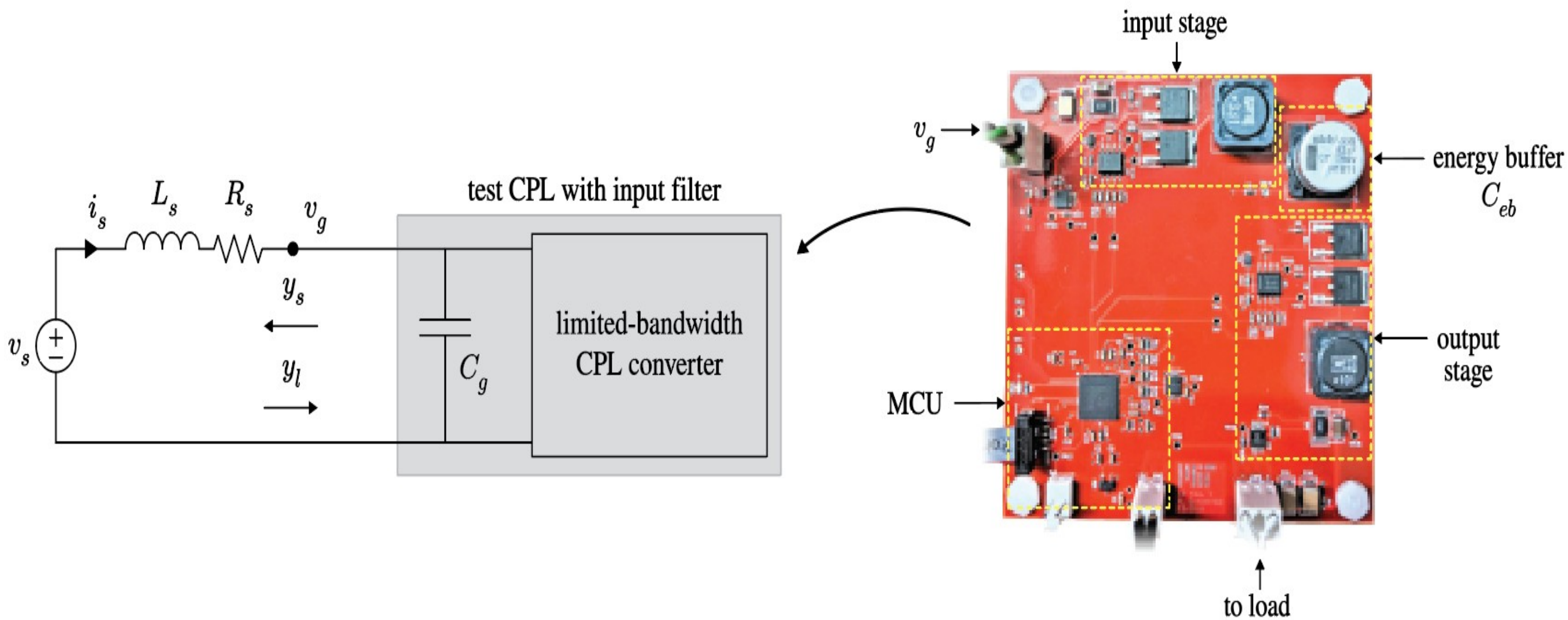
Energy Buffered CPL Implementation

- Controllable input impedance with input current control.
- Energy buffer maintained with additional, low-bandwidth loop:



Experimental Setup

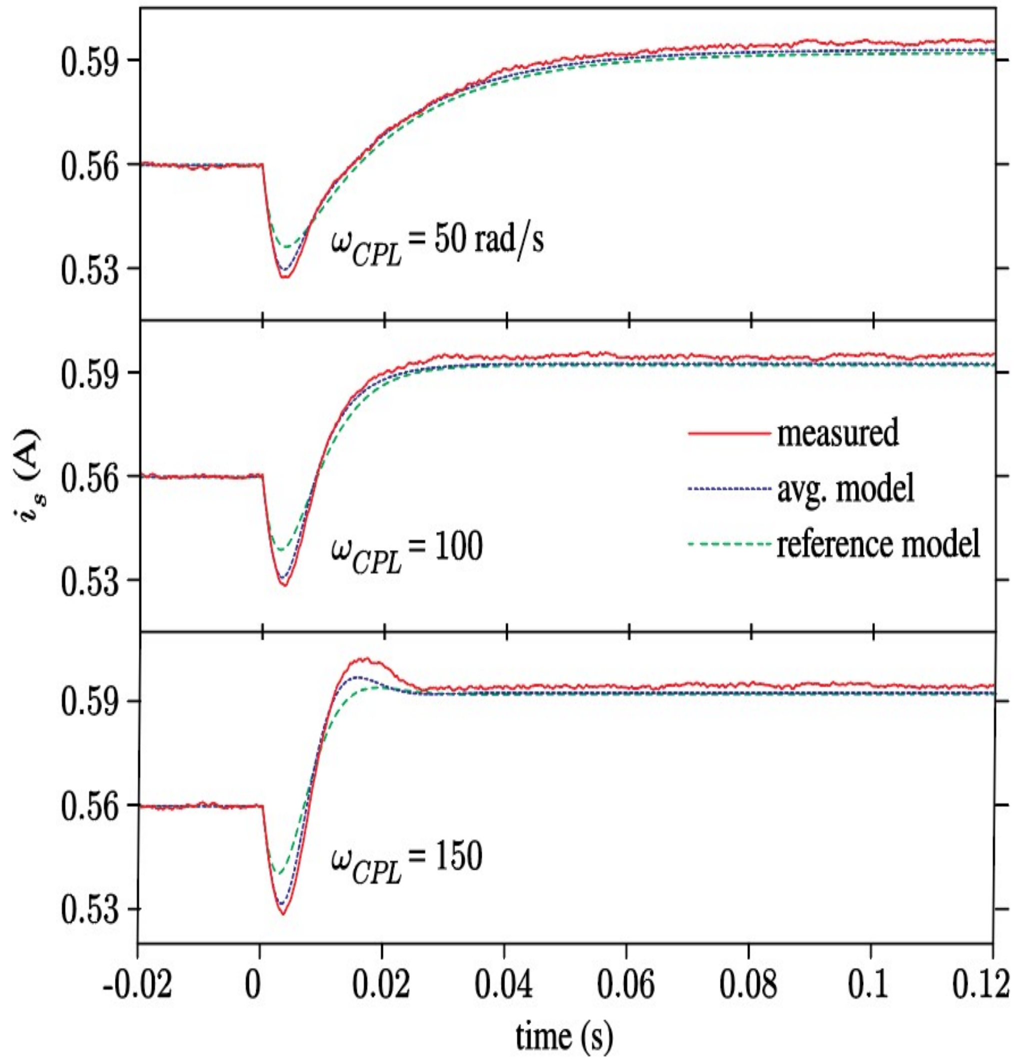
Bandwidth-limited CPL with energy buffer implemented on a 100-V DC test system:



Experimental Results

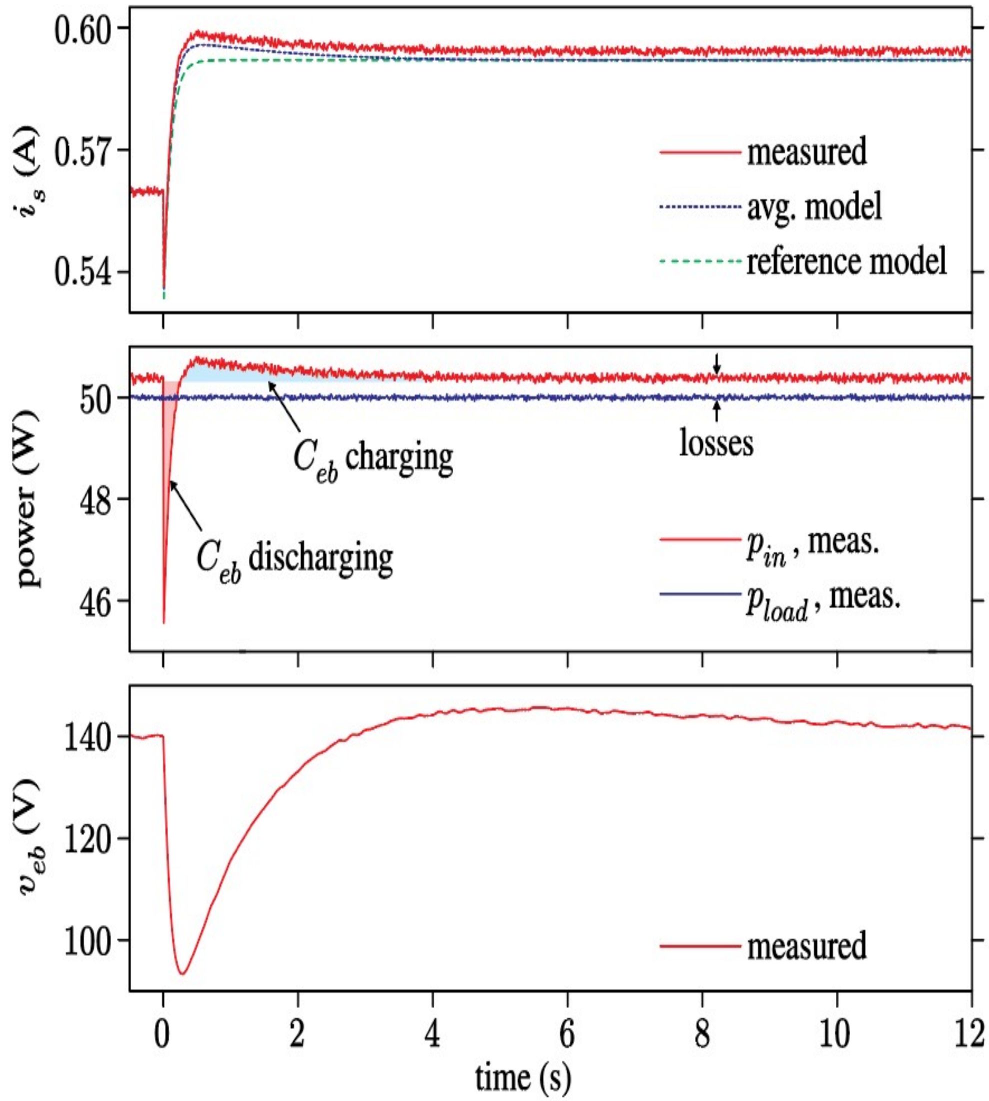
- Measured input current agrees with model and varies with CPL bandwidth

- Reducing the bandwidth improves system damping



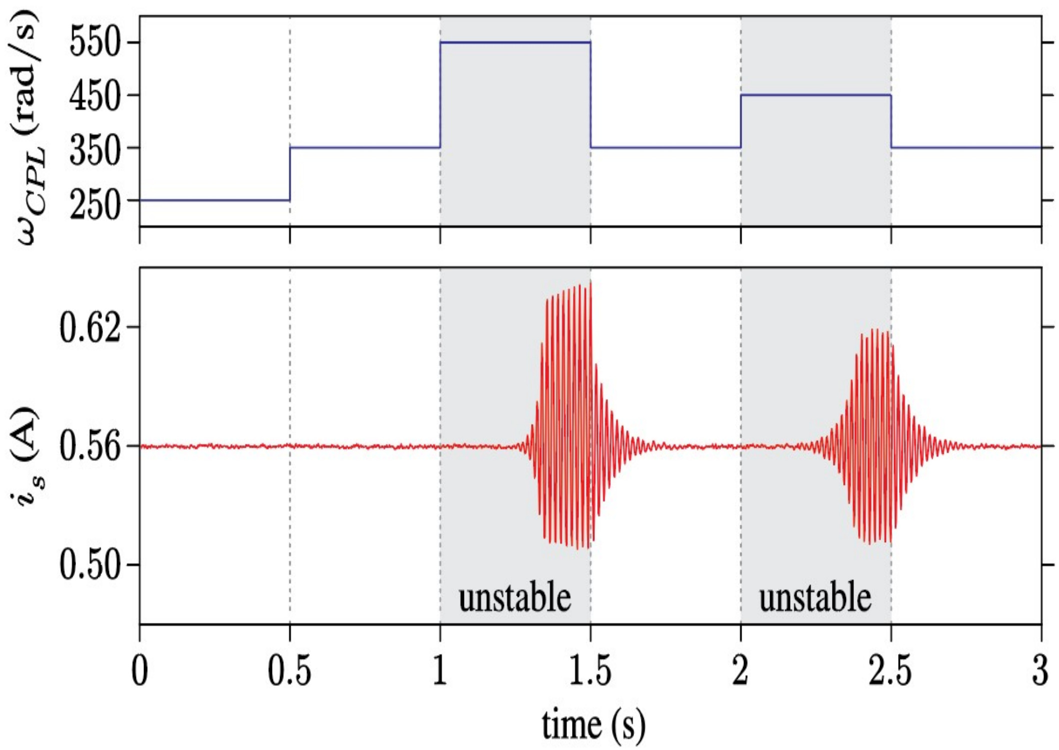
Experimental Results

- Energy buffer discharges and recharges during the input transient
- Buffer must store enough energy to ride through the transient



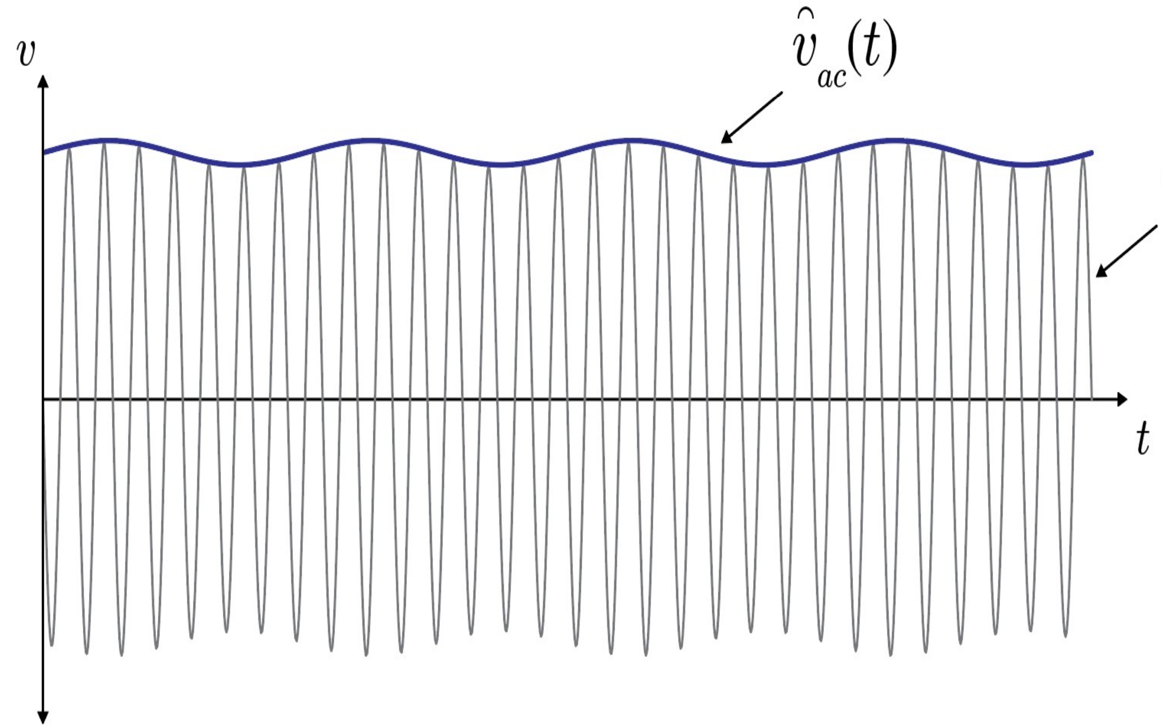
Experimental Results: DC systems

- Stability effects of varying CPL bandwidth
- Can decrease the bandwidth to stabilize a system that has become unstable.



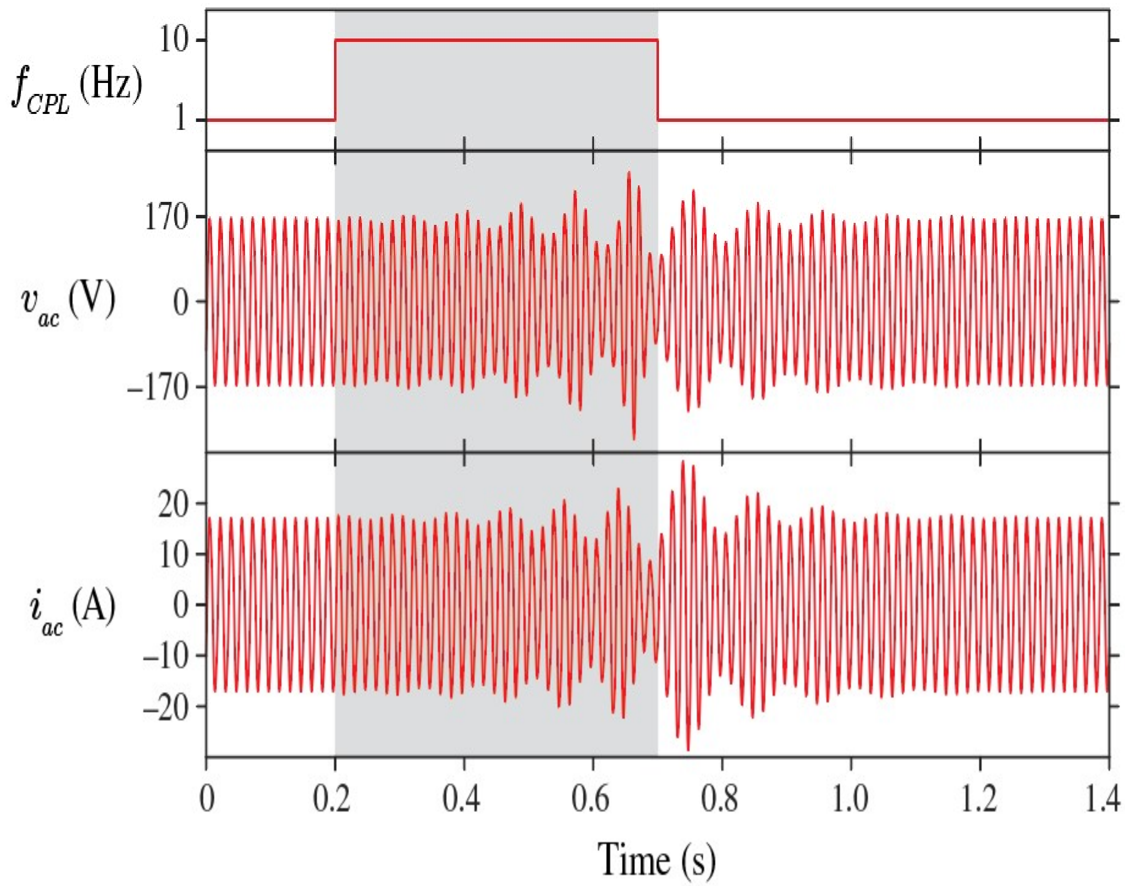
AC System Extension

- Approach extends to AC systems, but the action of rectifiers places interest on the envelope of the voltage and current:



AC System Results

- Have successfully demonstrated that CPL bandwidth can also both cause or correct instabilities in AC systems



Latest Results

"Impedance Modeling for Line-Frequency Rectified Constant-Power Loads, "accepted for publication in IEEE Access

“Voltage Measurement of Multi-Wire Cables with a Noncontact Electrode-Array Sensor" is “in review” IEEE Transactions on Instrumentation & Measurement