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U.S. Department Of Energy

Power Electronics Program Kickoff

Modular Wide-bandgap String Inverters for Low-cost Medium-voltage Transformer-less PV Systems

Brian Johnson (PI), Daniel Kirschen: University of Washington

Dragan Maksimovic, Robert Erickson: University of Colorado Boulder

Gabsu Seo: National Renewable Energy Laboratory

Kraig Olejniczak: Wolfspeed

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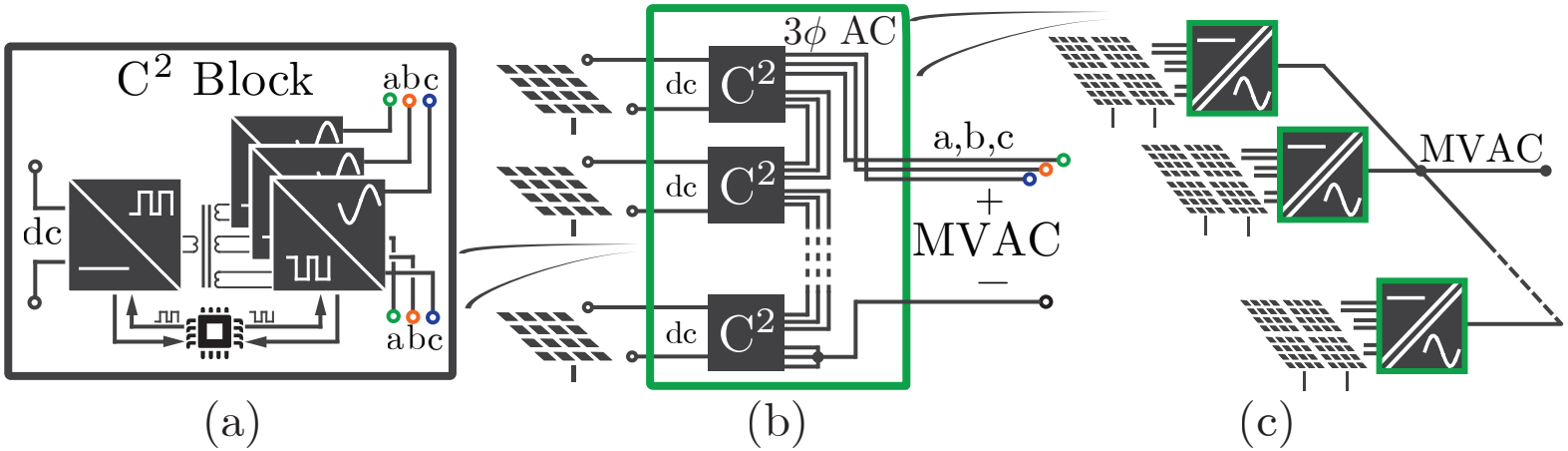
The Main Idea: A Circuits to Systems Approach

- A dc to three-phase ac **C**onverter + **C**ontrol (C^2) building block is proposed
- Each C^2 block performs string-level PV maximum power point tracking
- The ac sides of each C^2 block are cascaded to obtain transformerless utility-scale inverters



Circuit + Controls (C^2) = Building-block

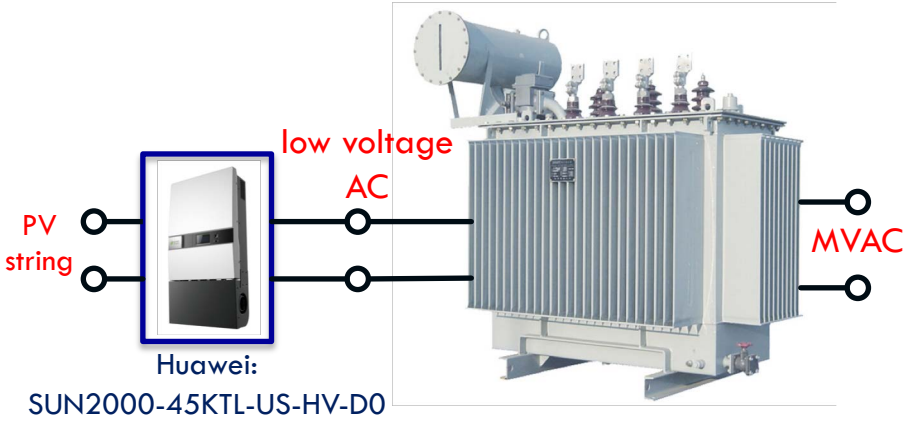
A modular medium voltage transformerless inverter

Ultra efficient and low-cost converters for PV plants

Comparison to State-of-the-Art Utility Inverters

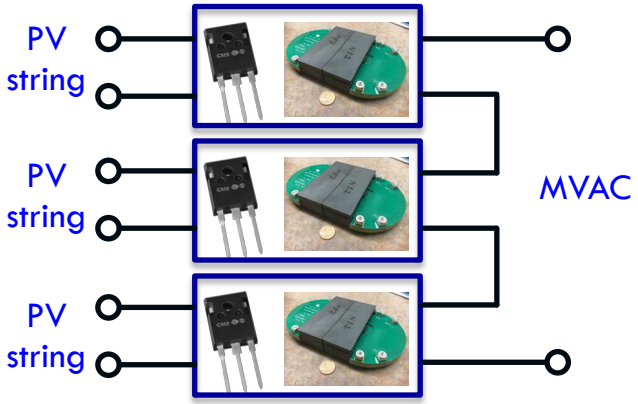
▪ Conventional:

Three-phase string inverters
+ line frequency transformers



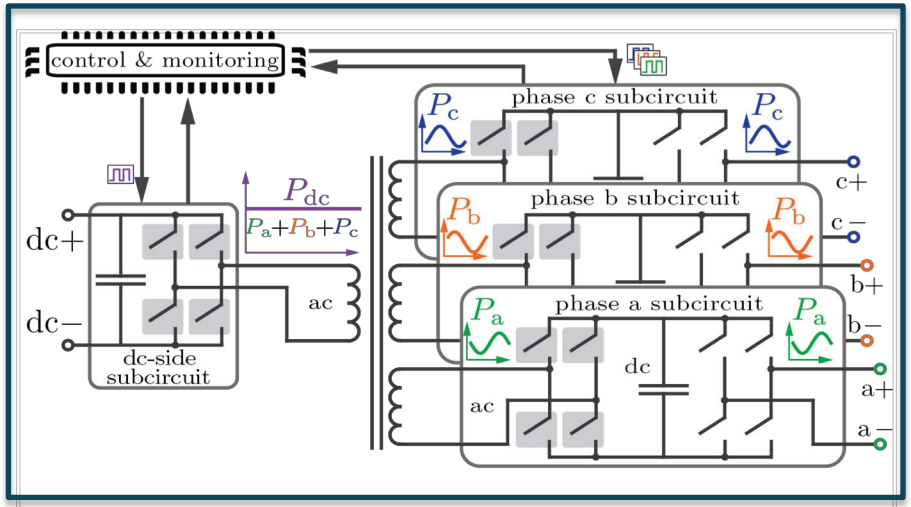
▪ Proposed:

Distributed wide-bandgap electronics
+ high frequency magnetics



Inverter×Transformer peak efficiency	0.983×0.99 = 97.3%	**99.1%**
Inverter×Transformer CEC efficiency	0.982×0.99 = 97.2%	**99.0%**
Inverter Capacitance	10 J/kW	**1 J/kW**
Inverter ac voltage	600 Vac	**13.2 kV ac**
Transformer needed?	Yes	**No**
Inverter isolated?	No	**Yes**

The Building Block



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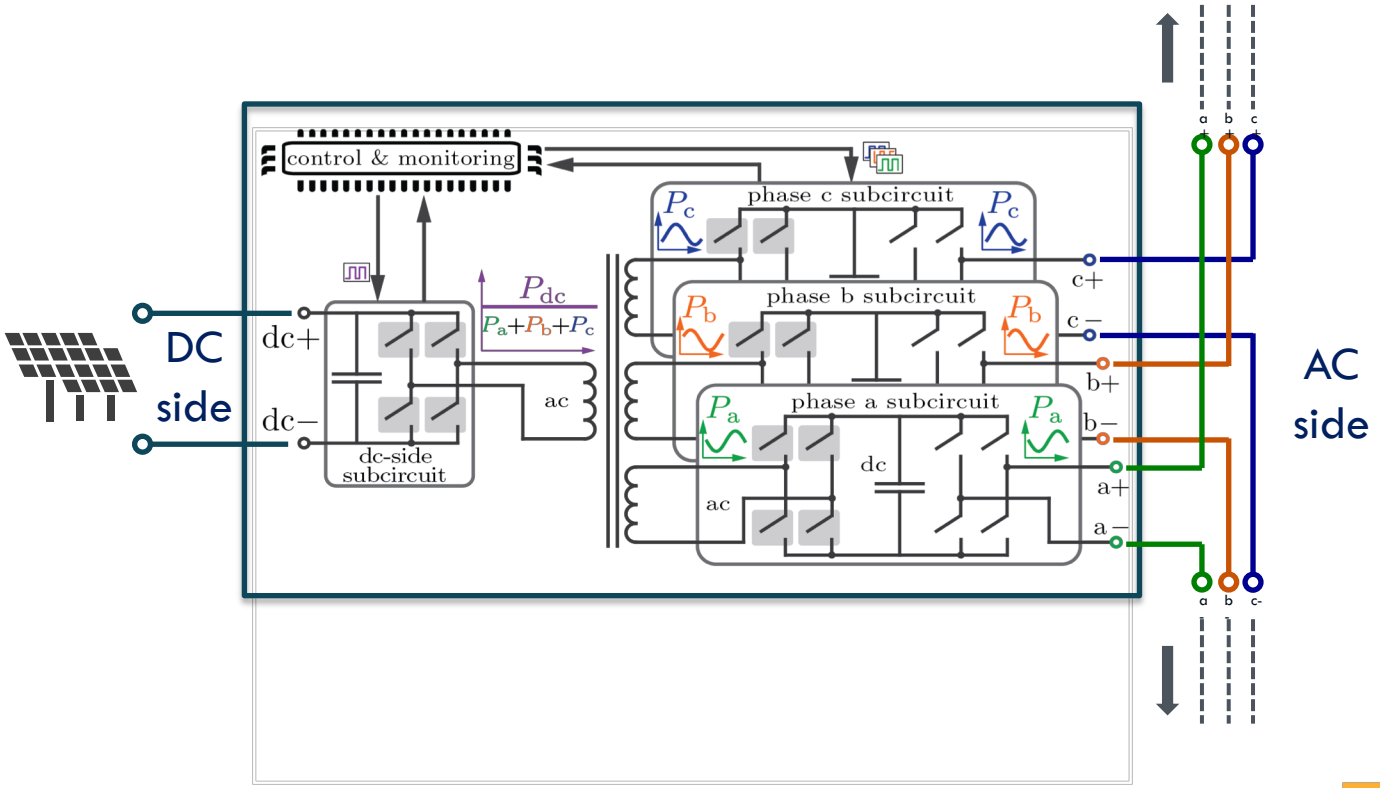
The Building Block

AC side connects to other units in stack



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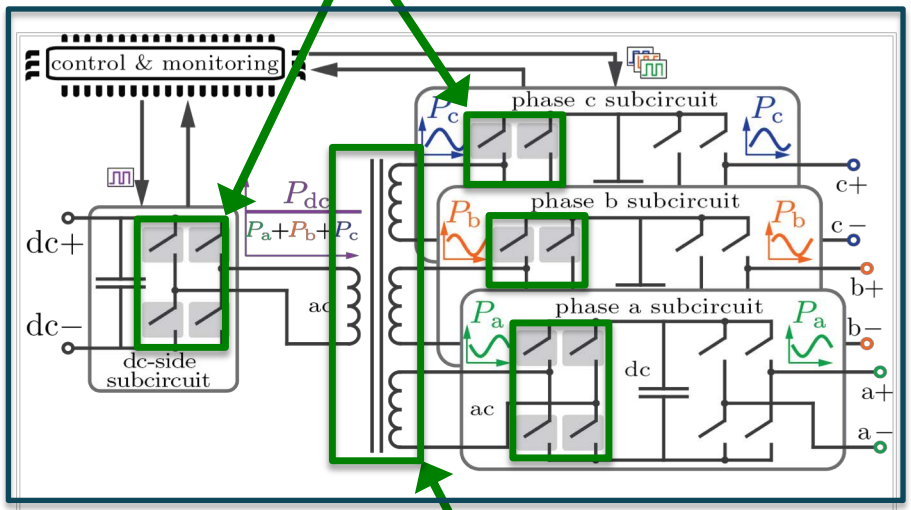
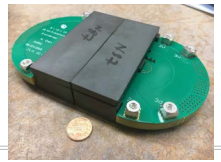
The Building Block: Converter Innovations

Silicon Carbide devices enable:

- Efficient power transfer
- >10x faster switching ⟹ compact magnetics



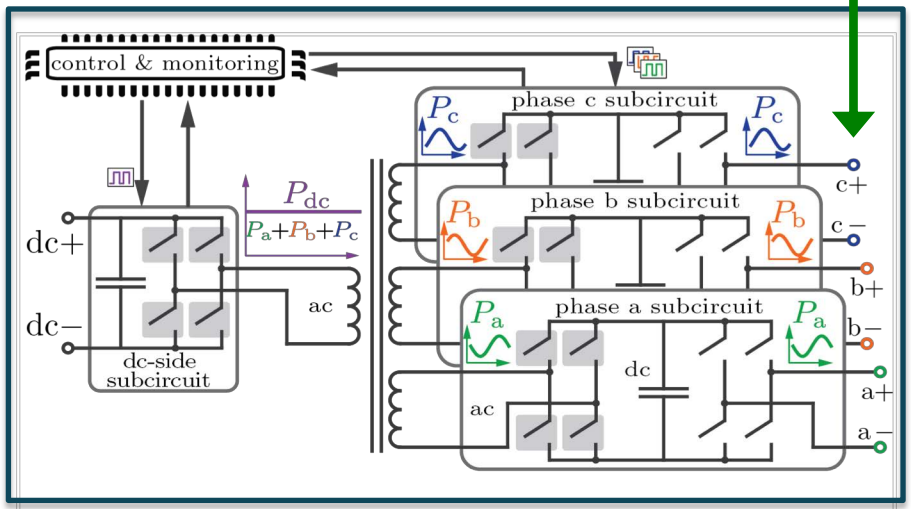


18kW Planar magnetics prototype

The Building Block

Constant power delivery: $P_a + P_b + P_c = P_{dc} = \text{constant}$

- Simplifies controls
- Minimizes capacitive energy storage



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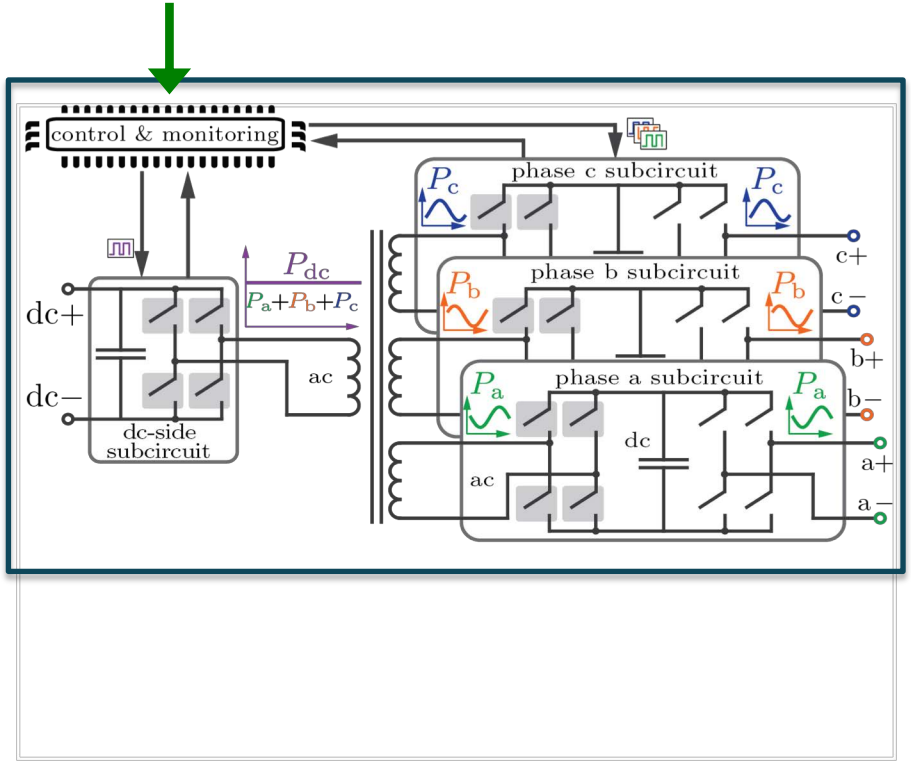
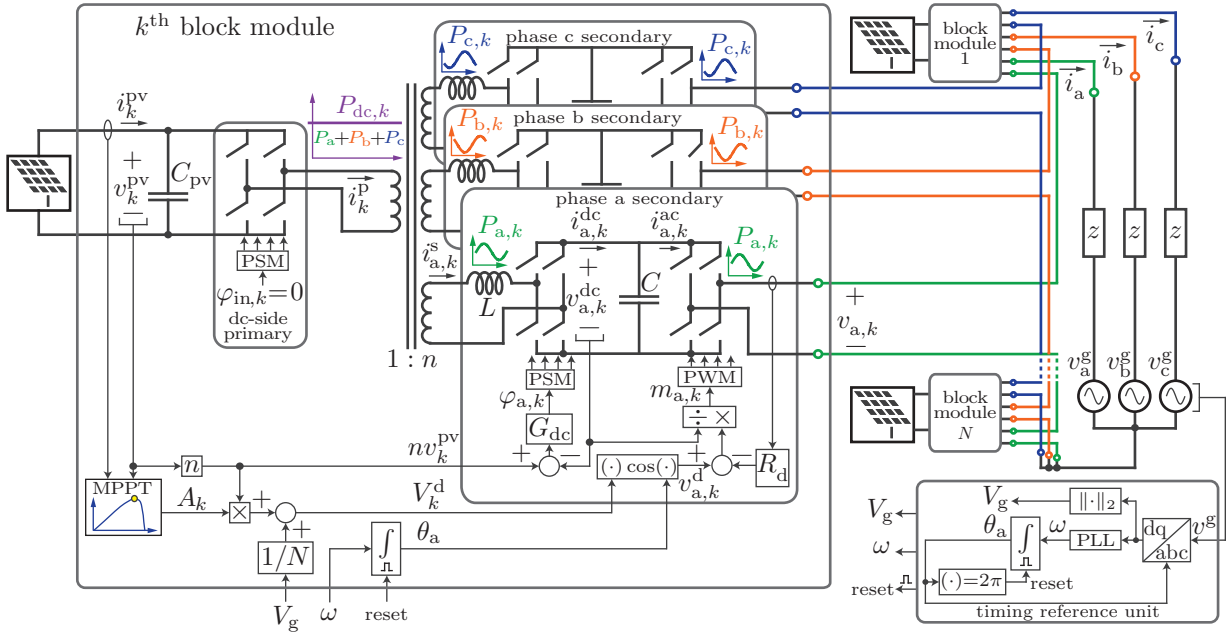
The Building Block

Take a closer look at controls



The Building Block: A Complete Controls Architecture

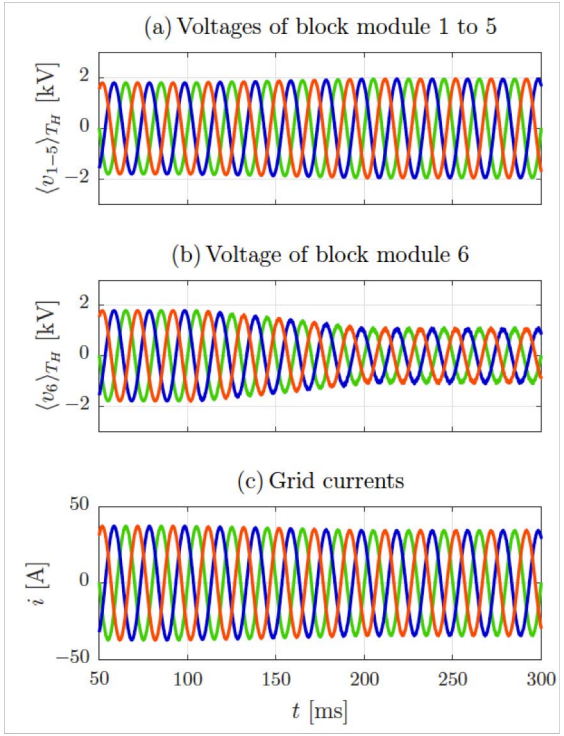


[1] Achanta, Johnson, Seo, Maksimovic, "A multilevel dc to three-phase ac architecture for photovoltaic power plants," in IEEE TEC, 2018.

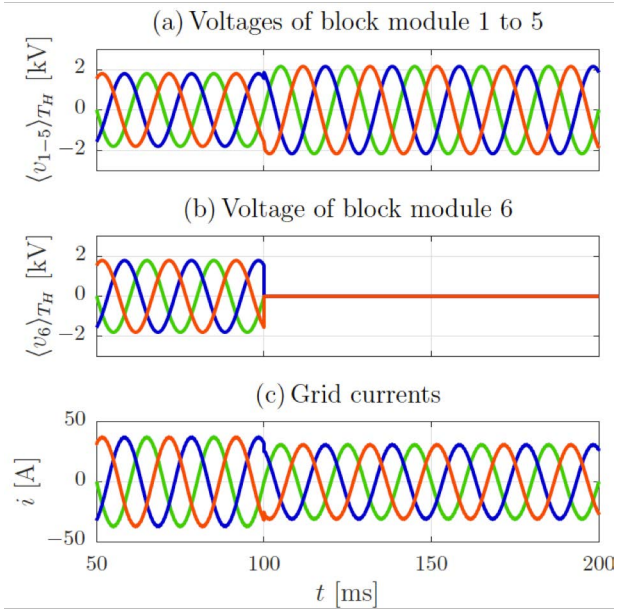
[2] Achanta, Johnson, Maksimovic, "Cascaded quadruple active bridge structures for multilevel dc to three-phase ac conversion," in APEC, 2018.

Decentralized Power Sharing

- Simulations of a 13.2kV, 600kW system with 6 blocks



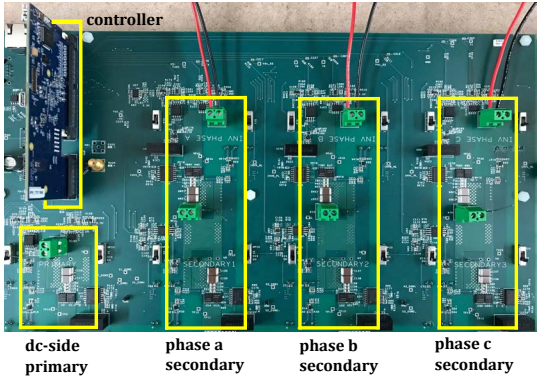
A decrease in power from block #6



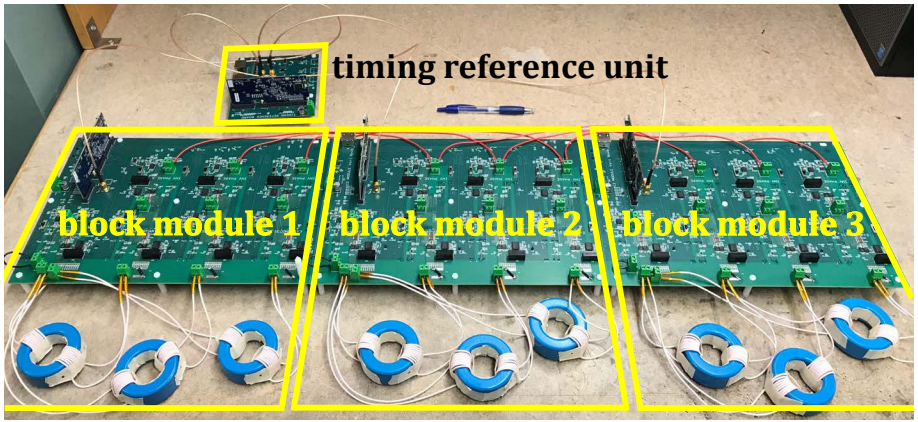
Failure in block #6

Preliminary Experiments

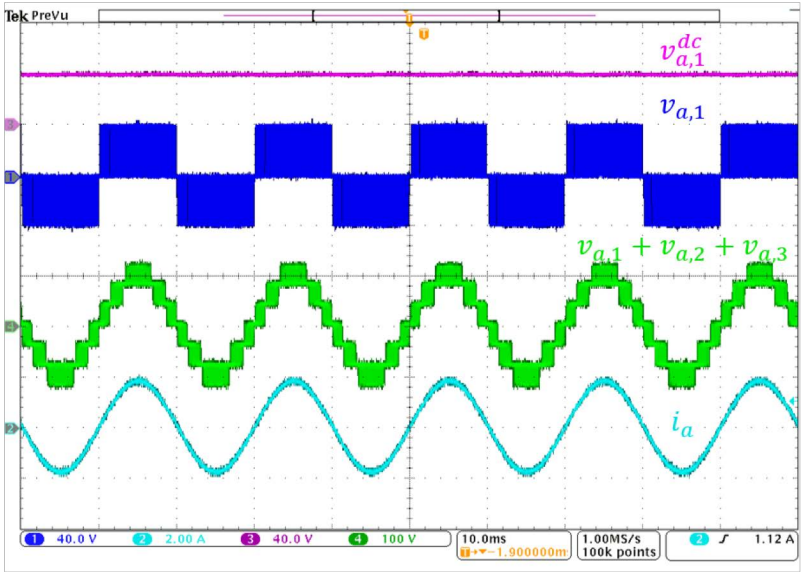
One C^2 module:



Three cascaded blocks:

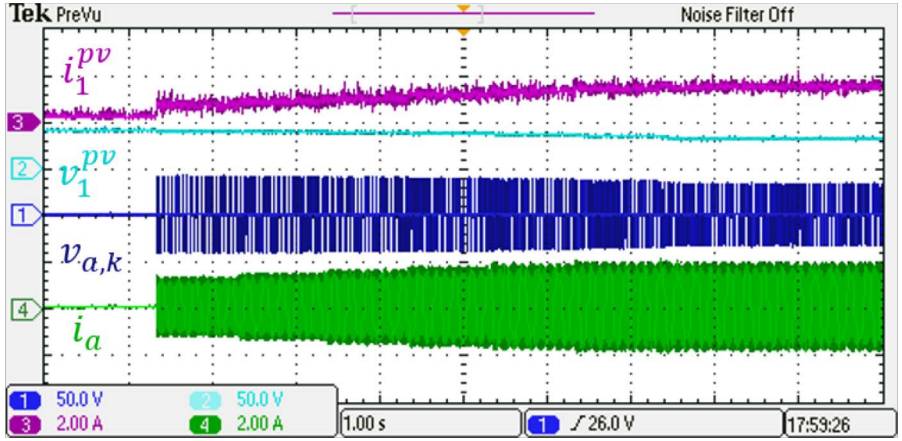


Decentralized Dc-link Controls & Multilevel Waveforms

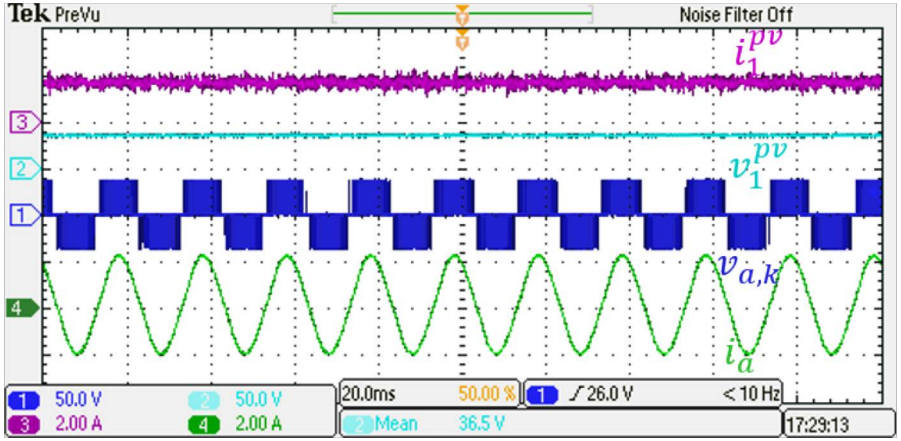


Regulated dc link voltage at block level and multilevel waveforms across stack

Maximum Power Point Tracking



Startup at zero power with PV



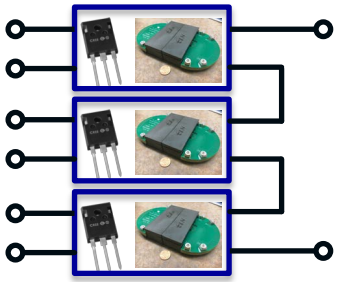
Convergence to maximum power point

An LCOE-driven Optimization Framework

- Challenges:
  - LCOE contains many cost contributions (e.g., BOS, wiring, PV modules, energy)

$$LCOE = \frac{C}{E} = \frac{C_0 + \sum_{t=1}^{t=T} \frac{C_t}{(1+i)^t}}{8760 \cdot P_{rated} \cdot \gamma \cdot \sum_{t=1}^{t=T} \frac{1}{(1+i)^t}}$$

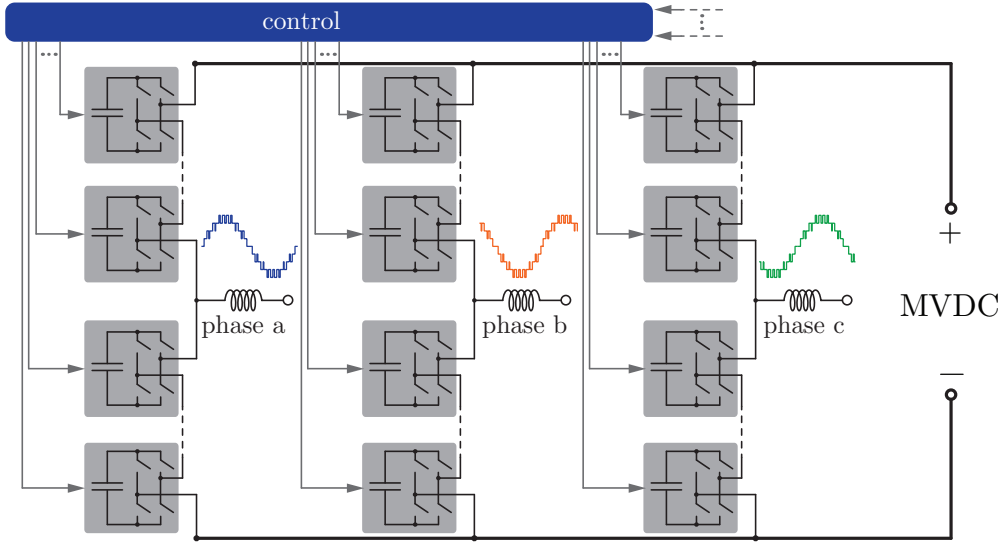
- Our Approach:
  - Compute "relative cost improvement" in comparison to state of the art benchmarks
  - Proposed optimization framework clearly ties converter design choices to LCOE impacts



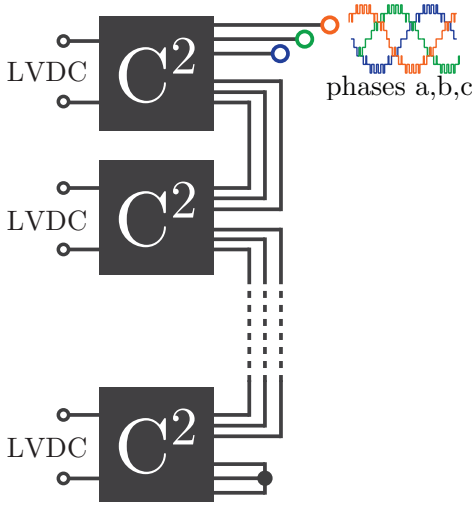
Design for lowest LCOE

State-of-the-Art Medium/High Voltage Converter Systems

- Existing: "Modular Multilevel Converter" (MMC)



- Proposed: Cascaded C^2 blocks



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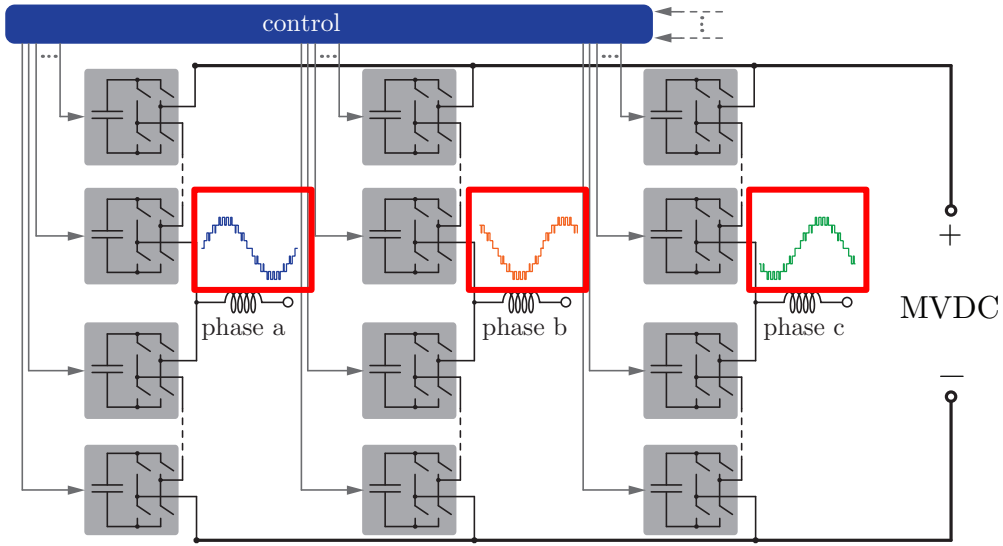
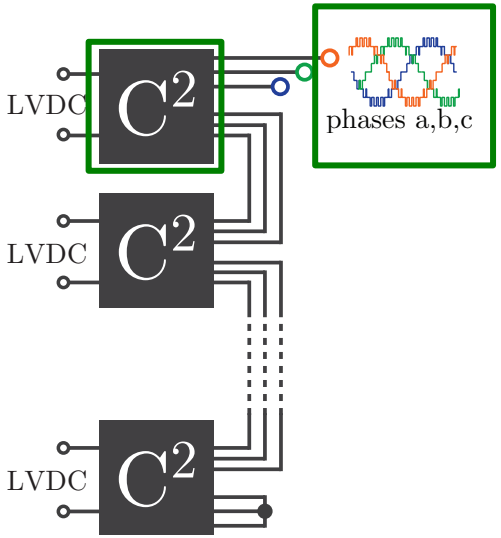


x Pulsating single phase power for each stack

- Proposed: Cascaded C^2 blocks



✓ Constant power transfer

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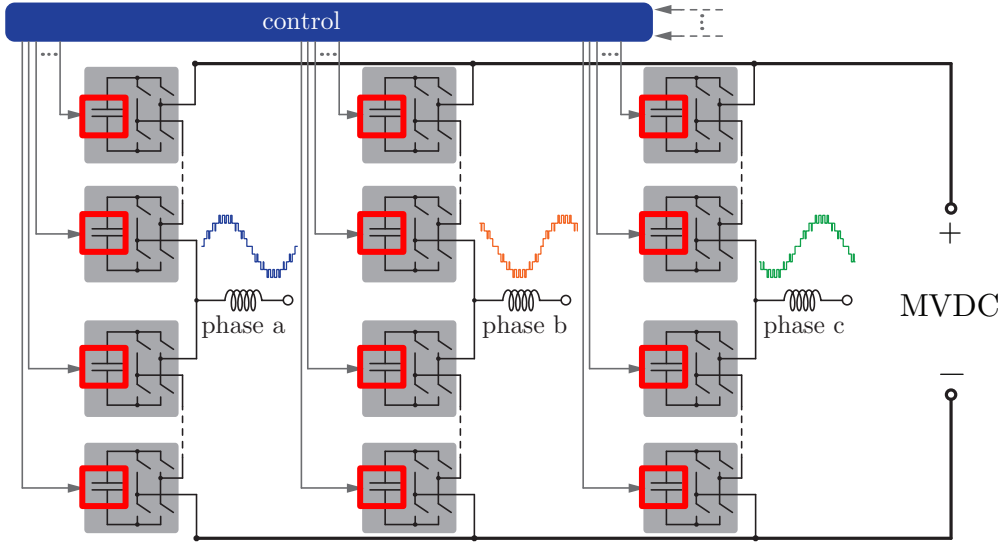

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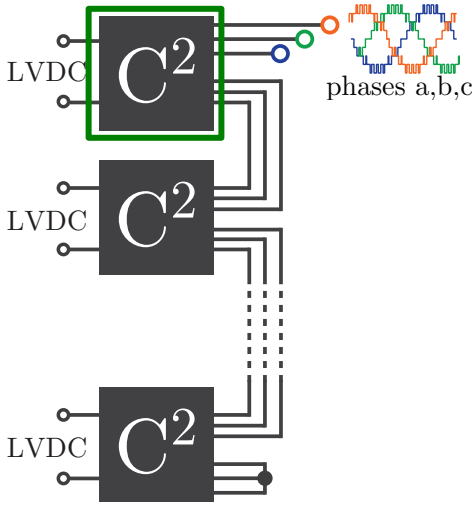
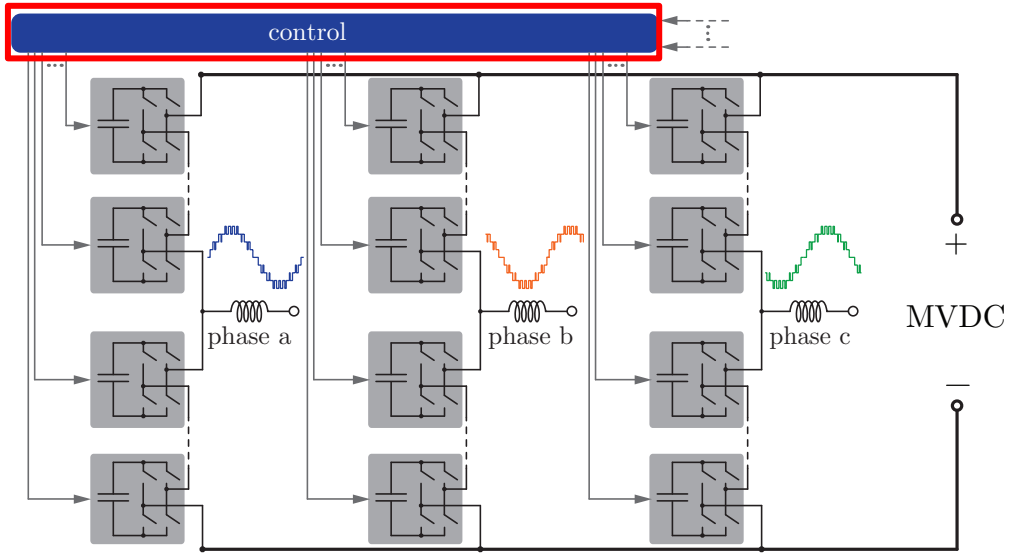


- x Pulsating single phase power for each stack
- x Large capacitor banks needed
- ✓ Constant power transfer
- ✓ Minimal capacitance needed

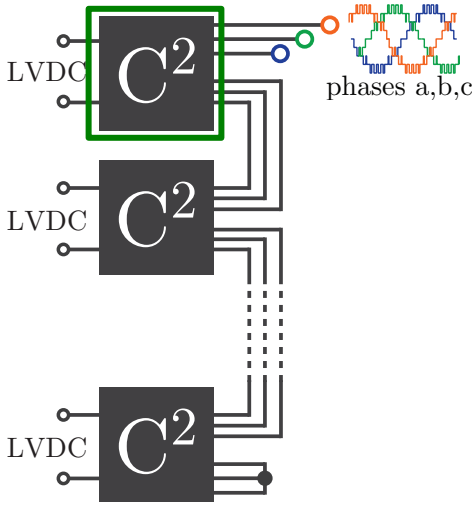
State-of-the-Art Medium/High Voltage Converter Systems

- Existing: "Modular Multilevel Converter" (MMC)



- x Pulsating single phase power for each stack
- x Large capacitor banks needed
- x Centralized capacitor balancing controls

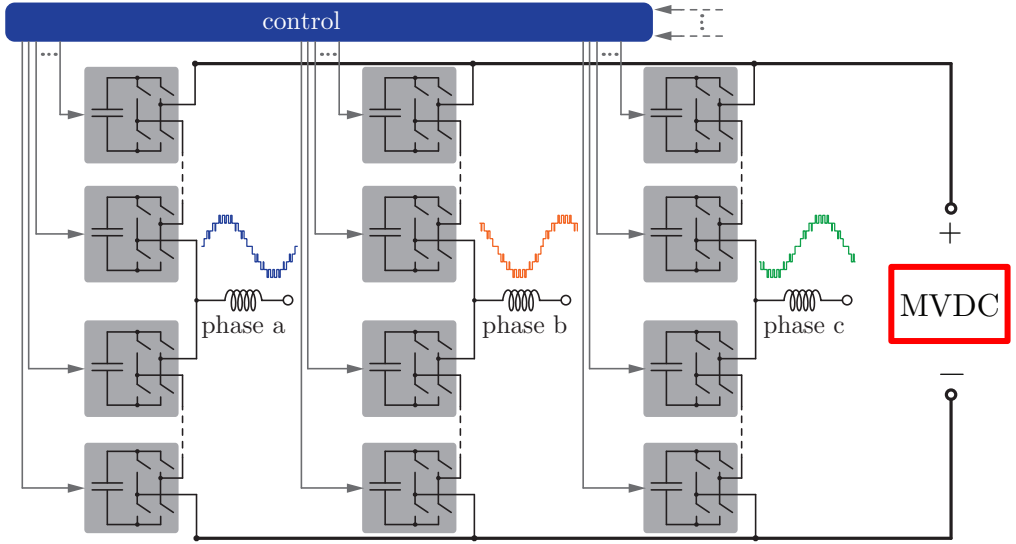
- Proposed: Cascaded C^2 blocks



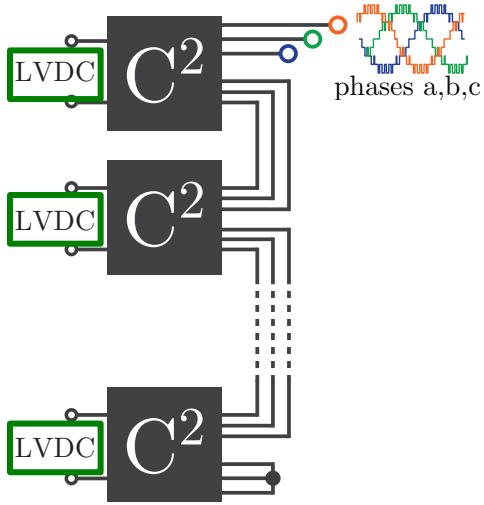
- ✓ Constant power transfer
- ✓ Minimal capacitance needed
- ✓ Streamlined controls

State-of-the-Art Medium/High Voltage Converter Systems

- Existing: "Modular Multilevel Converter" (MMC)



- Proposed: Cascaded C^2 blocks



- x Pulsating single phase power for each stack
- x Large capacitor banks needed
- x Centralized capacitor balancing controls
- x Medium voltage dc input voltage needed

- ✓ Constant power transfer
- ✓ Minimal capacitance needed
- ✓ Streamlined controls
- ✓ Low voltage dc (LVDC) supported

Timeline and Objectives

Formulate optimal design

$$\underset{\Delta\gamma,\Delta C_0}{\text{maximize}} \quad \frac{\Delta\gamma}{\gamma} + \frac{\Delta C_0}{C} - \frac{\Delta\gamma}{\gamma}\cdot\frac{\Delta C_0}{C}$$

Create **low voltage** testbed to develop/validate controls

G/NG: DC link control

Build **13.2kV** consisting of 6 cascaded C^2 blocks

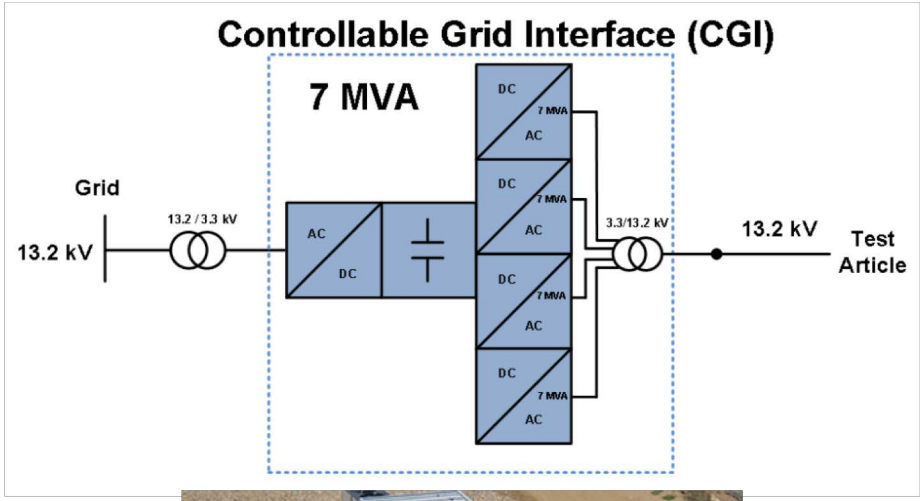
G/NG: Medium voltage isolation

Validate medium voltage system on NREL's CGI

MVAC system w/ >98.5% CEC efficiency

Year 1 | Year 2 | Year 3

Demo on NREL's Controllable Grid Interface



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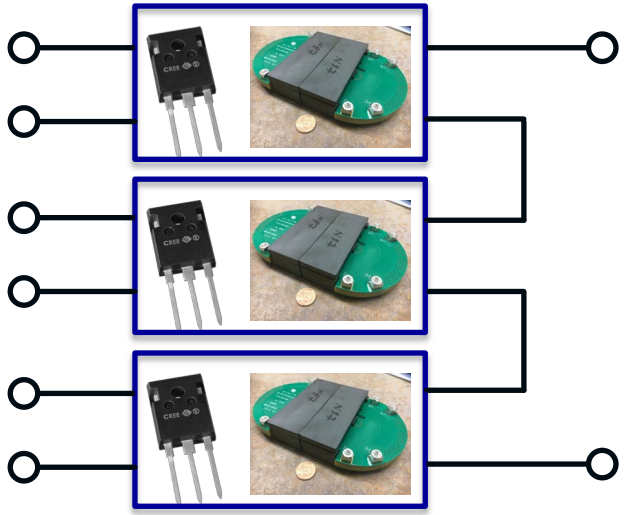

Anticipated Outcomes

- First medium voltage demonstration of C^2 technology
- Lowest LCOE design and accompanying design framework
- Suite of intellectual property + publications
- A comprehensive market competitiveness comparison
- Industry Advisory Board + final workshop will pave path to adoption

Thanks for your attention!