A 99.4% Efficient 450 W Hard Disk Drive Storage Server with Multiport Ac-Coupled Differential Power Processing (MAC-DPP) Architecture

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PRINCETON POWERLAB

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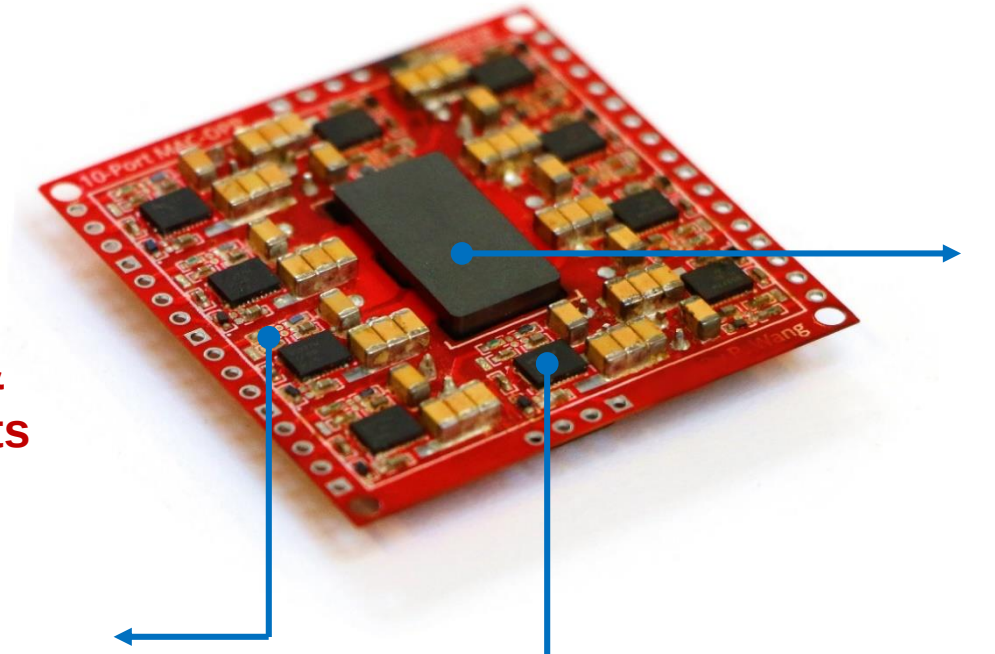
ECCE Student Project Demonstration Video Display

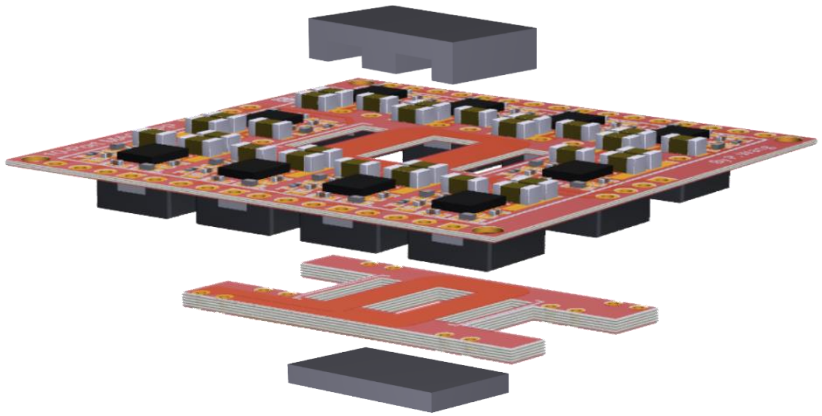
- Power rating: > 450 W
- Power density: > 630 W/in^3
- System efficiency: > 99%
- Hot-swapping capability

Click →



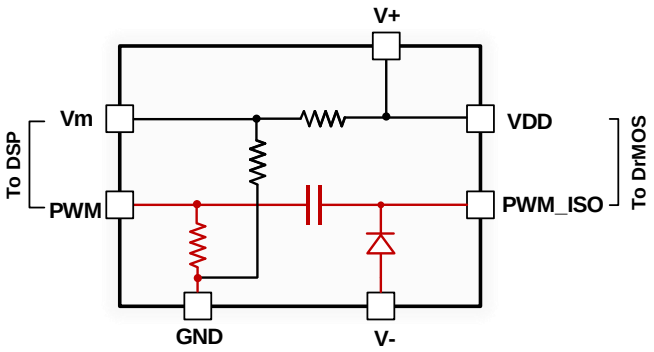
Stacked-PCB Planar Magnetics

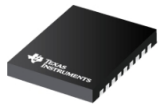
- 10x magnetics core area reduction



Modular Voltage Sampling & Bootstrap Gate Drive Circuits

- Modular & Scalable





DrMOS, TI-CSD95377Q4M

- 3.5 mm x 4.5 mm
- 35 A max continuous current

Data Center Energy Consumption

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Data Center Industry

CO_2

=

=

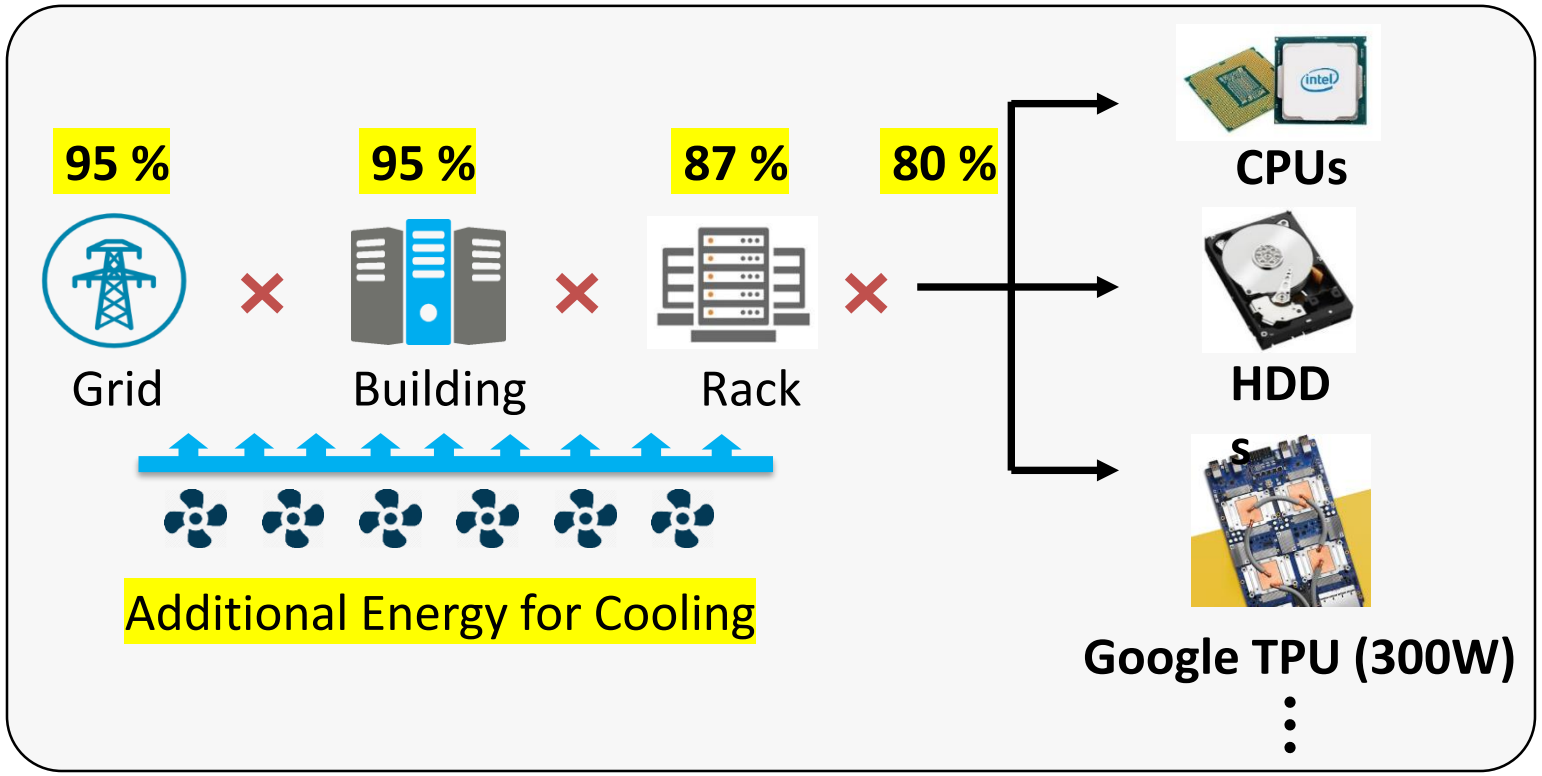
kWh

Airline Industry

- Consuming 90 billion kilowatt-hours per year in the U.S.[1]
- Contributing 2% of the U.S. total electricity consumption (3% in worldwide)
- Comparable CO_2 emission as the entire airline industry

Power Delivery Architecture in Data Center

➢ Conventional Power Delivery Architecture[2]



- Low grid to load efficiency:

≈ 60% → 40% → HEAT

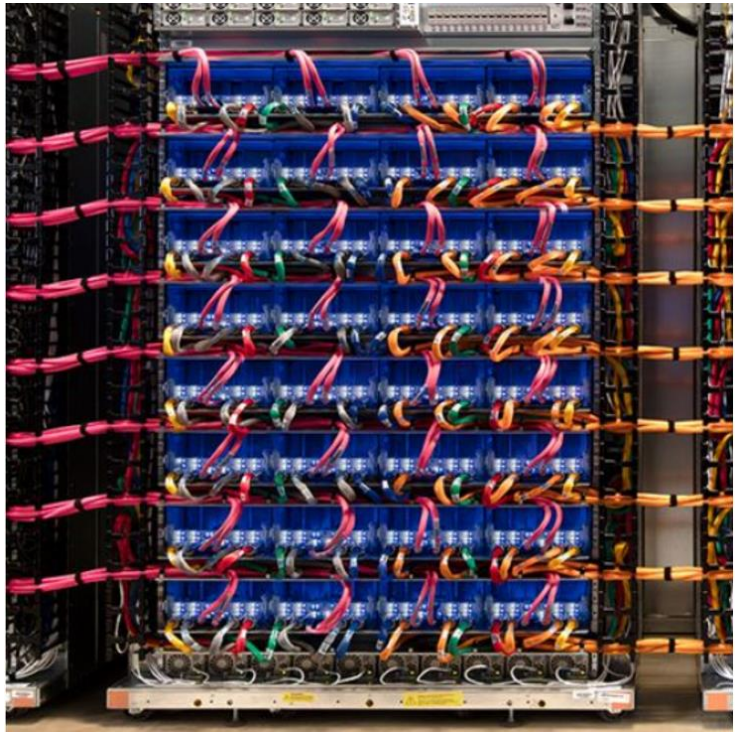
- Emerging AI Applications
  - ➔ Higher current
  - ➔ Higher distribution losses

➢ Target for Advanced Power Architecture:

- Deliver power with less conversion stages
- **Improve conversion efficiency at each stage**

Large-Scale Modular Loads on Rack

- **Google TPU Training Pod**
- **Facebook AI Accelerator**
- **Hard Drive Disk Array**



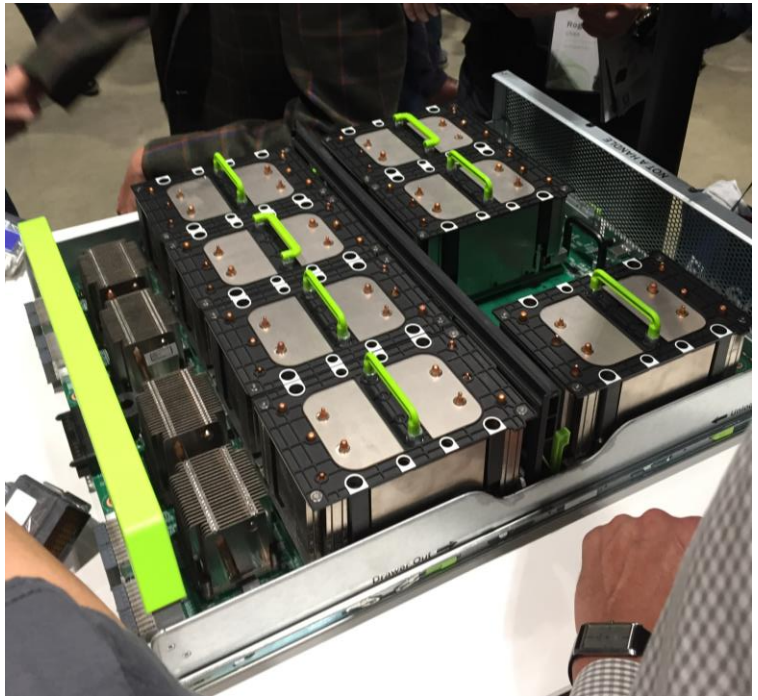
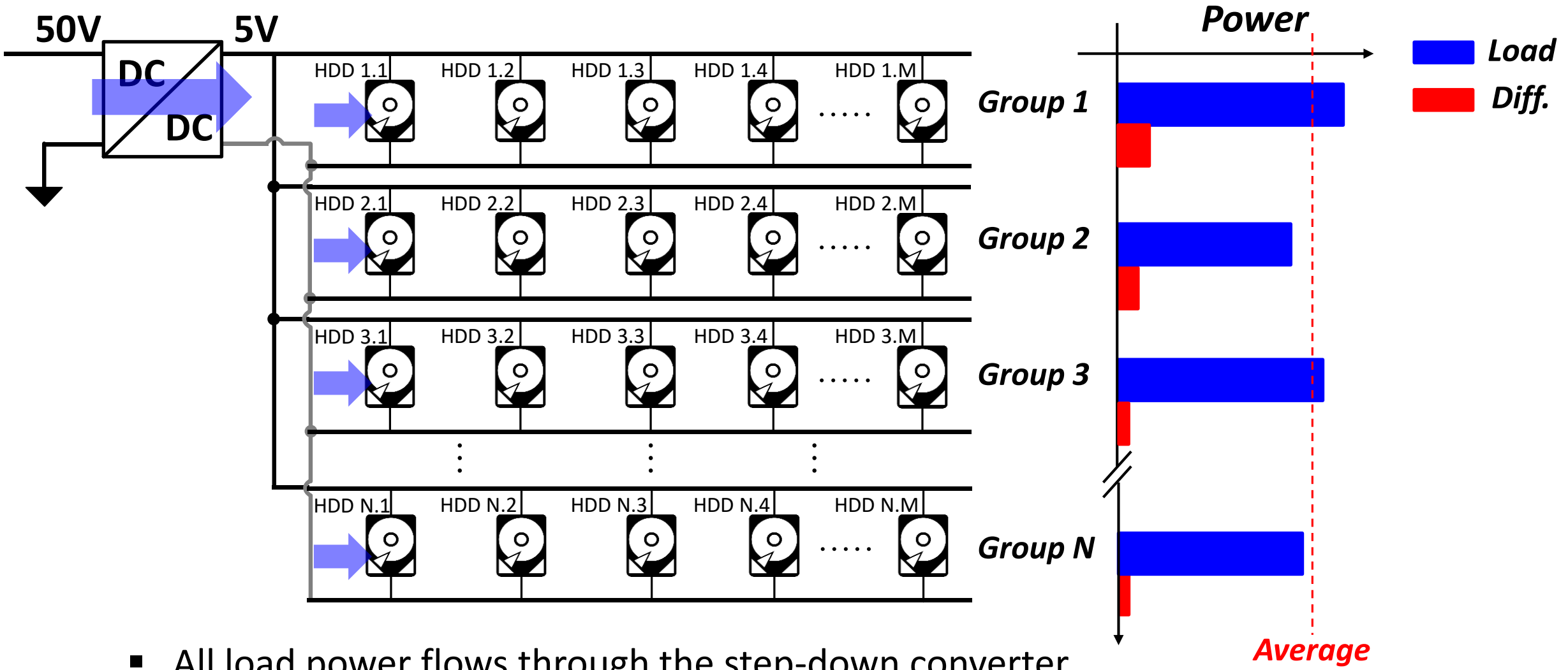


Fig. 3: Examples of Large-Scale Modular Loads in Contemporary Data Center

- Large-scale identical modules for intensive computing/storage applications
- Perform identical task with similar power consumption

Differential Power Processing for HDD Array

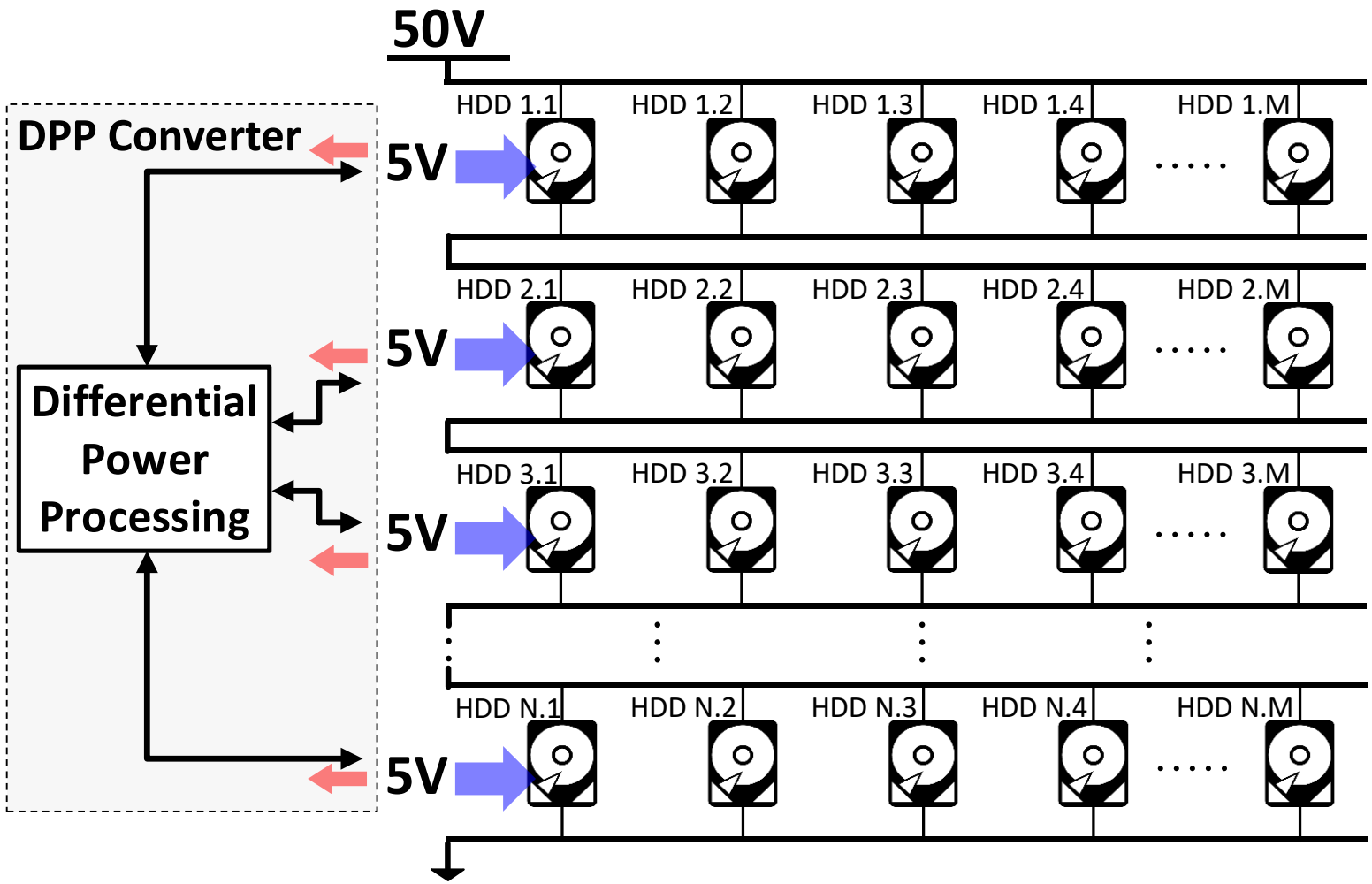
➢ Conventional Voltage Step Down Architecture

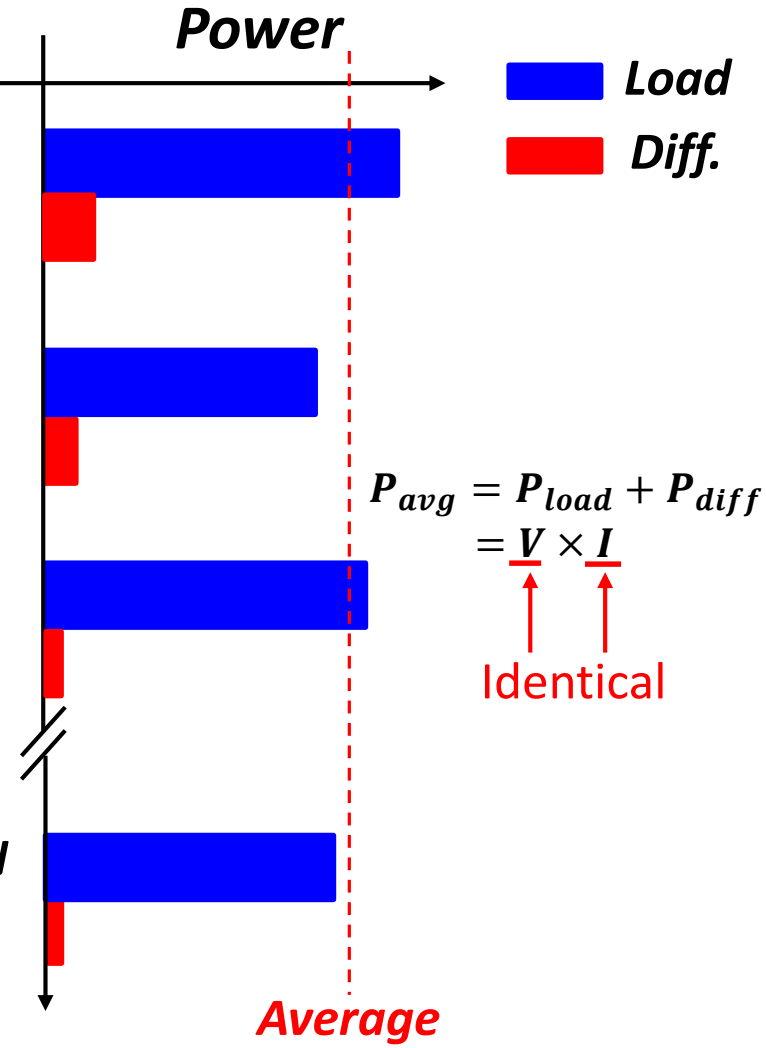


- All load power flows through the step-down converter.

Differential Power Processing for HDD Array

- **Series-Stacked Power Architecture**





- Only small amount of differential power processed by the differential power processing (DPP) converter.

DPP Converter Topology

- **Ladder DPP[3]**
- **Switched Capacitor DPP[4]**
- **Dc-Coupled DPP[5]**

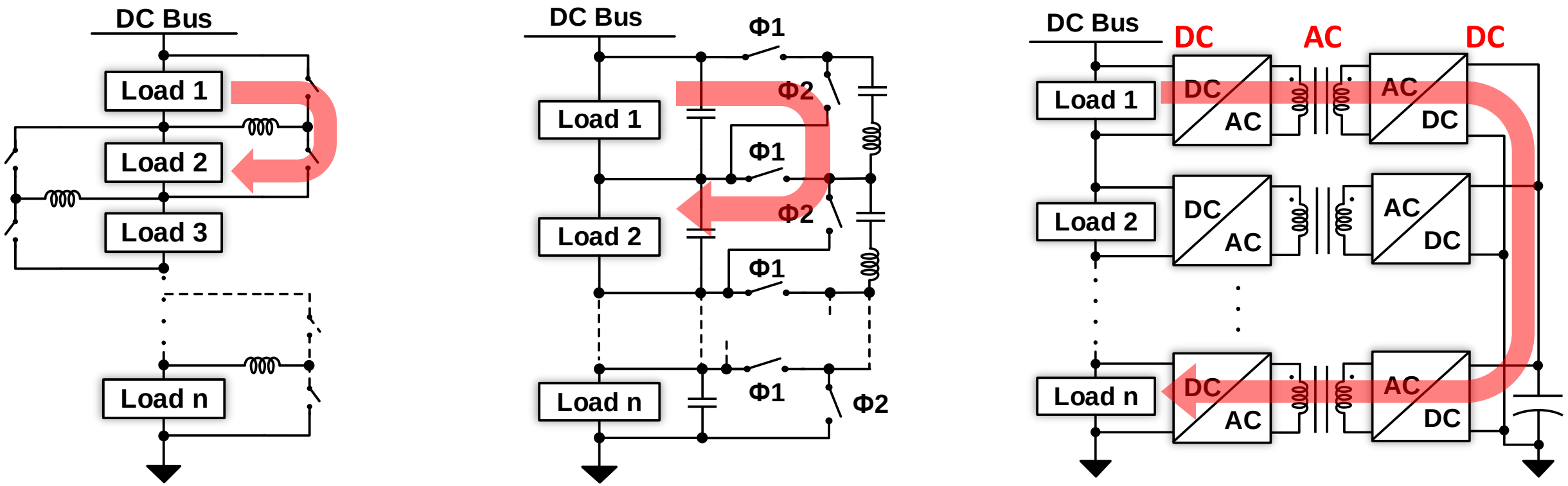


Fig. 5: Three Existing DPP Topologies

- **Ladder DPP & Switched Capacitor DPP**: DPP only between two neighboring ports
- **Dc-Coupled DPP**: Multiple magnetics; Two dc-ac-dc conversion stages

Multiport Ac-Coupled (MAC) DPP Converter

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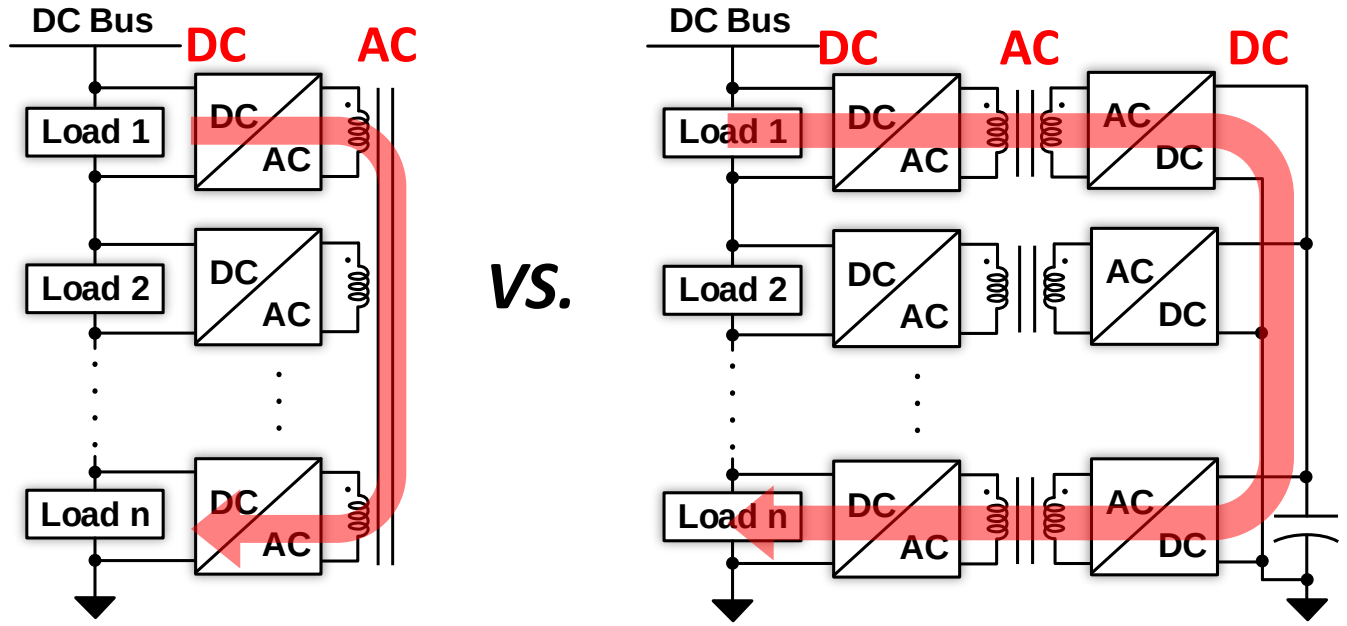
➢ MAC-DPP Compared with Dc-Coupled DPP



MAC-DPP ***Dc-Coupled DPP***

Advantages

- Higher power density
- Higher conversion efficiency
- Lower cost

Challenges

- Closely-coupled power flow
- Modeling and control

Number of Devices	MAC-DPP	Dc-Coupled DPP	Benefits
Dc-ac units	N	2N	Lower cost
Transformers	1	N	Higher power density
Dc-ac-dc conversion stages[6]	1	2	50% loss reduction

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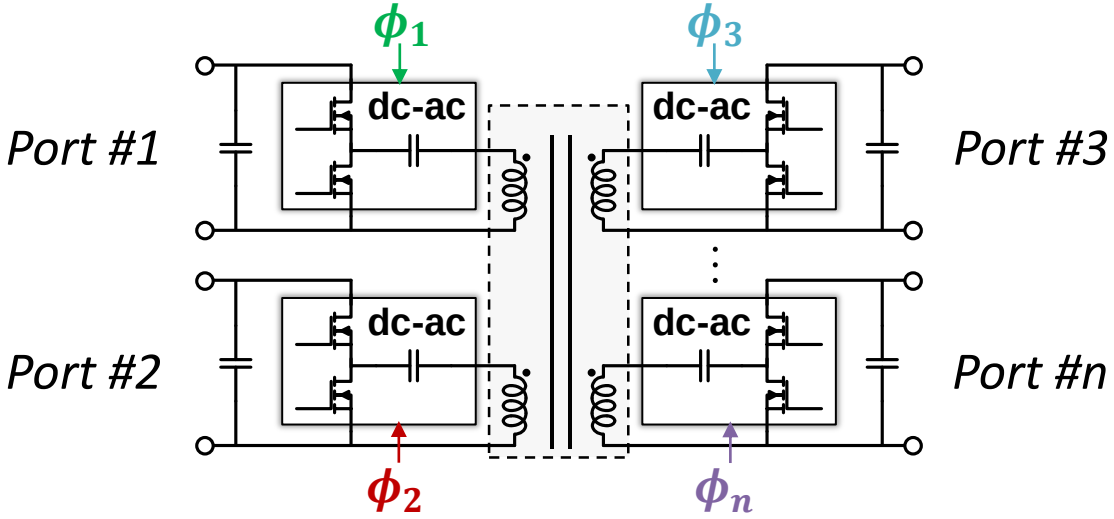
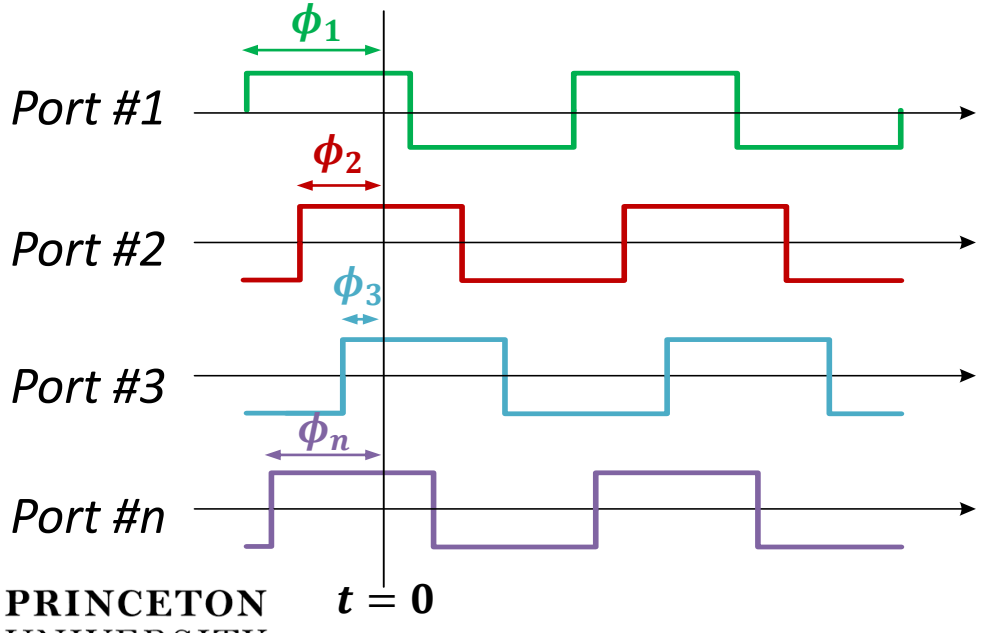
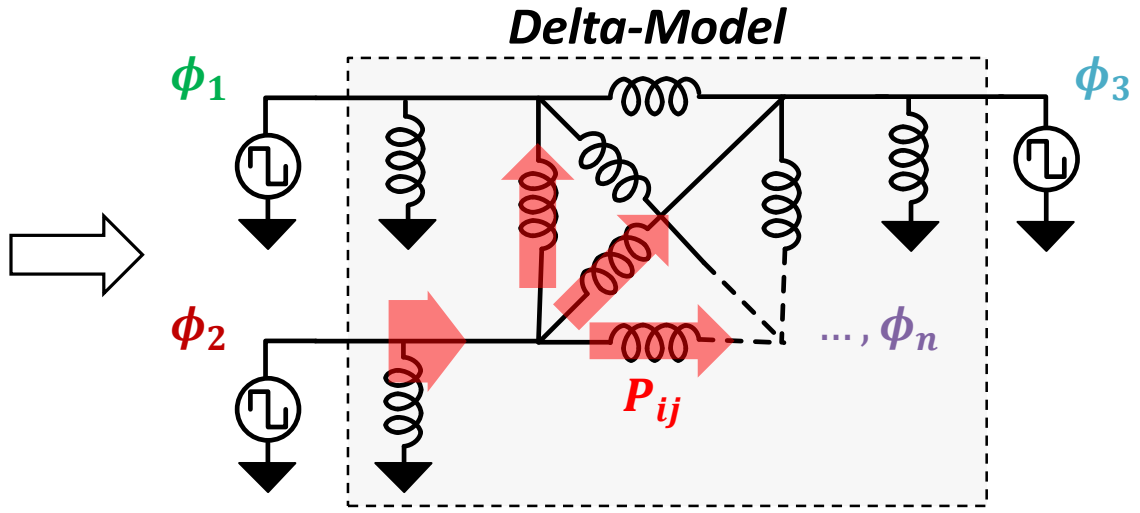
Power Flow Modulation

➢ Multi-port Phase-Shift Modulation





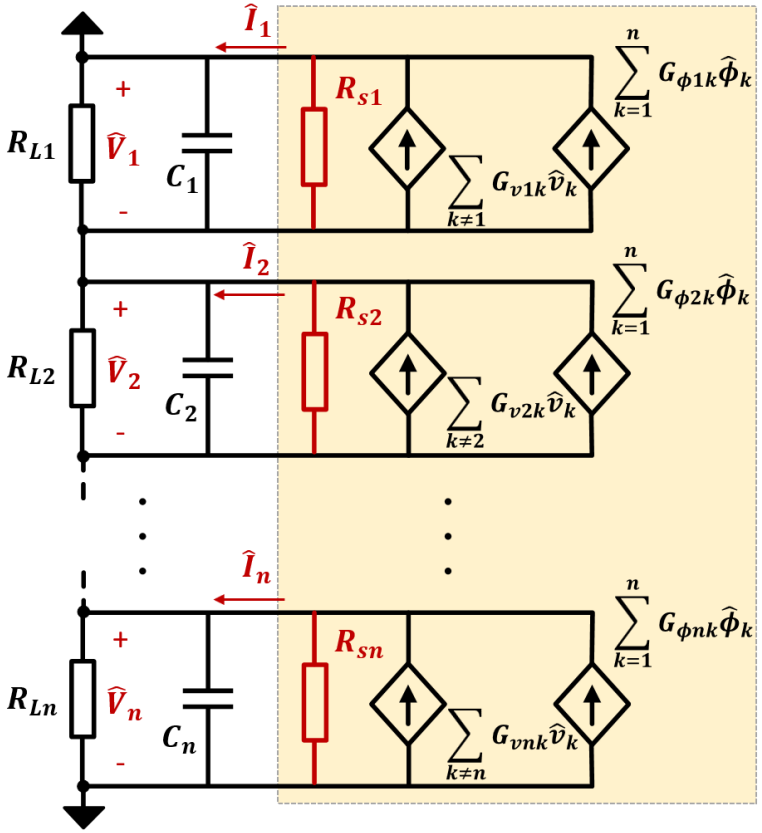


- All ports transferring power simultaneously.
- Total input power flow at *Port #i*:

$$P_i = \sum_{k \neq i} \frac{V_i V_k}{2\pi f L_{ik}} \phi_{ik} \left(1 - \frac{|\phi_{ik}|}{\pi}\right)$$

- Closely-coupled power flow
- Modulating phase-shifts $\{\phi_1, \cdots, \phi_n\}$

Small Signal Model



- **Step 1:** Large Signal Current

$$I_i = \frac{P_i}{V_i} = \sum_{j\neq i} \frac{V_j}{2\pi f L_{ij}} \phi_{ij} \left(\frac{|\phi_{ij}|}{\pi} - 1\right)$$

$\frac{\partial I_i}{\partial V_j}$

$\frac{\partial I_i}{\partial \phi_j}$

- **Step 2:** Small Signal Current Modeling

$$\begin{bmatrix} \hat{I}_1 \\ \hat{I}_2 \\ \vdots \\ \hat{I}_n \end{bmatrix} = \begin{bmatrix} 0 & G_{v12} & \cdots & G_{v1n} \\ G_{v21} & 0 & \cdots & G_{v2n} \\ \vdots & \vdots & \ddots & \vdots \\ G_{vn1} & G_{vn2} & \cdots & 0 \end{bmatrix} \begin{bmatrix} dV_1 \\ dV_2 \\ \vdots \\ dV_n \end{bmatrix} + \begin{bmatrix} G_{\phi 11} & G_{\phi 12} & \cdots & G_{\phi 1n} \\ G_{\phi 21} & G_{\phi 22} & \cdots & G_{\phi 2n} \\ \vdots & \vdots & \ddots & \vdots \\ G_{\phi n1} & G_{\phi n2} & \cdots & G_{\phi nn} \end{bmatrix} \begin{bmatrix} \hat{\phi}_1 \\ \hat{\phi}_2 \\ \vdots \\ \hat{\phi}_n \end{bmatrix}$$

G_v $\qquad$ G_ϕ

$$G_{vij} = \frac{\phi_{ij}}{2\pi f L_{ij}} \left(\frac{|\phi_{ij}|}{\pi} - 1\right) \qquad G_{\phi ij} = \begin{cases} \frac{V_j}{2\pi f L_{ij}} \left(1 - \frac{2|\phi_{ij}|}{\pi}\right), j \neq i \\ \sum_{j\neq i} \frac{V_j}{2\pi f L_{ij}} \left(\frac{2|\phi_{ij}|}{\pi} - 1\right), j = i \end{cases}$$

- **Step 3:** Considering the load structure

$$\begin{bmatrix} \hat{V}_1 \\ \hat{V}_2 \\ \vdots \\ \hat{V}_n \end{bmatrix} = \begin{bmatrix} -Z_1 || \sum_{k\neq 1} Z_k & \frac{Z_1 Z_2}{\sum_{k=1}^{n} Z_k} & \cdots & \frac{Z_1 Z_n}{\sum_{k=1}^{n} Z_k} \\ \frac{Z_2 Z_1}{\sum_{k=1}^{n} Z_k} & -Z_2 || \sum_{k\neq 2} Z_k & \cdots & \frac{Z_2 Z_n}{\sum_{k=1}^{n} Z_k} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{Z_n Z_1}{\sum_{k=1}^{n} Z_k} & \frac{Z_n Z_2}{\sum_{k=1}^{n} Z_k} & \cdots & -Z_n || \sum_{k\neq n} Z_k \end{bmatrix} \times \begin{bmatrix} \hat{I}_1 \\ \hat{I}_2 \\ \vdots \\ \hat{I}_n \end{bmatrix}$$

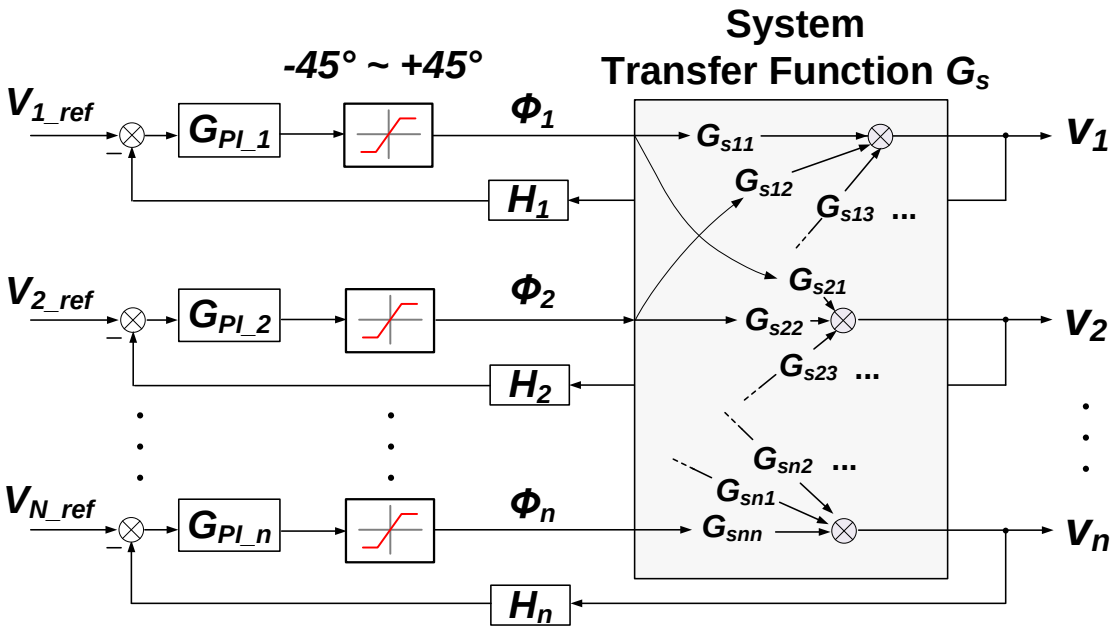
G_z

- **Step 4**. Obtaining System Transfer Function: $\hat{\boldsymbol{V}} = (\boldsymbol{I} - \boldsymbol{G_z G_v})^{-1} \boldsymbol{G_z G_\phi} \times \hat{\boldsymbol{\phi}}$

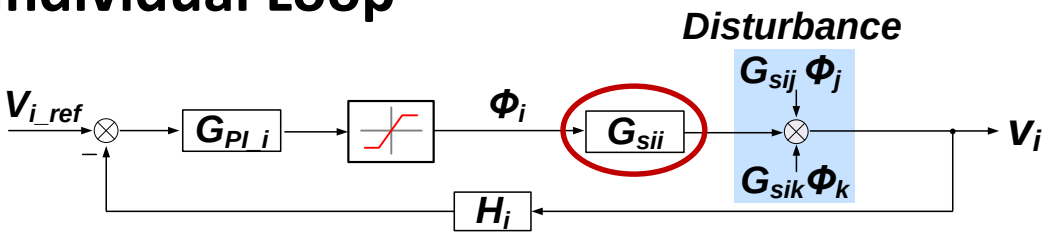
P. Wang, Y. Chen, Y. Elasser and M. Chen, "Small Signal Model for Very-Large-Scale Multi-Active-Bridge Differential Power Processing (MAB-DPP) Architecture," *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Toronto, ON, Canada, 2019, pp. 1-8.

Closed-Loop Voltage Regulation

➢ Distributed Phase-Shift (DPS) Control [7]

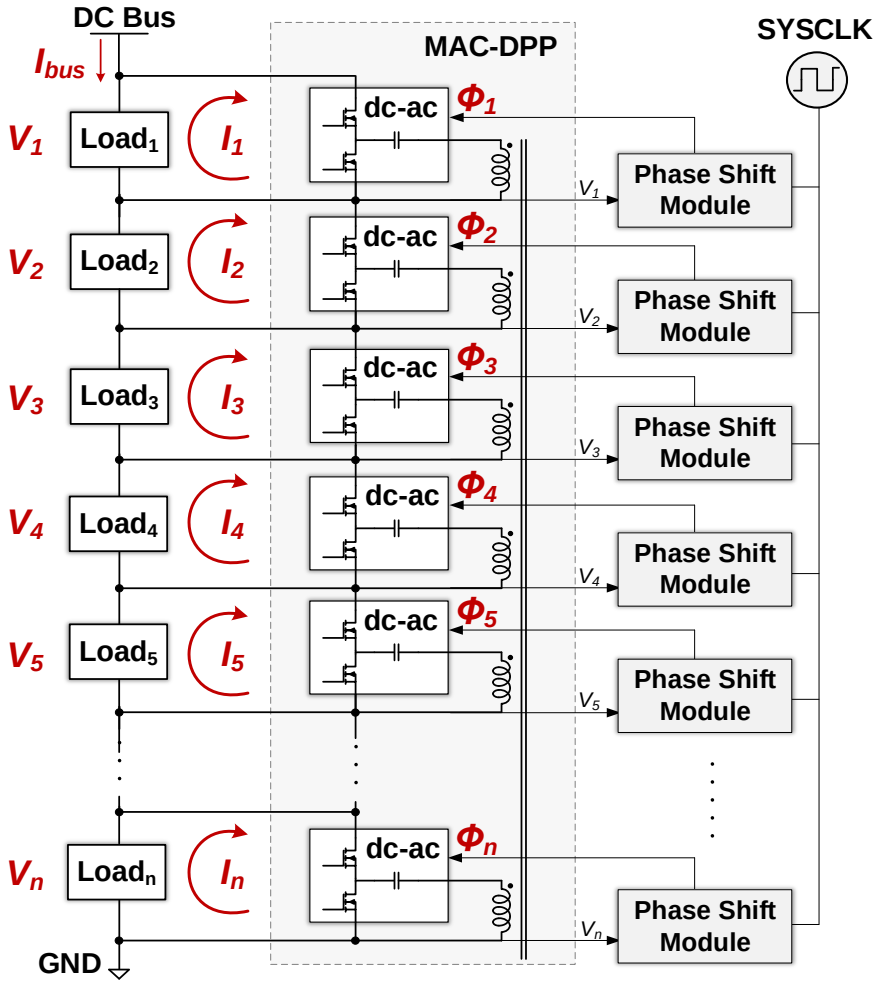


- **Individual Loop**



  - Design PI parameters based on G_{sii}

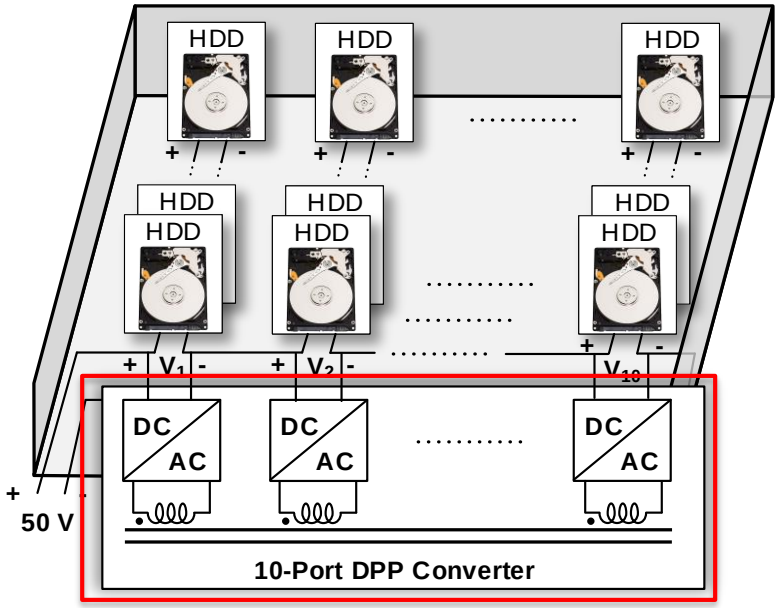
▪ System Implementation

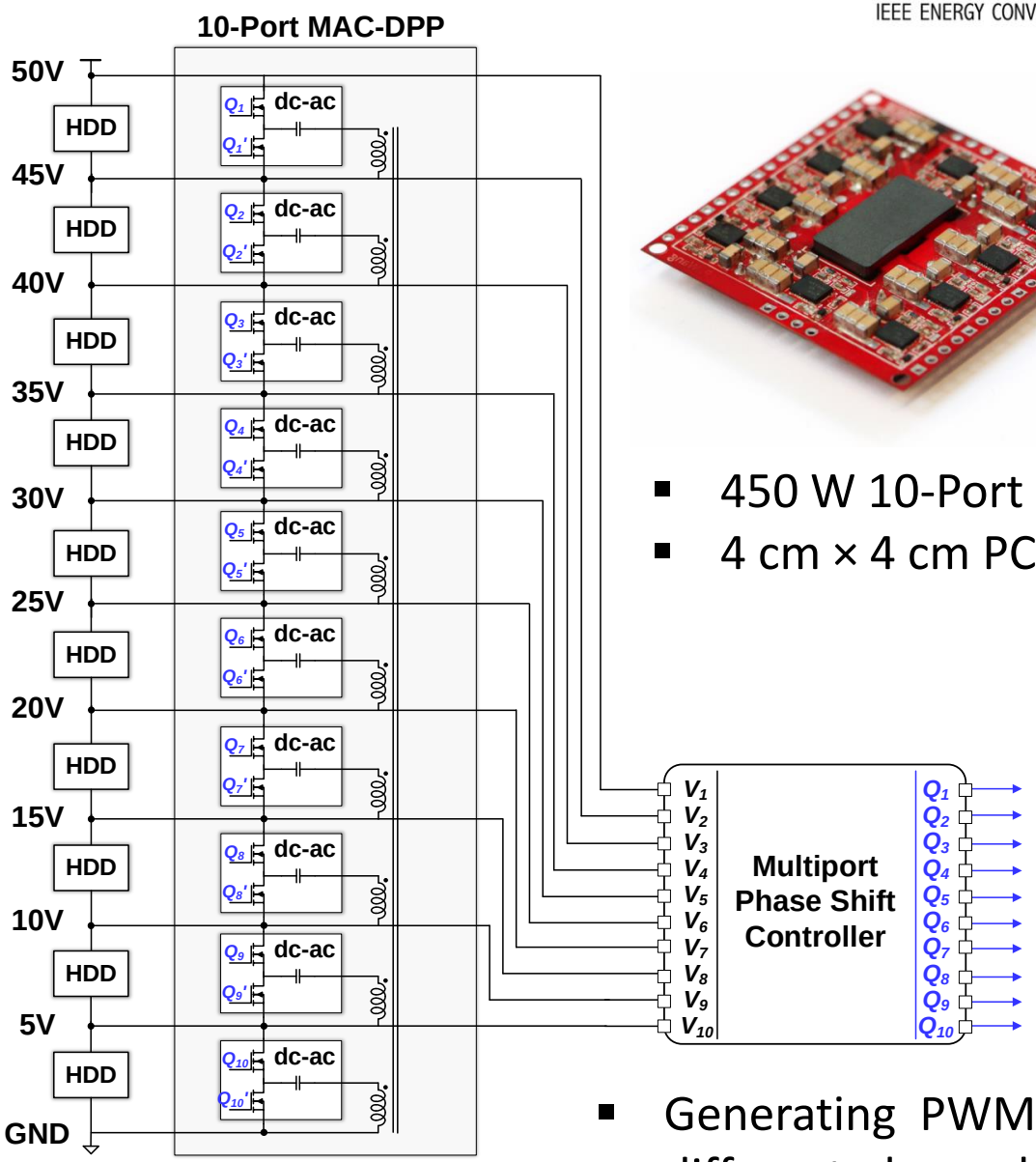


- Enable fully-modular building block

MAC-DPP for Data Storage Server

➢ 50-HDD Data Storage Server





- 10 series-stacked voltage domains (5 × 2.5-inch HDDs at each domain)
- 450 W 10-port MAC-DPP converter
- Ultra-high efficiency and power density
- Hot-swapping capability

- 450 W 10-Port MAC-DPP
- 4 cm × 4 cm PCB area

- Generating PWMs with different phase-shifts

450W 10-Port MAC-DPP Prototype

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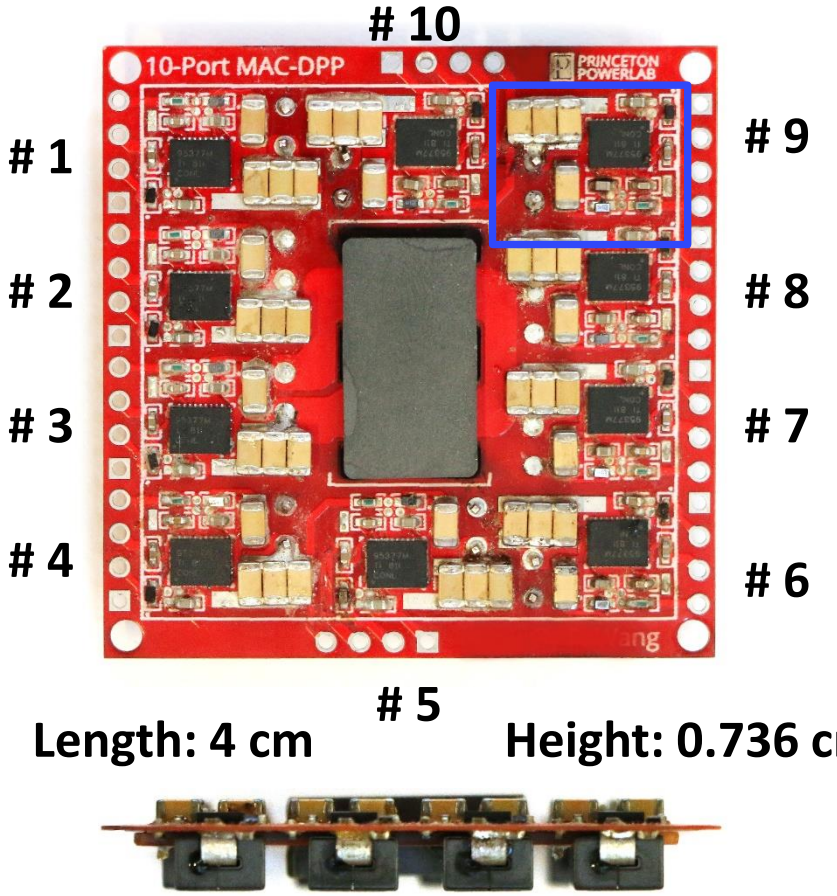
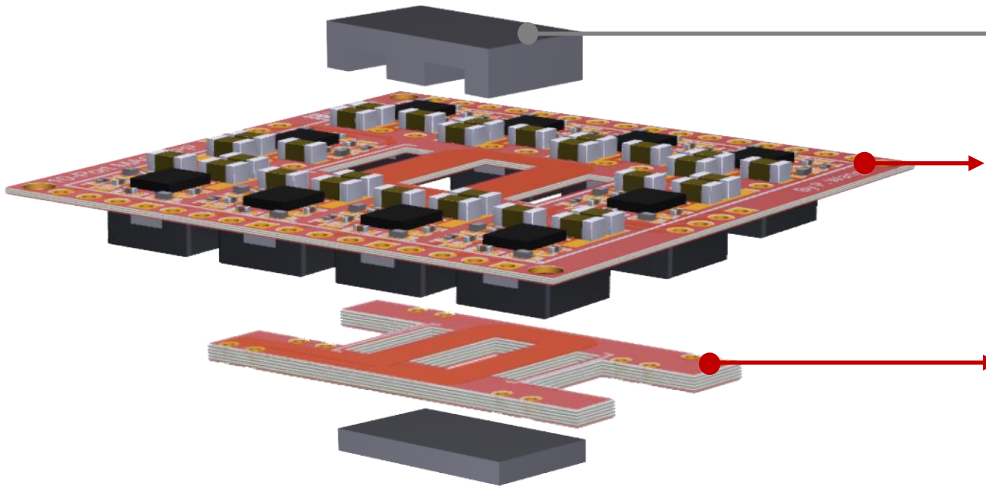
➢ Highly-Modular & Ultra-Compact



Length: 4 cm **Height: 0.736 cm**

➢ Stacked PCB Planar Magnetics

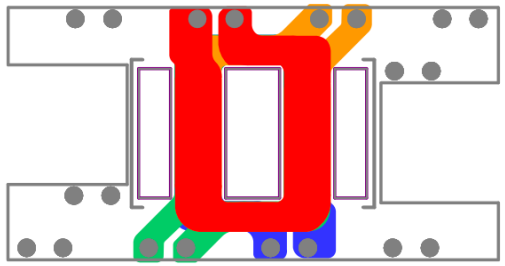


Magnetic Core
(1.8 cm × 1 cm)

Main Power Board
(Thickness: 0.4 mm)

Bottom Cover
(Thickness: 1.2 mm)

- **Main Power Board:**



Four Windings

- **Bottom Cover:**

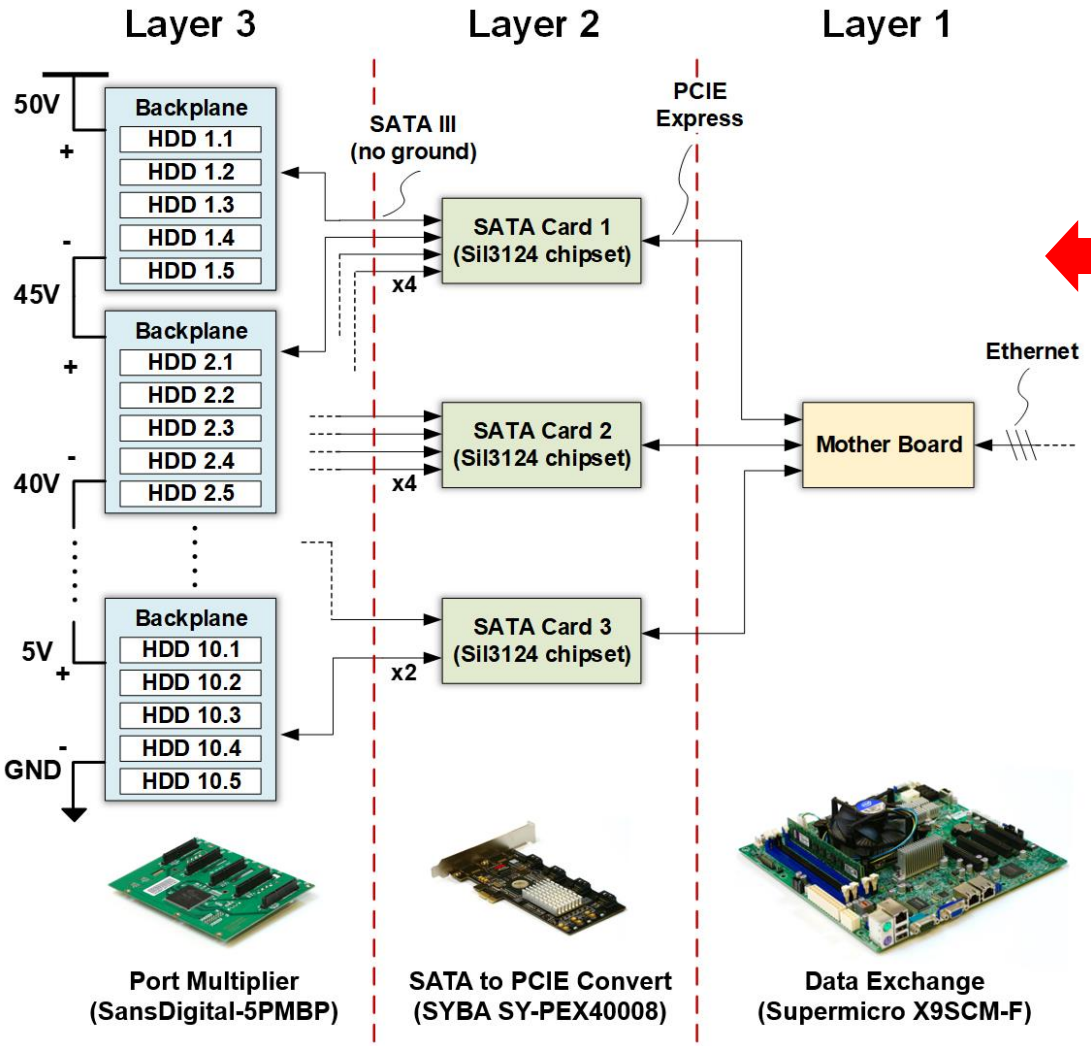
Six Windings

- **Volume:** $(1.57\ \text{in})^2 \times 0.29\ \text{in} = 0.71\ \text{in}^3$
- **Power Density:** $\frac{450\text{W}}{0.71\text{in}^3} = 633\text{W/in}^3$

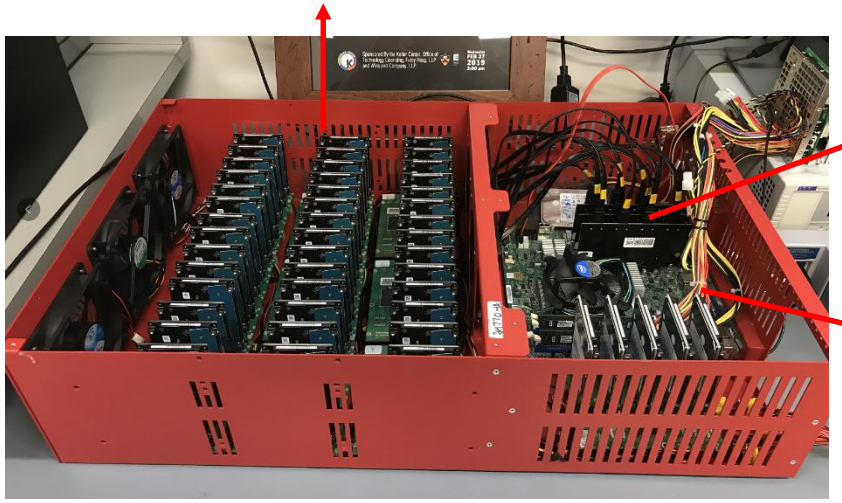
Two-PCB vertical-stacked magnetics design
10x magnetics size reduction

Communication Structure

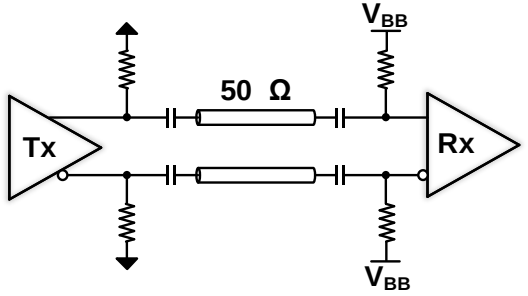
➢ Three-Layer Communication Link



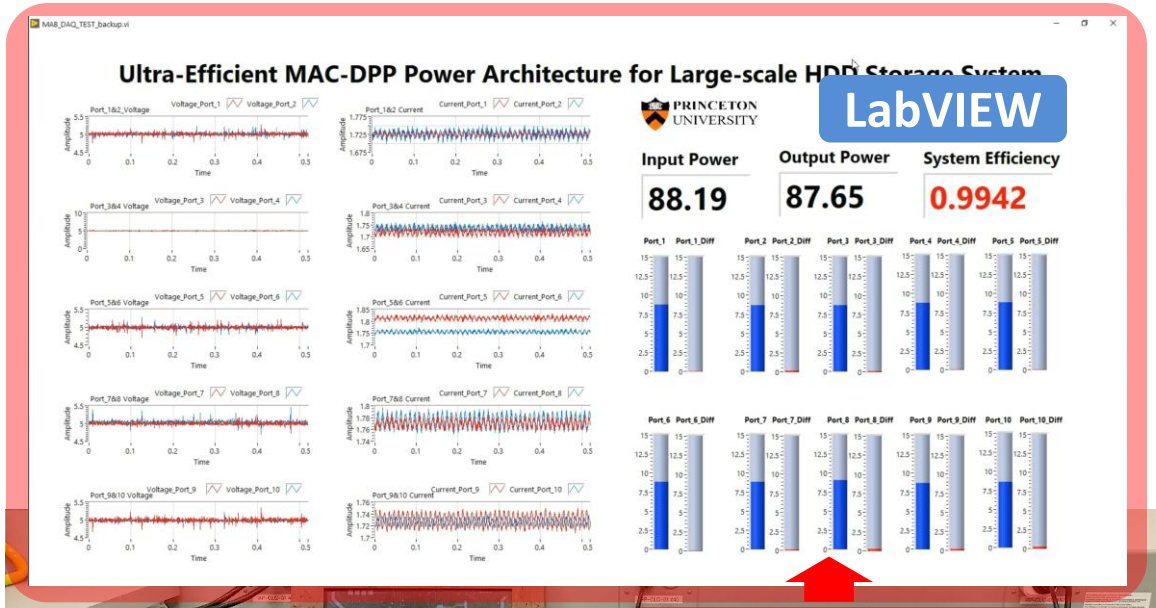
HDD Array with Backplanes

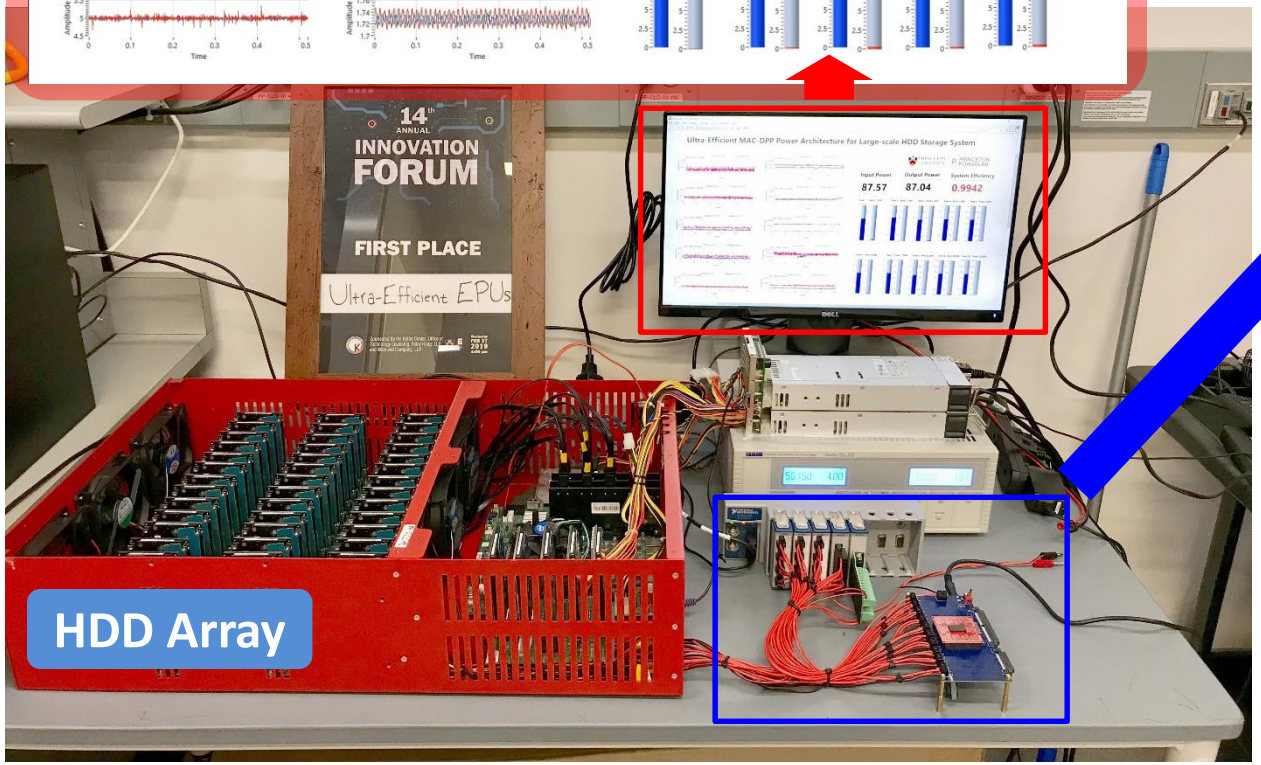


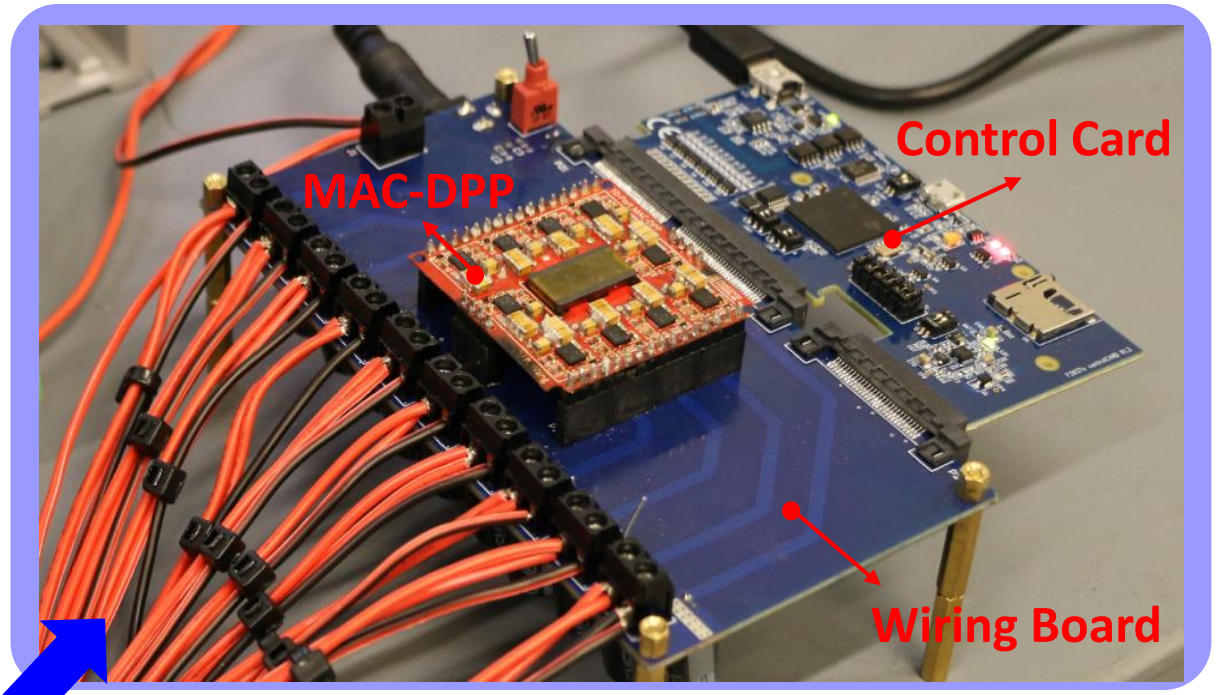
- Five HDDs parallel on one voltage domain
- Standard SATA differential signal with blocking capacitors across different voltage domains
- Tested full reading/writing of HDDs at different voltage domains.



HDD Testbench with DAQ Measurement System





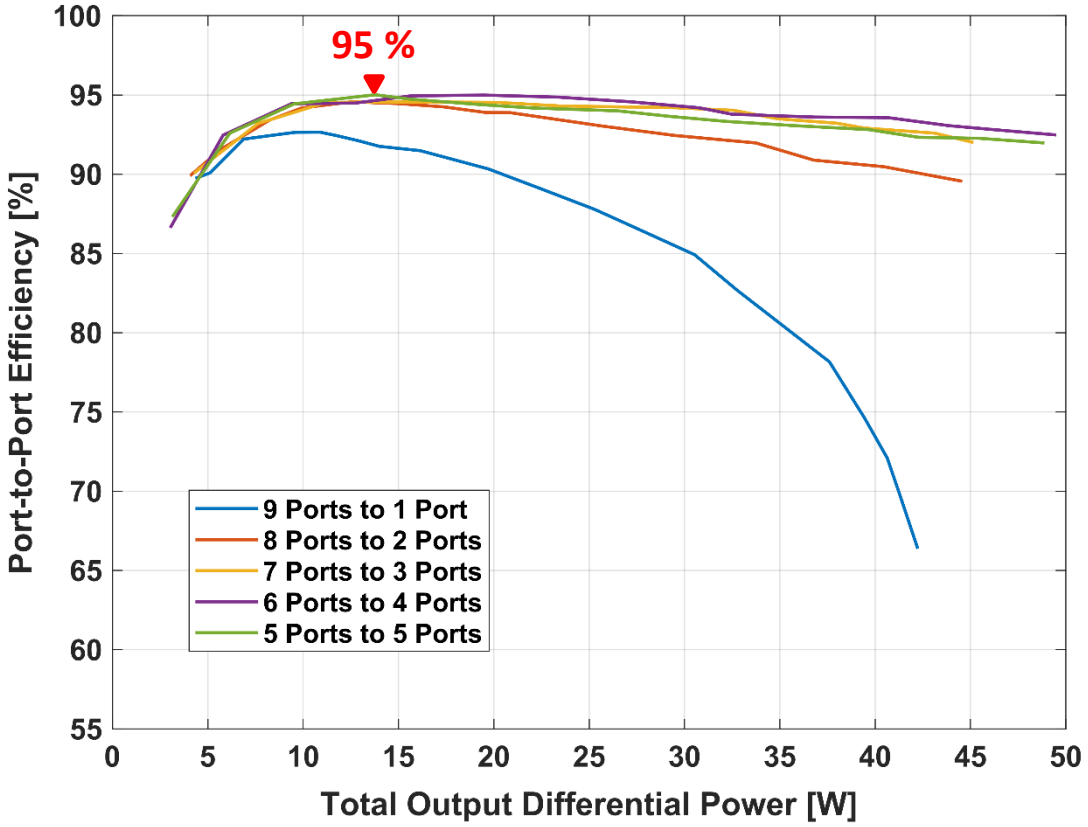


- Tested with Backblaze 50-HDD server
- Power monitoring system with LabVIEW
- Tested full reading/writing, hot-swapping capability of HDDs
- HDD server system efficiency: over 99.4%

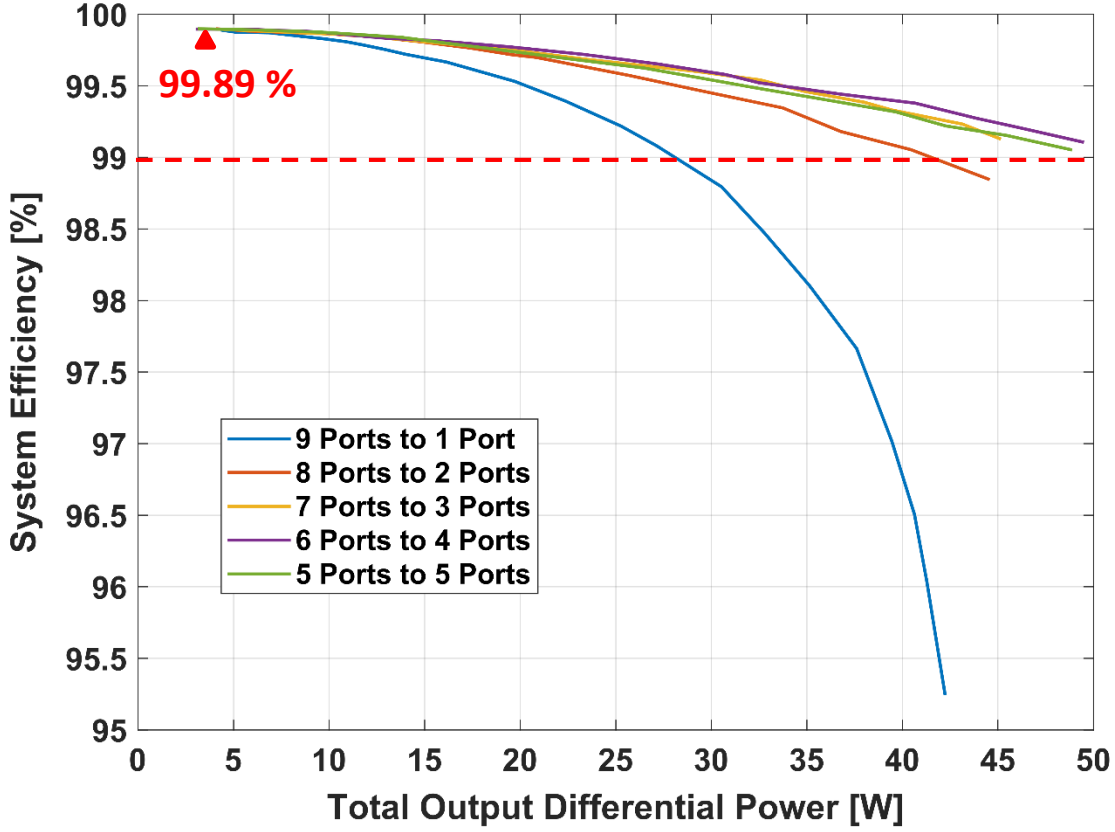
--- Collaborated with Jing Yuan

Efficiency Measurement

- **Port-to-Port Conversion Efficiency**



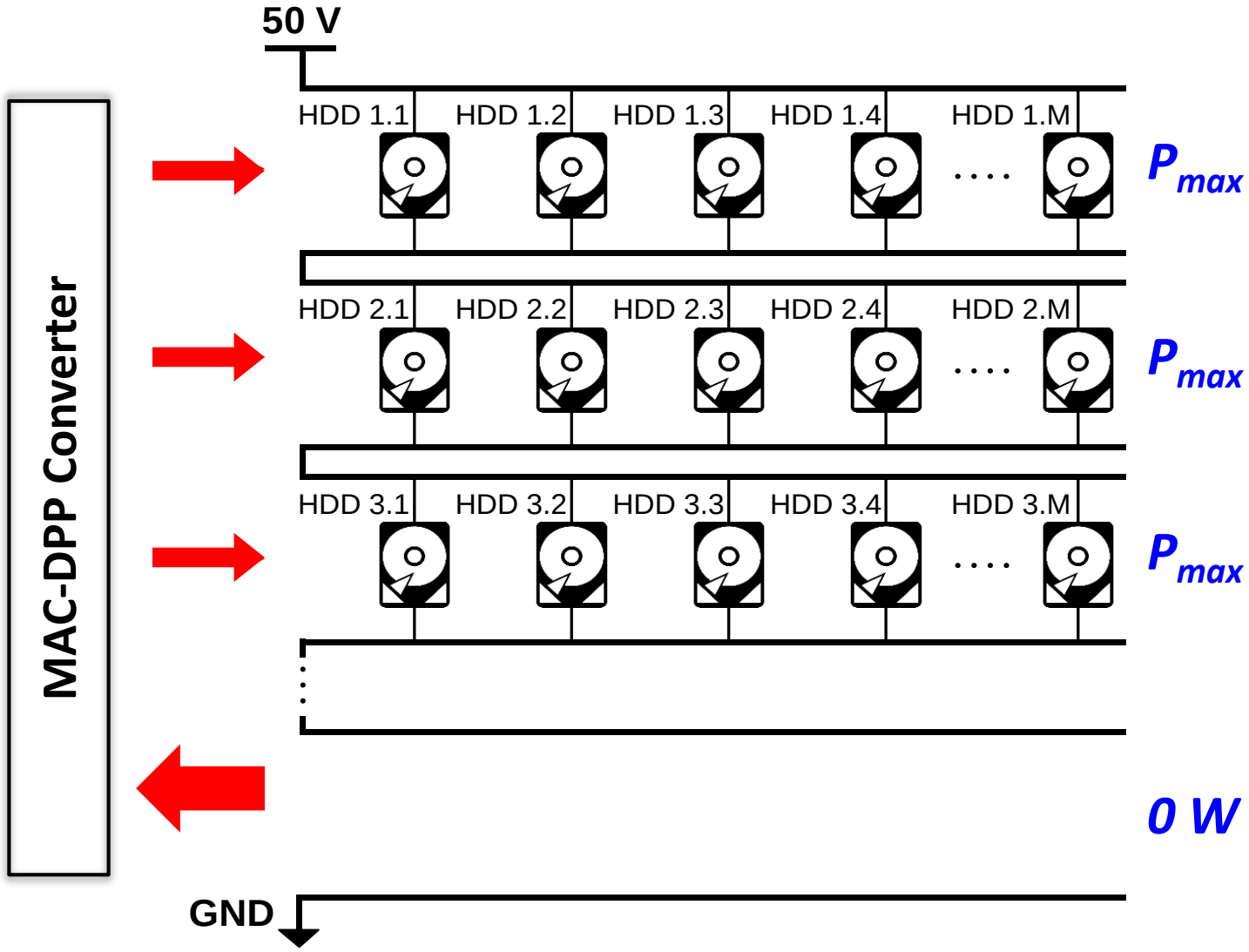
- **System Conversion Efficiency**



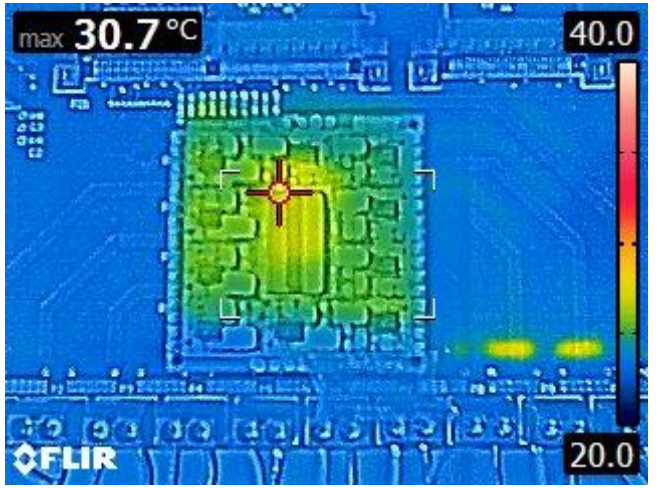
- Achieved 95% peak port-to-port efficiency when delivering 14 W from 5 Ports to 5 Ports
- **Over 99.8% peak system efficiency with 450 W load power**

Hot-Swapping Thermal Image

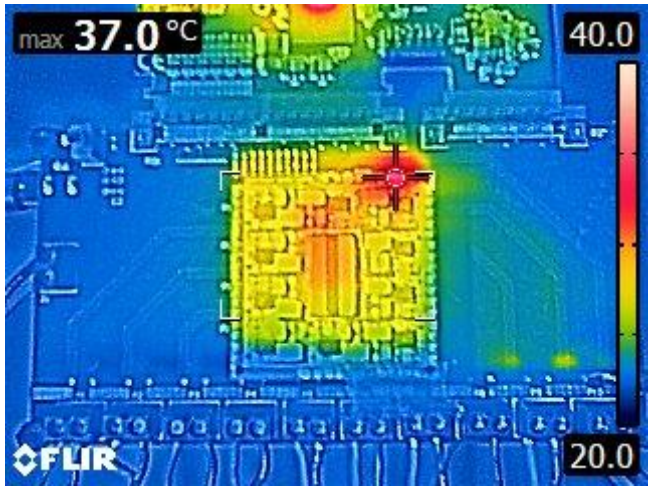
➢ Worst-Case Hot-Swapping Scenario



- ***Normal Operation***



- ***Worst-Case Hot-Swapping***



Hot-Swapping Transient Response

Fig. 25: Transient response when removing all 5 HDDs from one voltage domain (Port #3) at HDD server.

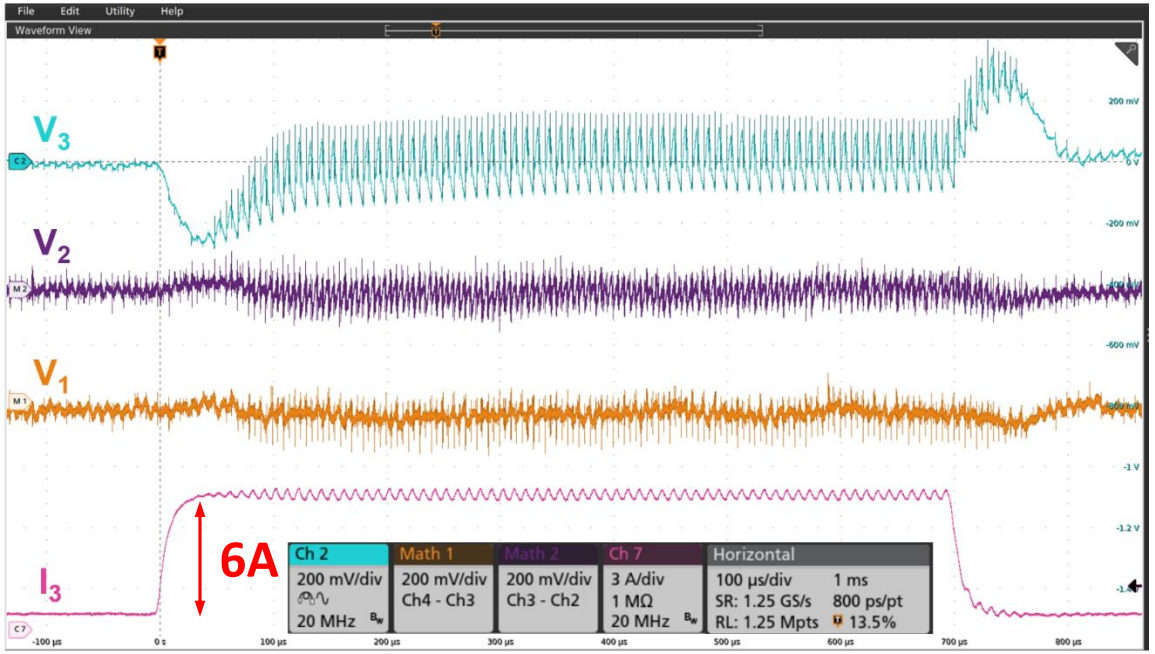


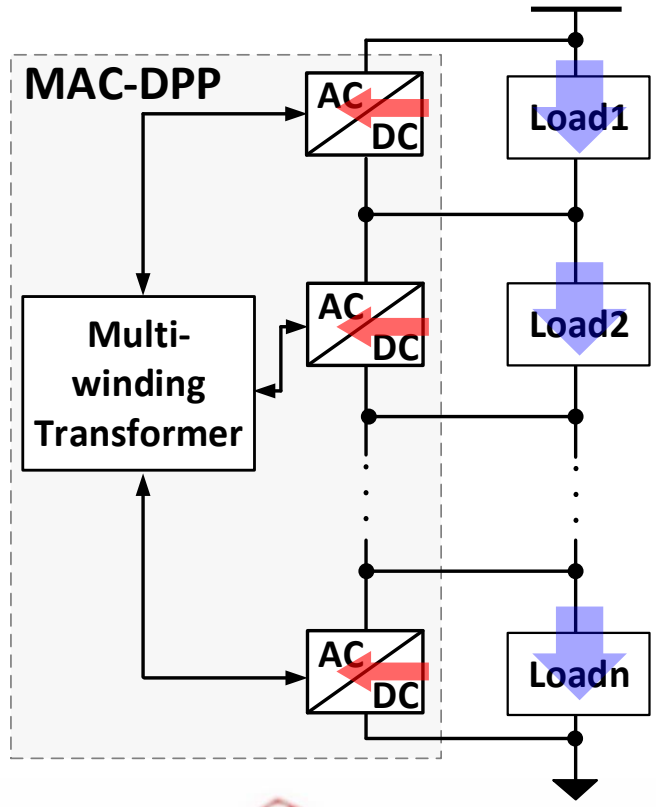
Fig. 26: Transient response of 30 W (6 A) step load change at Port #3.

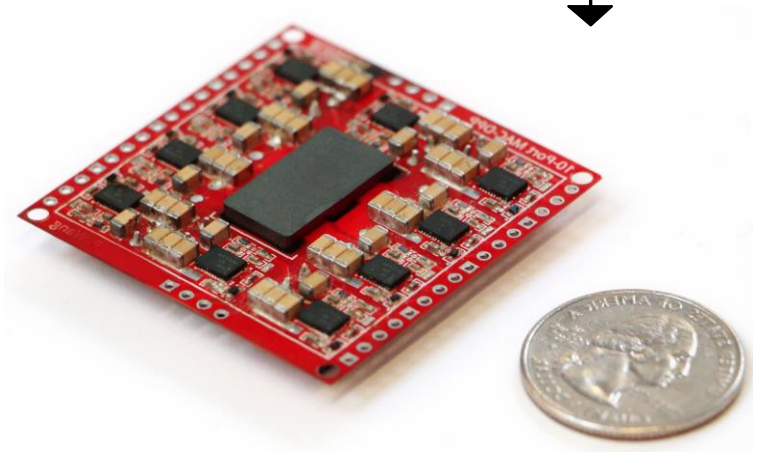
- Worst hot-swapping scenario
- Smooth voltage transient with all other HDDs working normally

- Extreme case considering inrush current of HDD motors
- Settling time less than 100 us
- Overshoot less than 250mV

Summary

- Proposed an ultra-efficient highly-compact MAC-DPP topology for series-stacked modular loads in data centers
- N times magnetics core area reduction; Single dc-ac-dc conversion stage
- Proposed distributed phase-shift control, enabling fully-modular building block
- Designed a 10-port MAC-DPP prototype
- 50-HDD storage server with DAQ measurement system
- **Power rating: Over 450 W**
- **Power density: over 630 W/in^3**
- **HDD Server System efficiency: Over 99.4%**
- Maintained normal reading/writing operation at worst hot-swapping scenario





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