SAND2022-5944C

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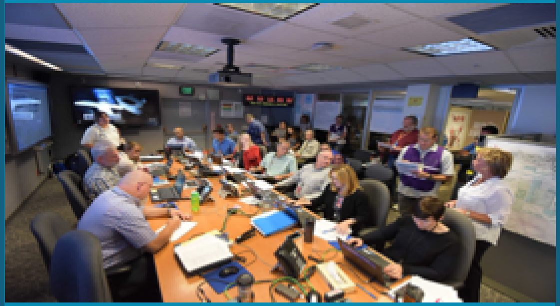
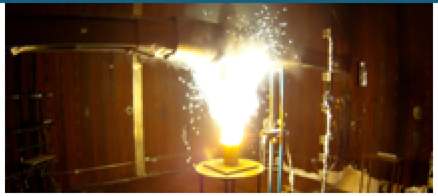
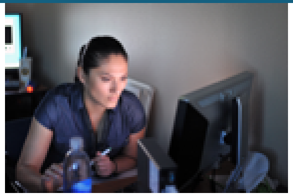
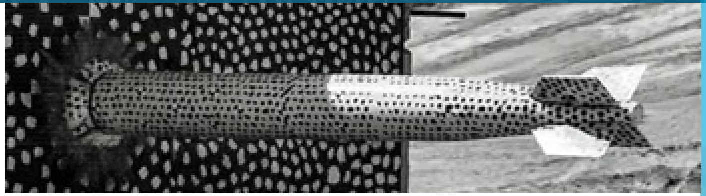
Energy Redistribution in Response to Thermal Runaway









PRESENTED BY

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Energy Storage Safety and Reliability Forum
May 4, 2022

U.S. DEPARTMENT OF ENERGY NNSA

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Critical Assessment of Conventional Power Conversion Approach

The Good

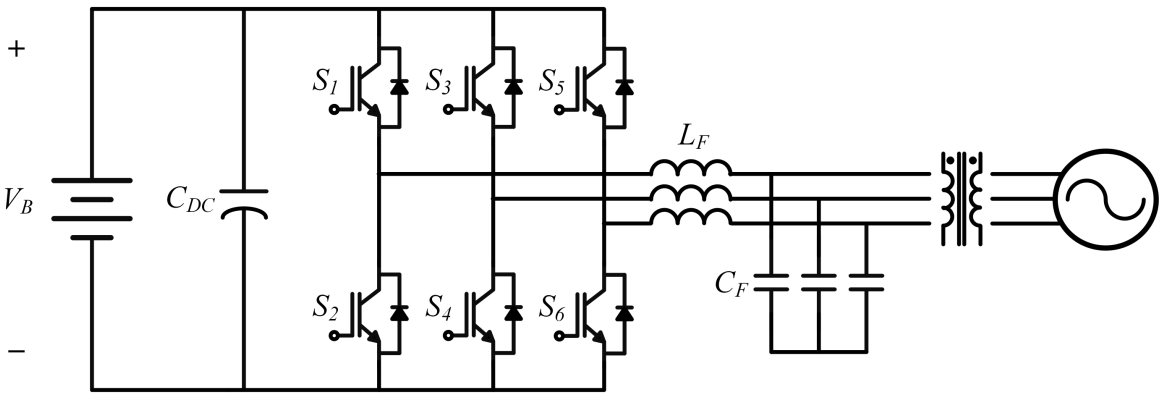
- \+ Simplicity: Simplest possible converter topology
- \+ Price: Lowest capital cost

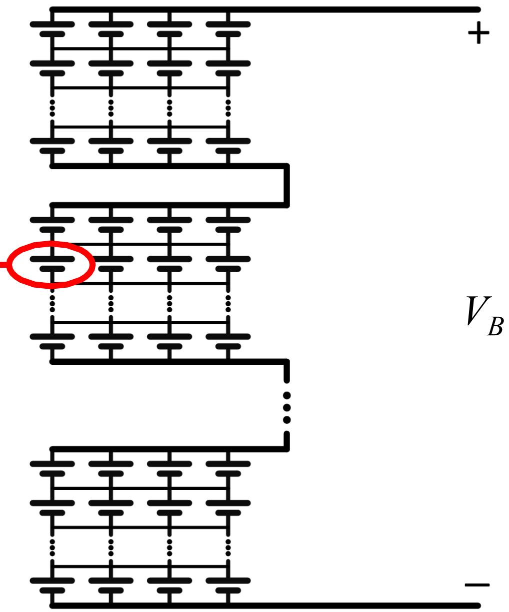
The Bad

- – Scalability: Storage system must be designed around min and max DC link voltage constraints
- – Flexibility: All storage devices must be identically matched or performance degrades
- – Storage Utilization: Effective power/energy of series-connected cell strings is limited by the weakest cell
- – Wasted Silicon: DC link voltage variation with SOC and system age leads inexorably to poor converter utilization
- – Reliability: Every cell in a series-connected string is a single point of failure

The Very Bad

- X The severity of these deficiencies increases as DC-link voltage increases
- X To achieve higher power, need higher working voltage
- X So the cost of a small increase in power capacity is a massive hit to efficiency, reliability, storage device utilization, and more





If this cell needs to be replaced, what happens to the rest?

Multi-Stage Power Conversion Structures

The increasing role of energy storage in grid operation will eventually require more **scalable**, **flexible**, and **fault tolerant** power conversion systems.

There are many candidate topologies, but all share one thing in common: **more granular control over storage resources**.

When we have these systems in place, **how can we use them to improve safety and reliability**?

Modular system architecture, plug-and-play replacement of DC-DC converter modules

Potential for fault-tolerance at the module-level, elimination of (most) single points of failure

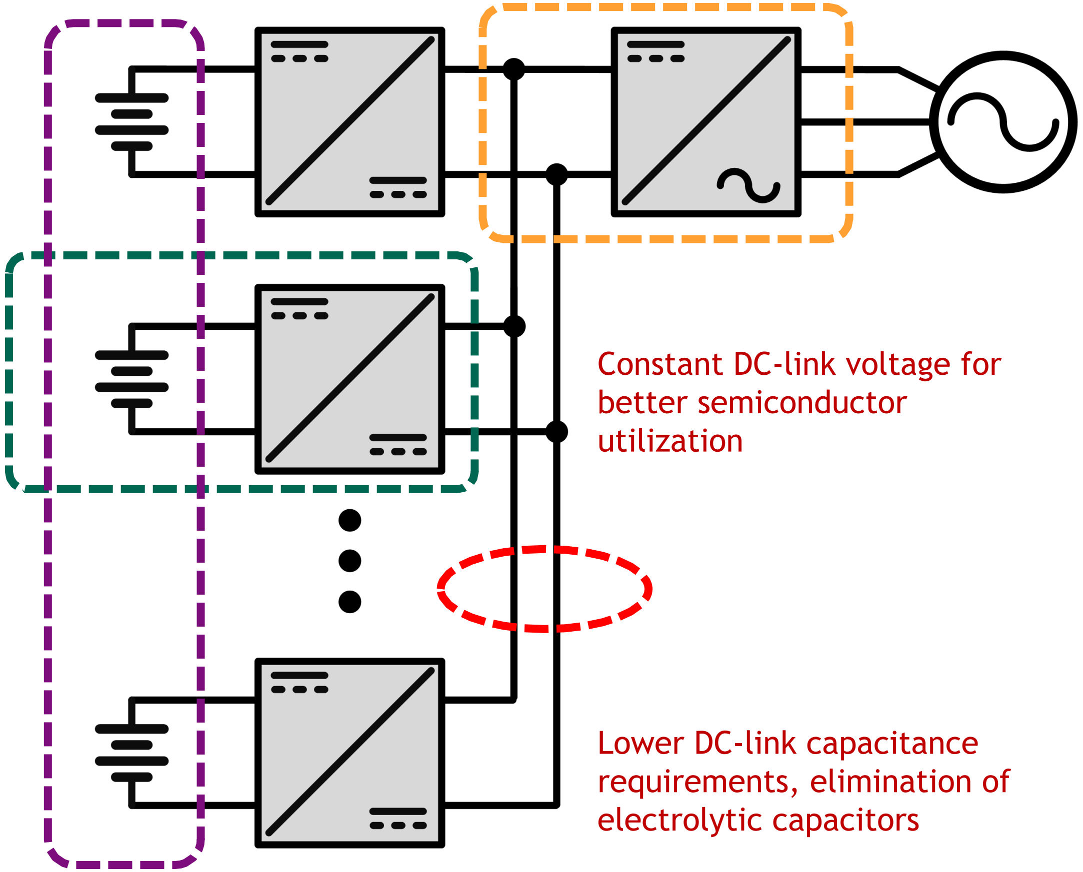
Non-uniform storage systems (e.g. second-life batteries, hybrid storage)

More effective ripple current suppression

Support for long-term evolution of storage device technologies

Multi-level inverters for DC-AC conversion at higher power, higher efficiency, better power quality

Elimination of line frequency transformers



Constant DC-link voltage for better semiconductor utilization

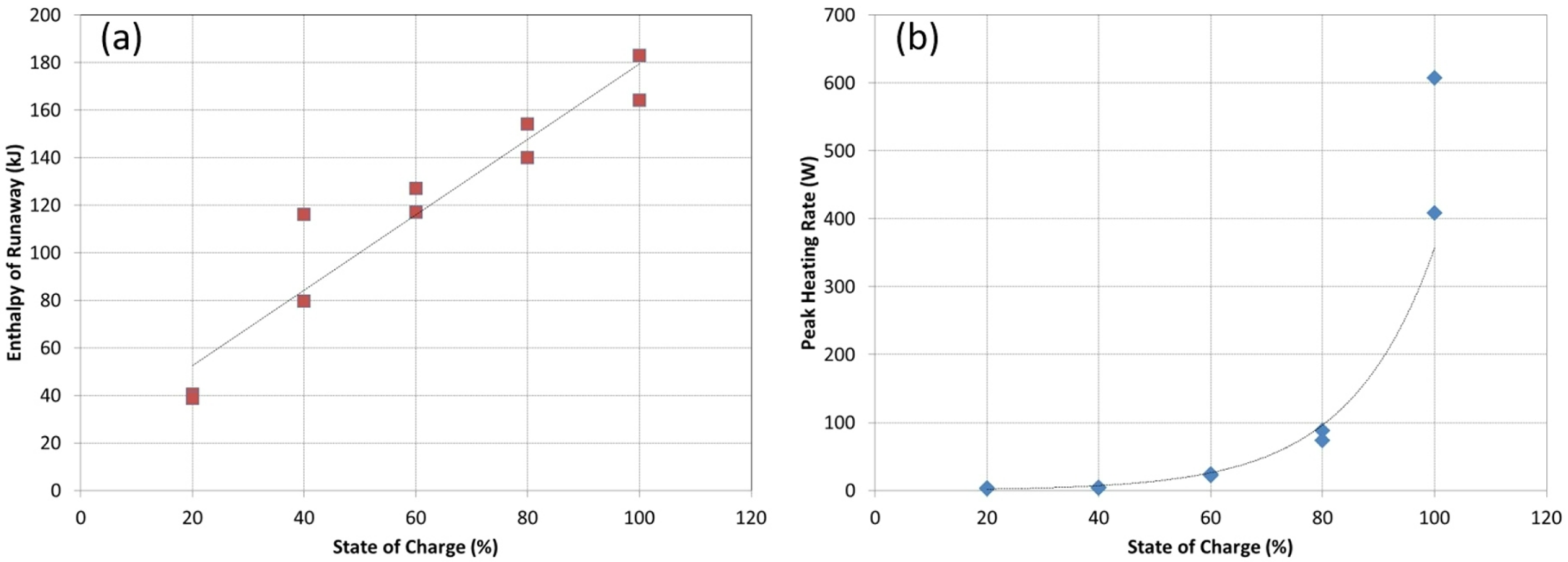
Lower DC-link capacitance requirements, elimination of electrolytic capacitors

Factors Influencing Thermal Runaway

What determines the severity of a thermal runaway event?

- Total energy released
- Rate at which energy is released
- Module-to-module thermal conductance versus heat dissipation

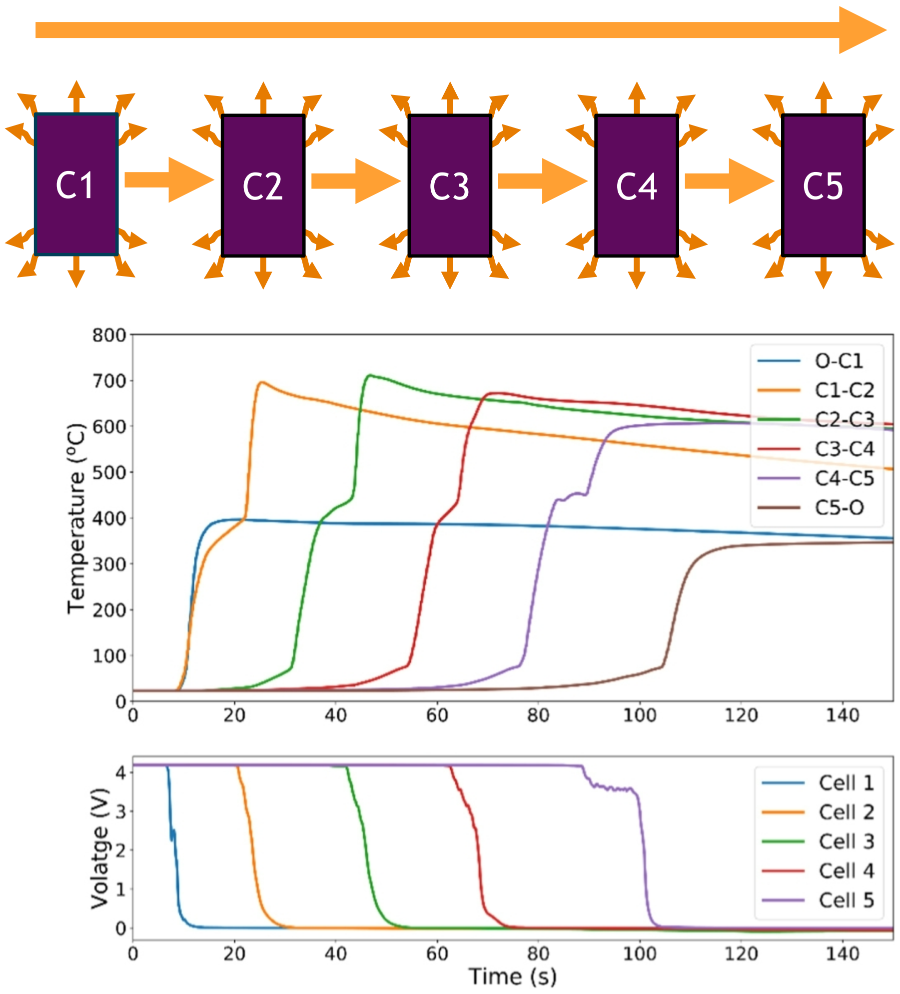
First two depend on state of charge, last on system design.



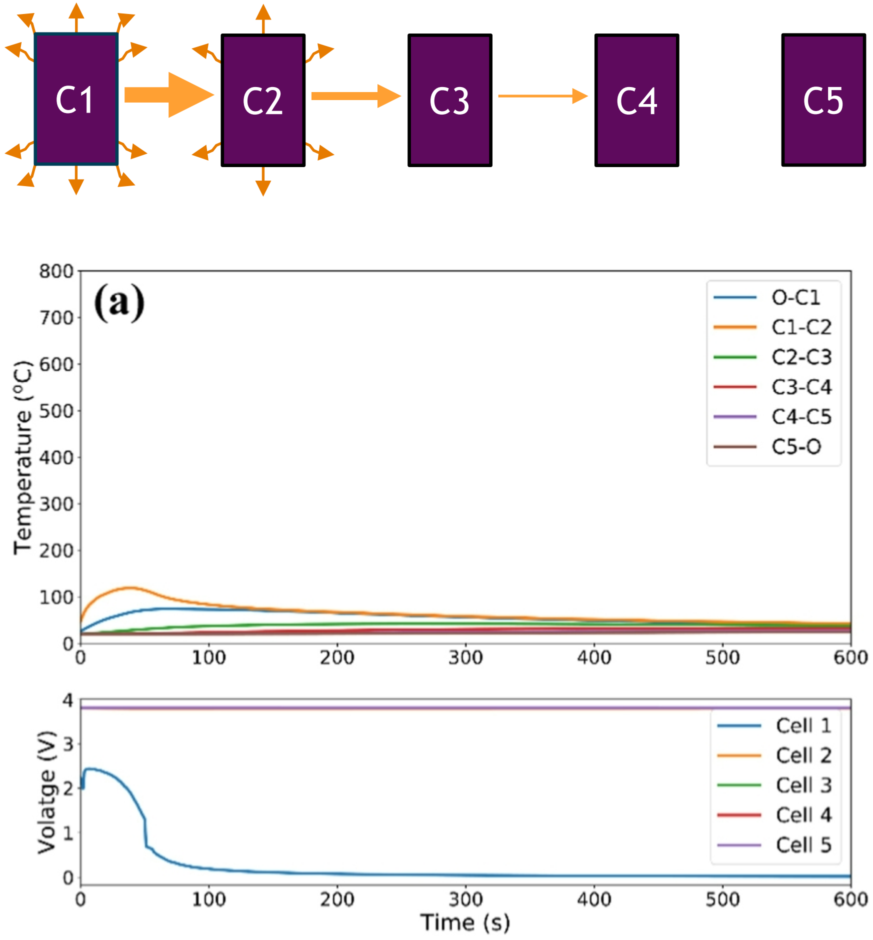
Lamb et al., *J. Electrochem Soc.*, 2021

Propagation and Mitigation of a Thermal Runaway Event

Propagation for cells at 100% SOC

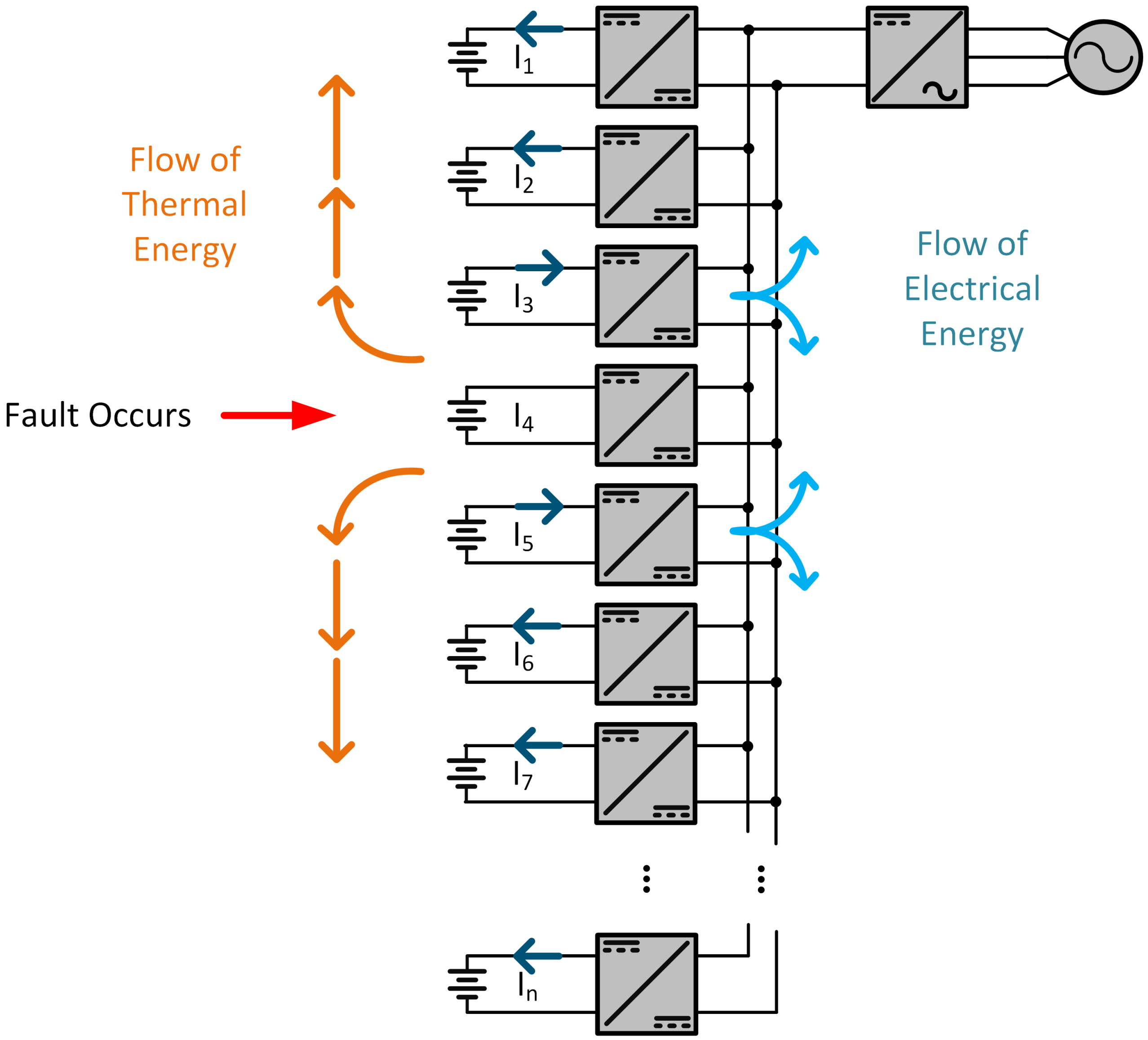


Mitigation for cells at 50% SOC

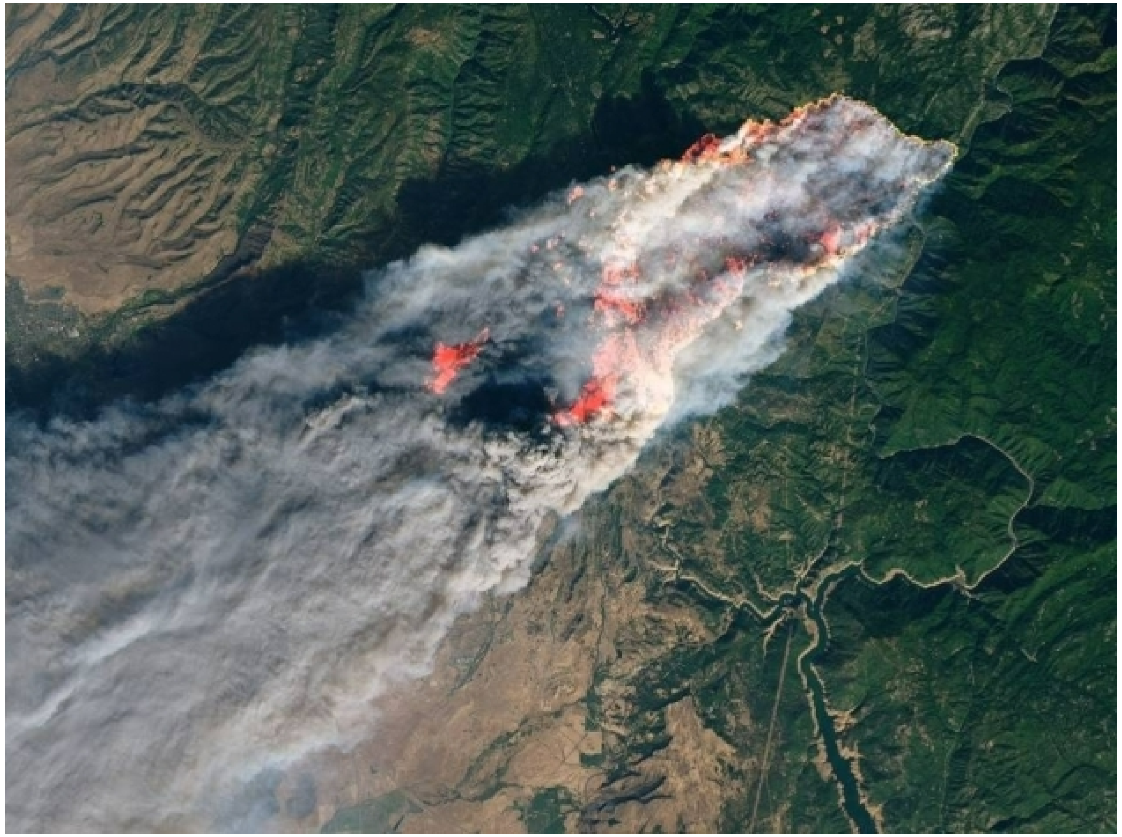


Torres-Castro et al., *J. Electrochem. Soc.*, 2020

Energy Redistribution



Wildfire Analogy



Propagation of a wildfire front depends on fuel

A firebreak is formed by removing the available fuel in the pathway of the fire

Where do you put the firebreak?

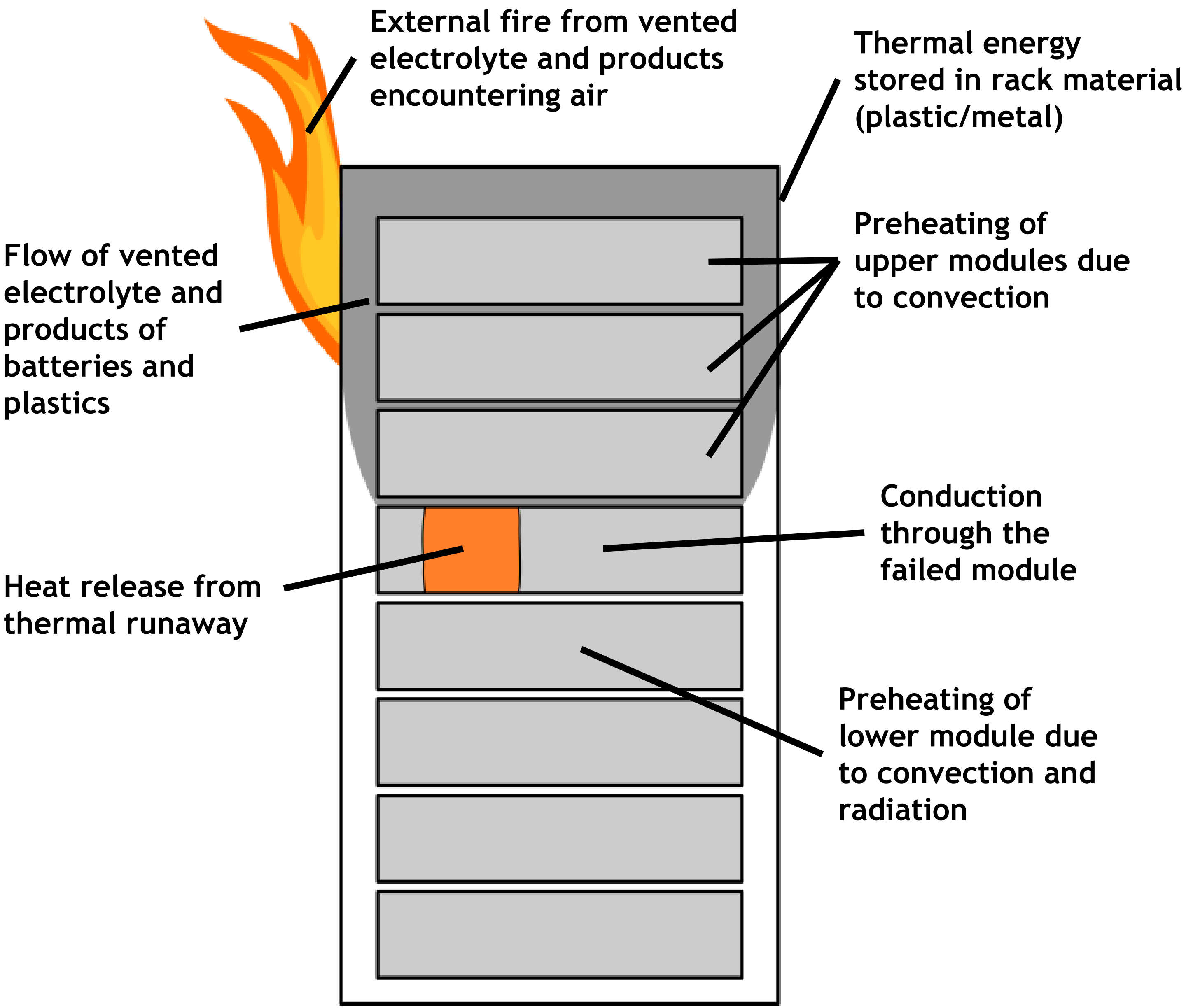
How wide does it need to be?

How much time do you have to respond?

Propagating Thermal Runaway

Question 1: Where to intervene?

- Which module(s) should be discharged to most effectively obstruct propagation of thermal runaway?
- Answer depends on location of initial failure event and pathways taken by thermal energy released from the failure
- Determination of thermal energy pathway is very complex, depends strongly on mechanical system structure



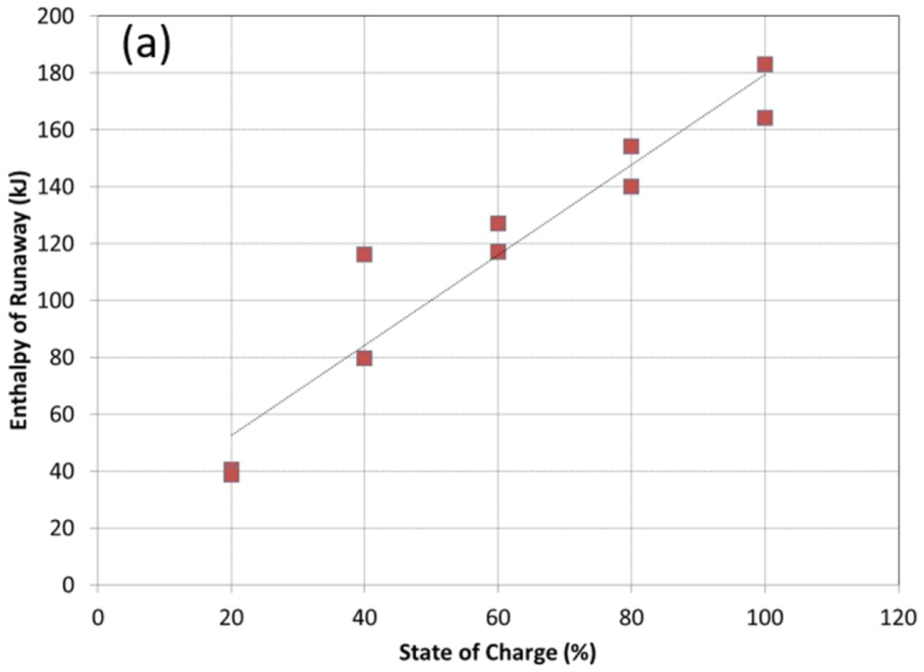
Propagating Thermal Runaway

Question 2: How deeply to discharge?

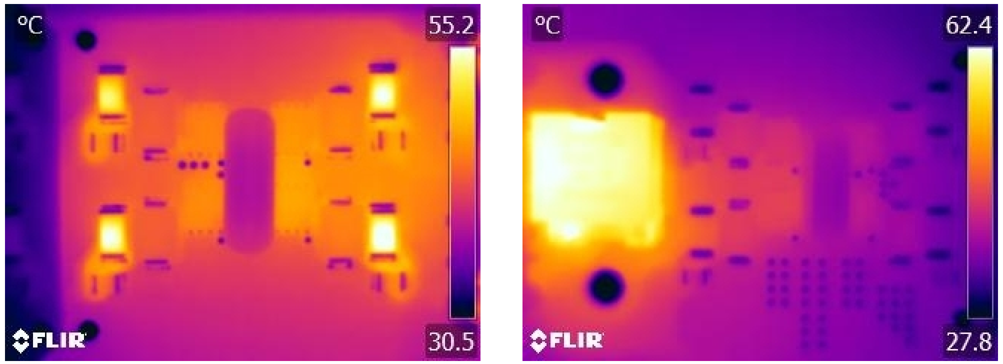
- Cell-to-cell propagation cannot continue at low SOC. Does this generalize to module-to-module propagation?
- Is there value in deeper discharge?

Question 3: How much time to respond?

- How long does module-to-module propagation take with no intervention?
- How does preheating due to rapid discharge affect propagation times?
- How long before the converter fails?
- How hard do you drive the converter?



Lamb et al., *J. Electrochem Soc.*, 2021

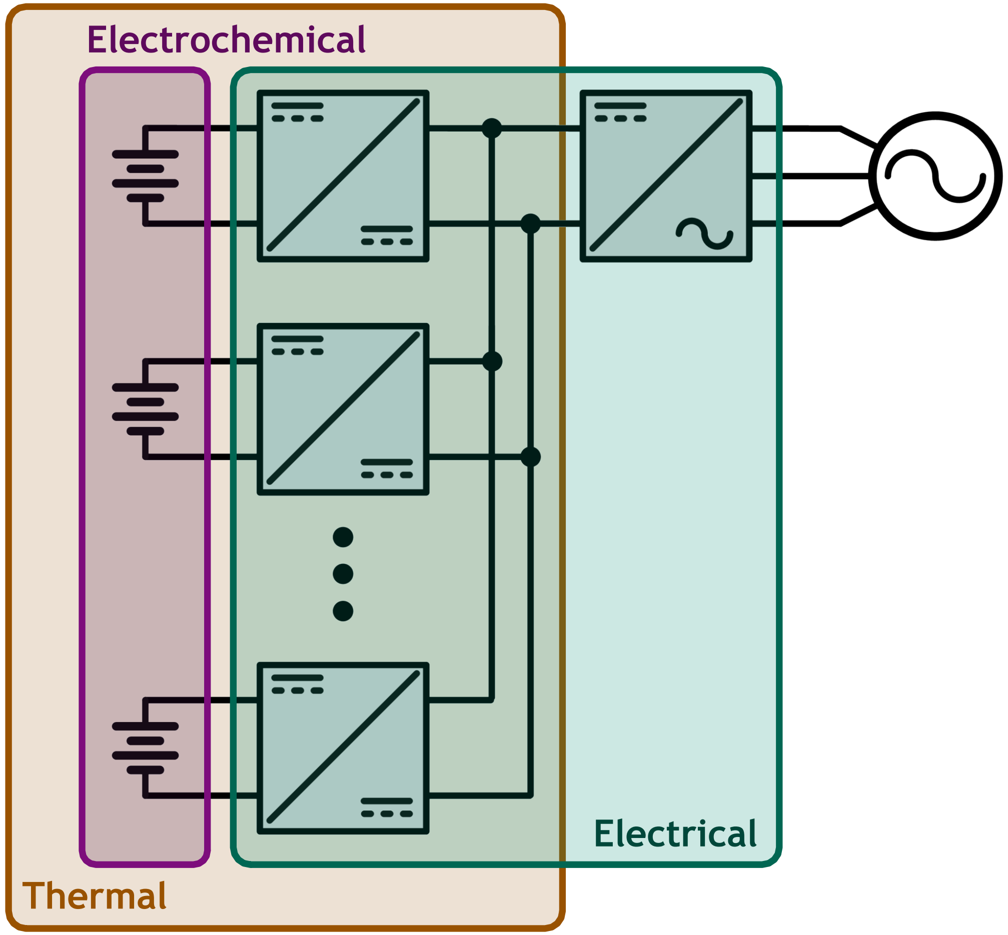


Component temperatures in DAB converter at low side (left) and high side (right) H-bridges when operating at 50% above max rated power

System-Level Simulation Studies

System Under Consideration

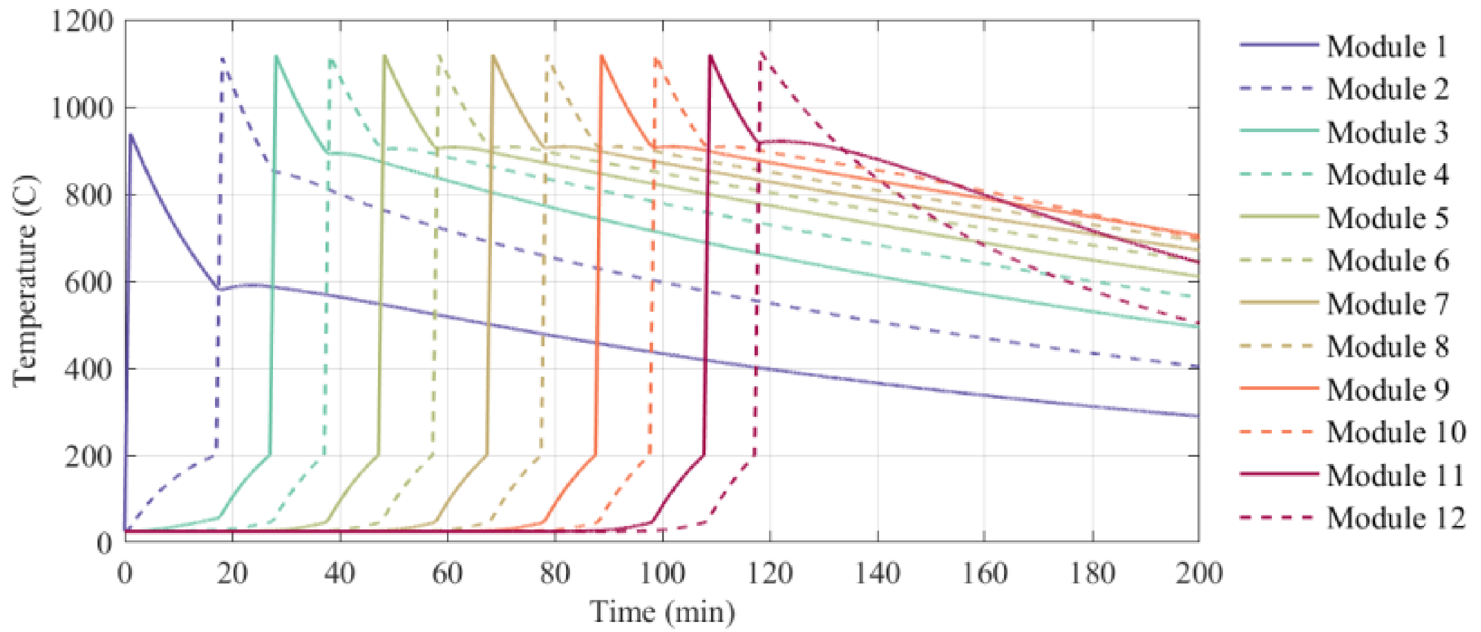
- 160kW/80kWh system organized into 12x rack-mount modules
- Each module consists of storage devices and a DC-DC converter, modules connect in parallel to common DC bus
- Storage modules
  - Rated power/energy 13.2kW/6.6kWh
  - Module capacity 128Ah, nominal voltage 52V
  - Capable of 2C continuous discharge
- DC-DC converters
  - Modeled as bidirectional buck converters for simplicity
  - Power/voltage ratings matched to storage modules
  - Converters fail when temperatures exceed 100° C

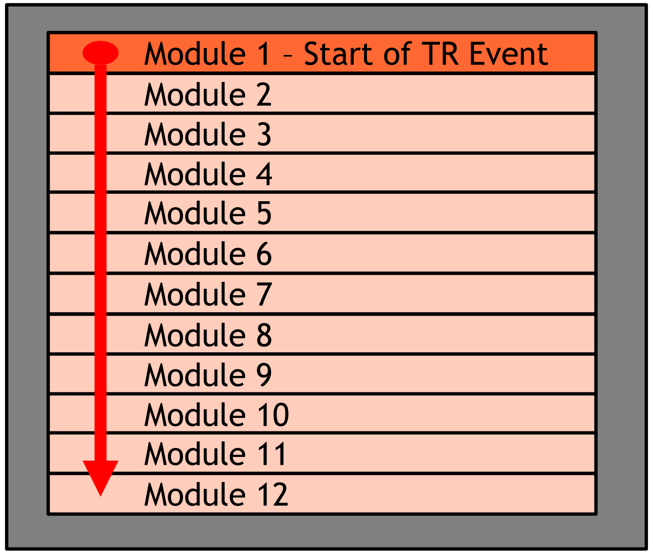


Modeling Thermal Behavior

- Thermal runaway triggered at module-level when temperature exceeds a predetermined threshold (200° C in current implementation)
- Amount of energy released and rate of energy release is a function of module SOC at time of failure
- Heat transfer between modules modeled with a linear thermal network
  - Thermal conductance is symmetric between all adjacent modules
  - Thermal conductance to ambient higher for edge modules, but otherwise equal for all modules

Case 1 – Propagation with No Intervention

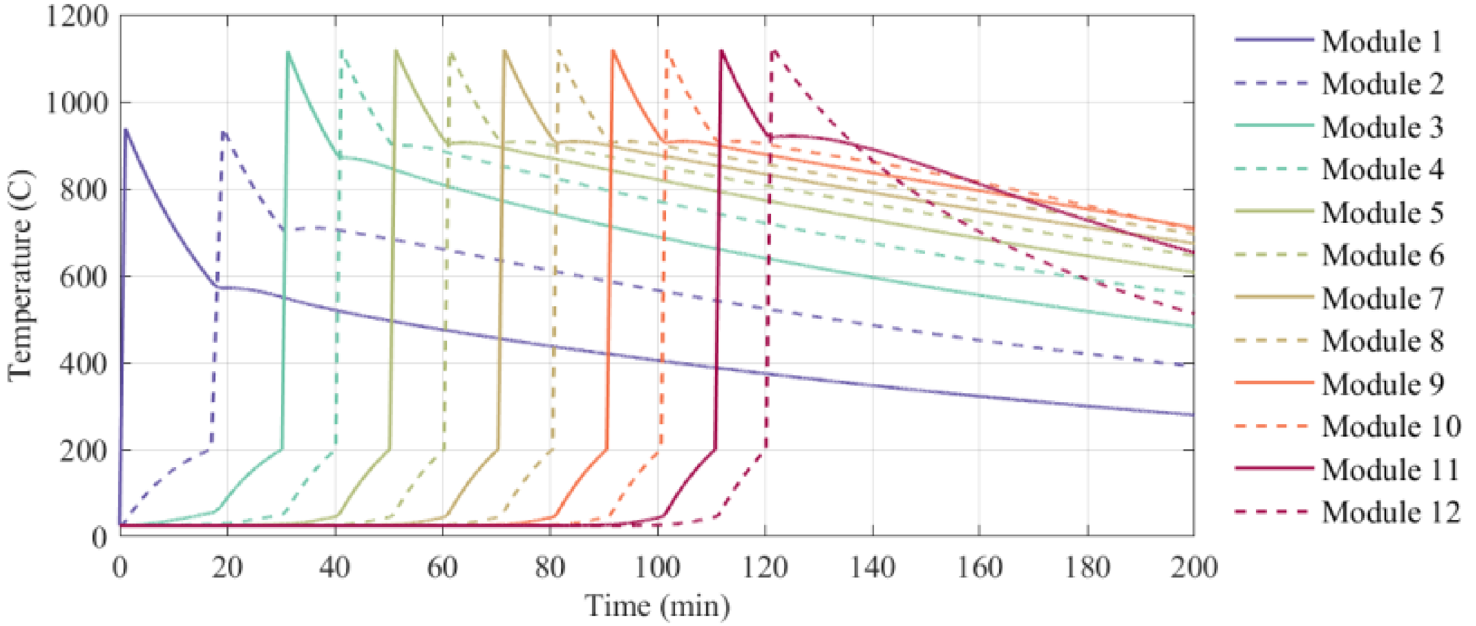


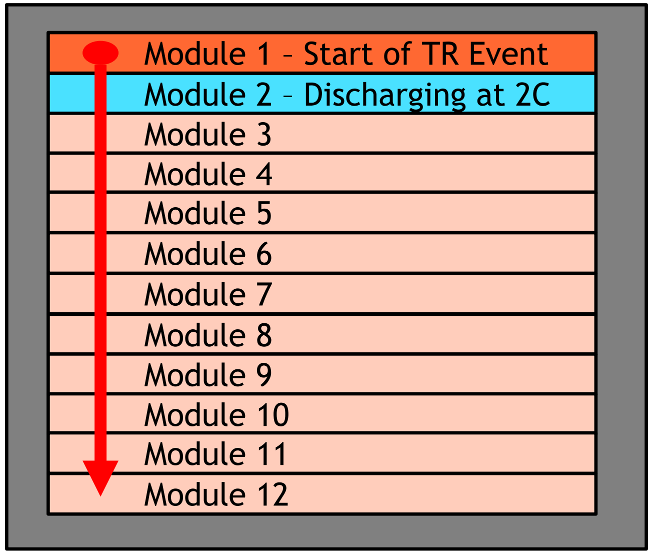


No Intervention

- Thermal runaway initiated in **module 1** at t = 0s
- All modules are at 97.5% SOC at time of initial failure
- No attempt made to mitigate propagation; all converters idle
- Edge module failures are easiest to visualize (only one direction of propagation), but model overpredicts the severity of these failure events due to semi-insulating boundary conditions

Case 2 – Intervention at Adjacent Module

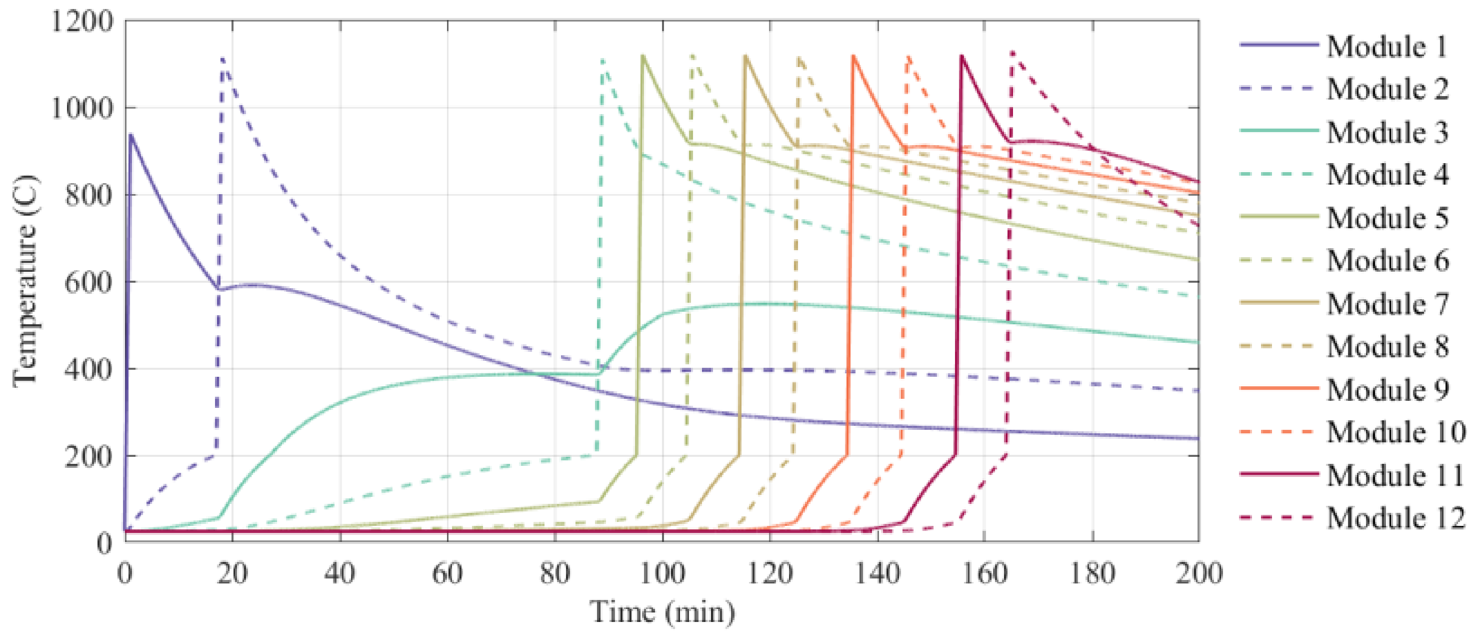


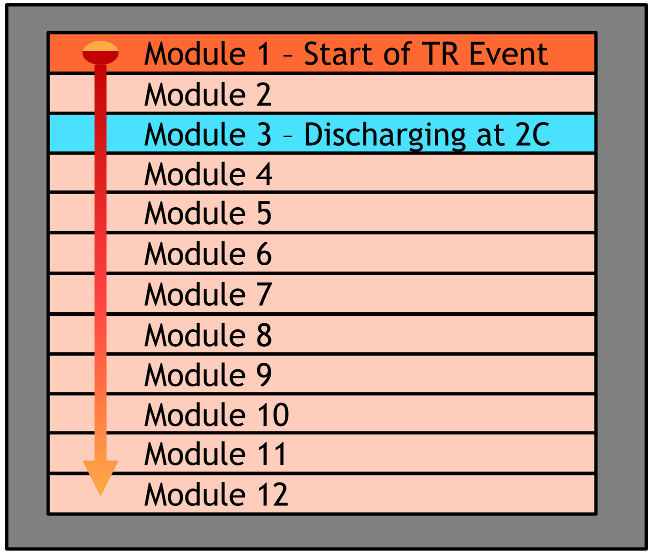


Failure – Propagation is Uninhibited

- System attempts to deplete **module 2** at discharge rate of 2C
- Module 2 temperature exceeds 100° C at ~5 min, only enough time to discharge to 81% SOC
- This level of discharge is not sufficient to obstruct propagation of thermal runaway

Case 3 – Intervention at Second Adjacent Module

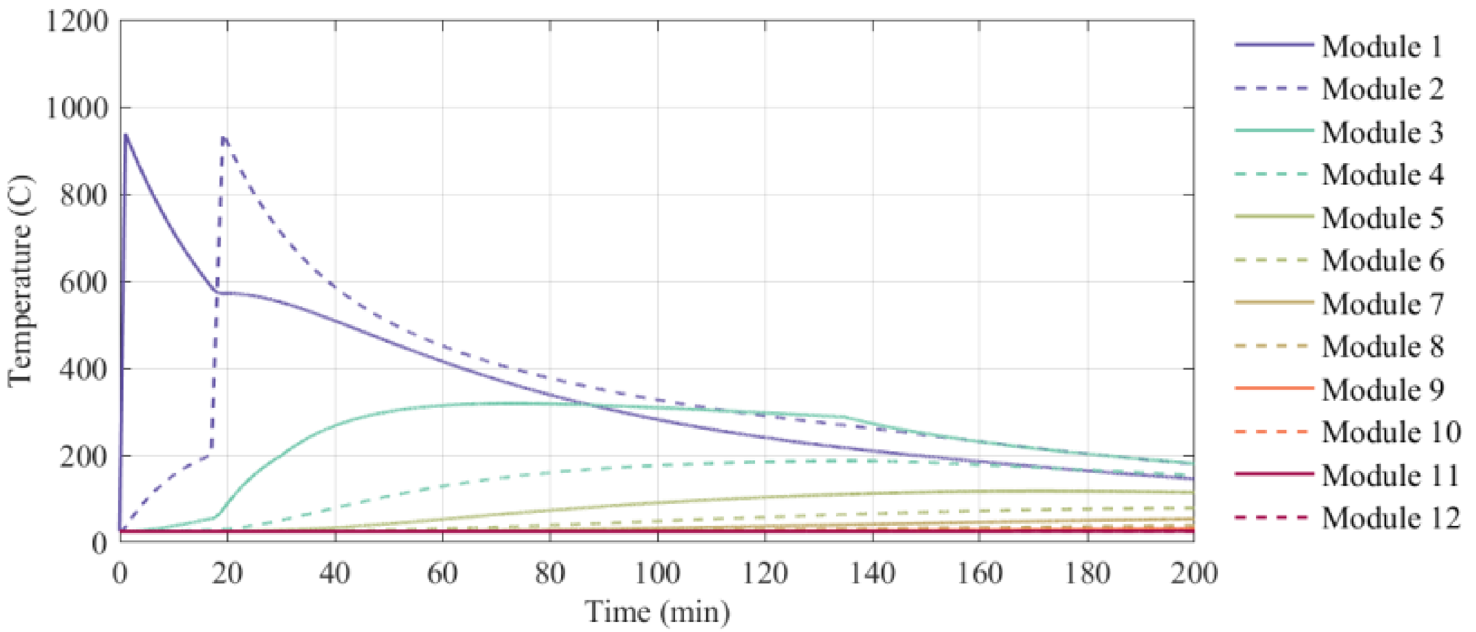


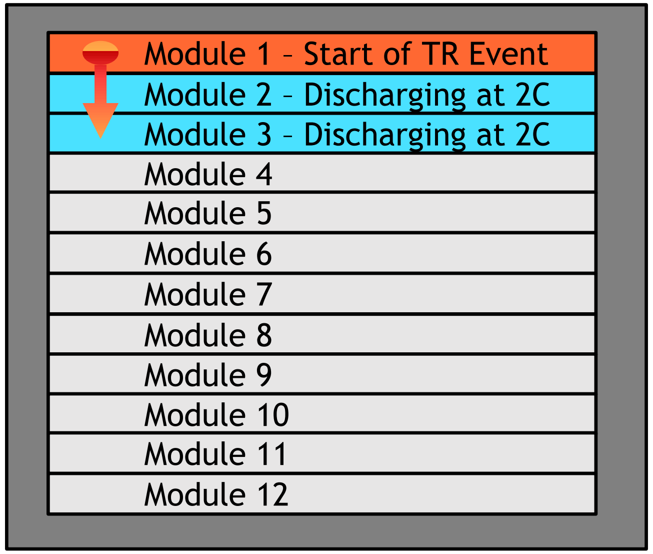


Partial Success – Propagation is Delayed

- System attempts to deplete **module 3** at discharge rate of 2C
- Module 3 temperature exceeds 100° C at ~21 min, long enough to discharge to 32% SOC
- Module 3 enters thermal runaway at about 27 min
- Propagation between modules 3 and 4 takes ~60 min (compare with <10 min in previous cases)

Case 4 – Intervention at First and Second Adjacent Modules



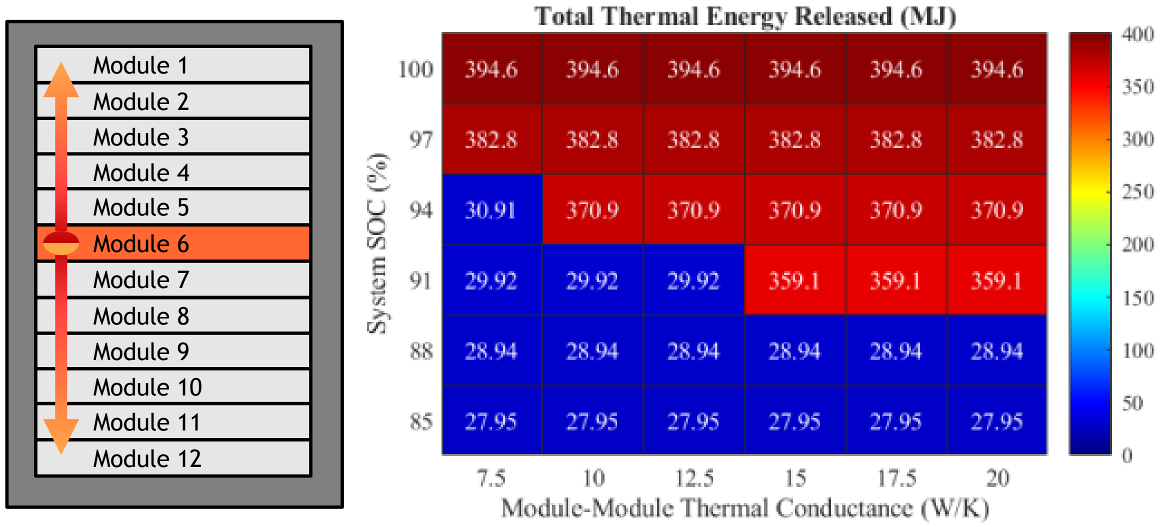


Success – Propagation is Arrested

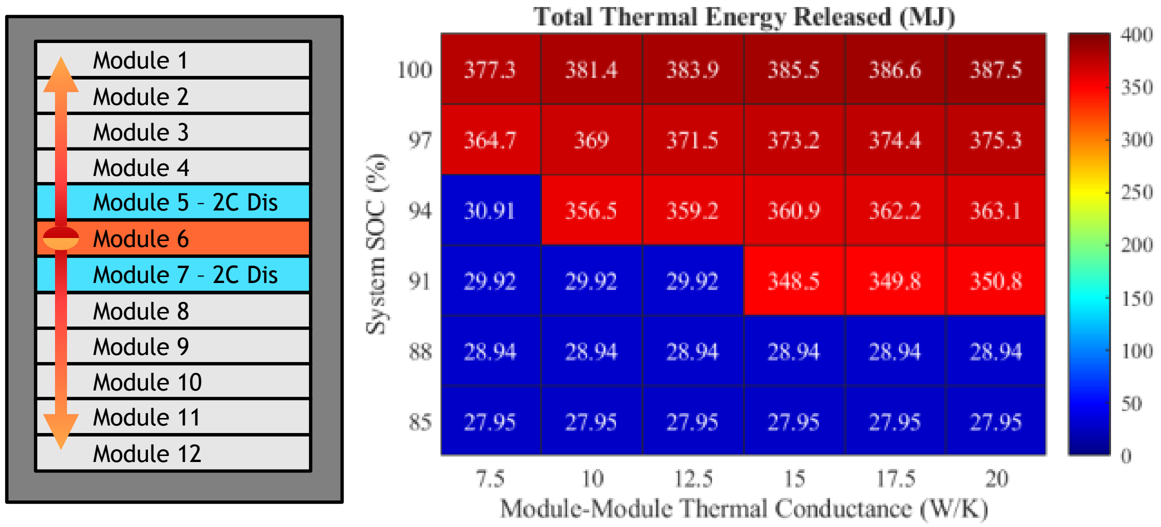
- System attempts to deplete **modules 2 and 3** at discharge rate of 2C
- Module 2 exceeds 100° C at 5 min, enters thermal runaway at 17 min with 81% SOC
- Module 3 exceeds 100° C at 21 min, enters thermal runaway at 30 min with 31% SOC
- Thermal runaway does not propagate between modules 3 and 4
- Total thermal energy release is 16.6% of no response case, 10.1% if energy from module 1 is excluded

Energy Release vs SOC, Thermal Conductance, and Response Type

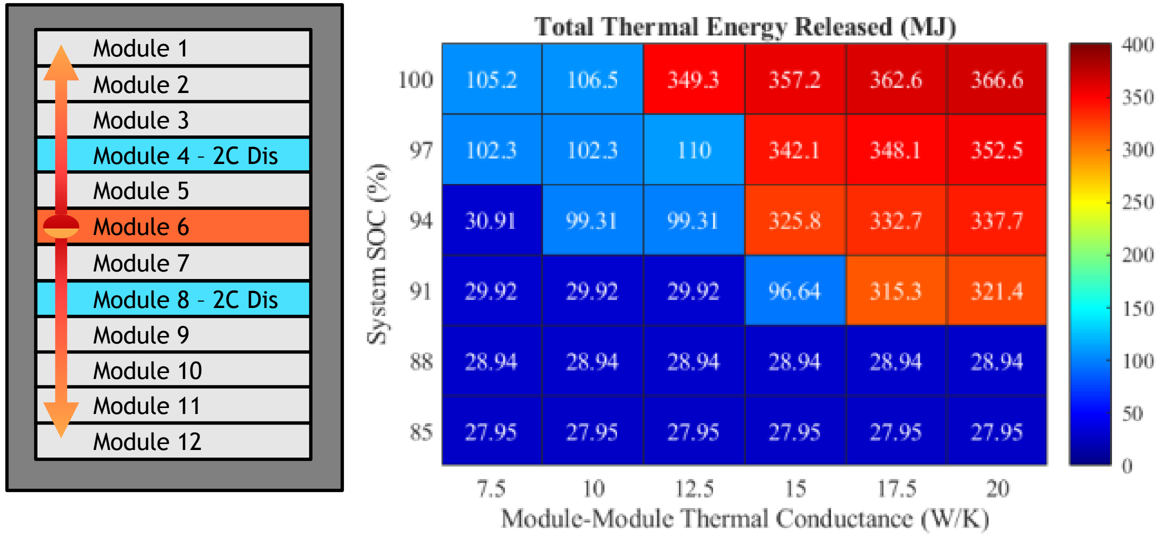
No Intervention



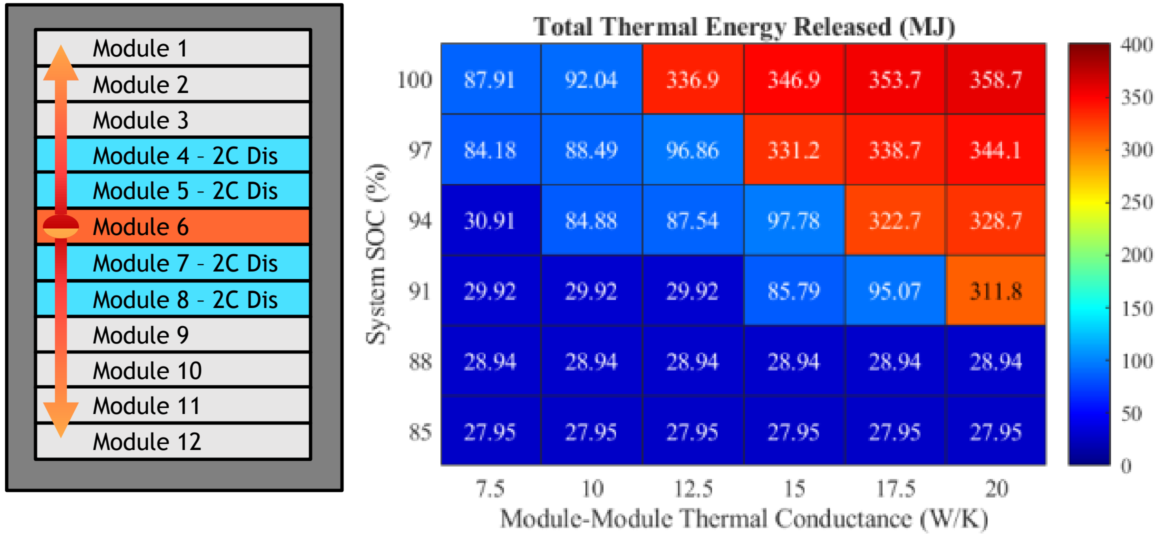
Intervention in 1st Adjacent Module



Intervention in 2nd Adjacent Module

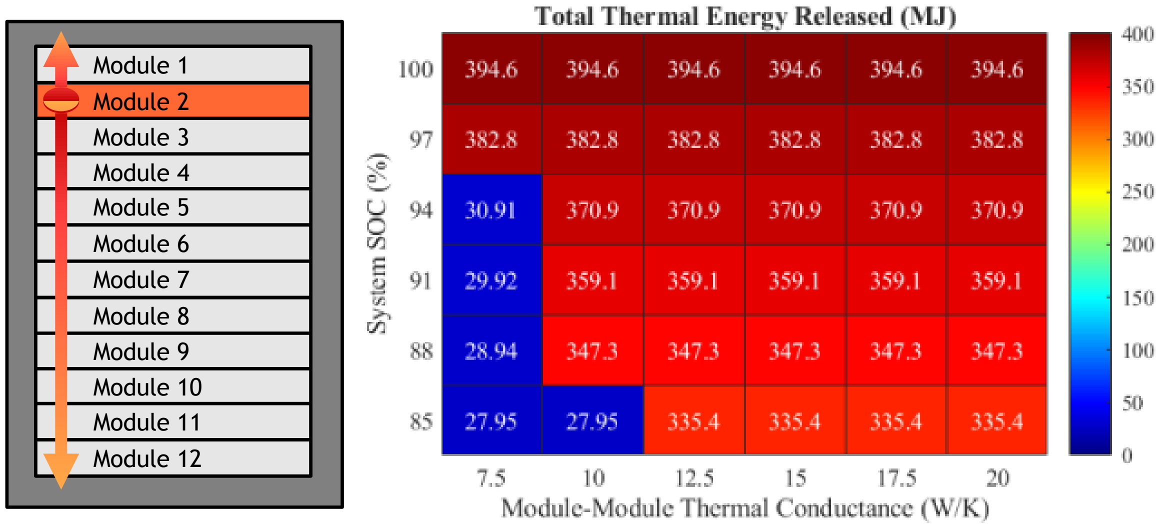


Intervention in 1st and 2nd Adjacent Modules

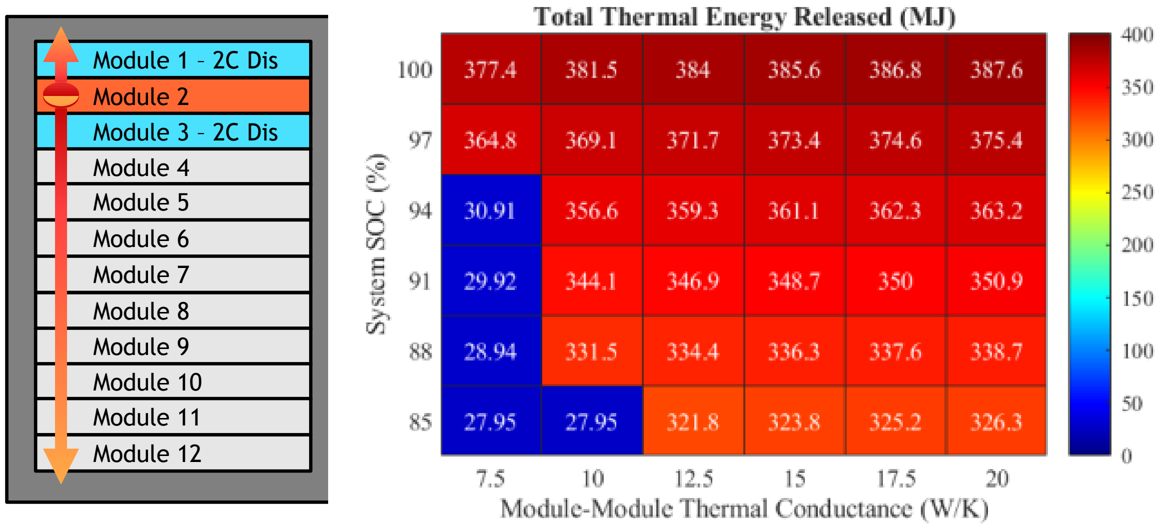


Energy Release vs SOC, Thermal Conductance, and Response Type

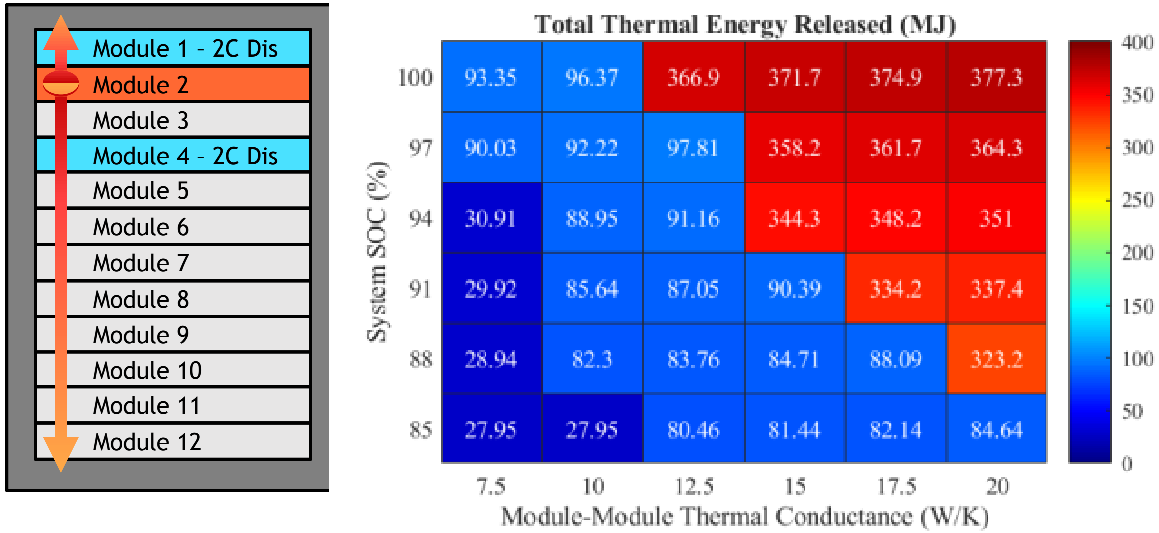
No Intervention



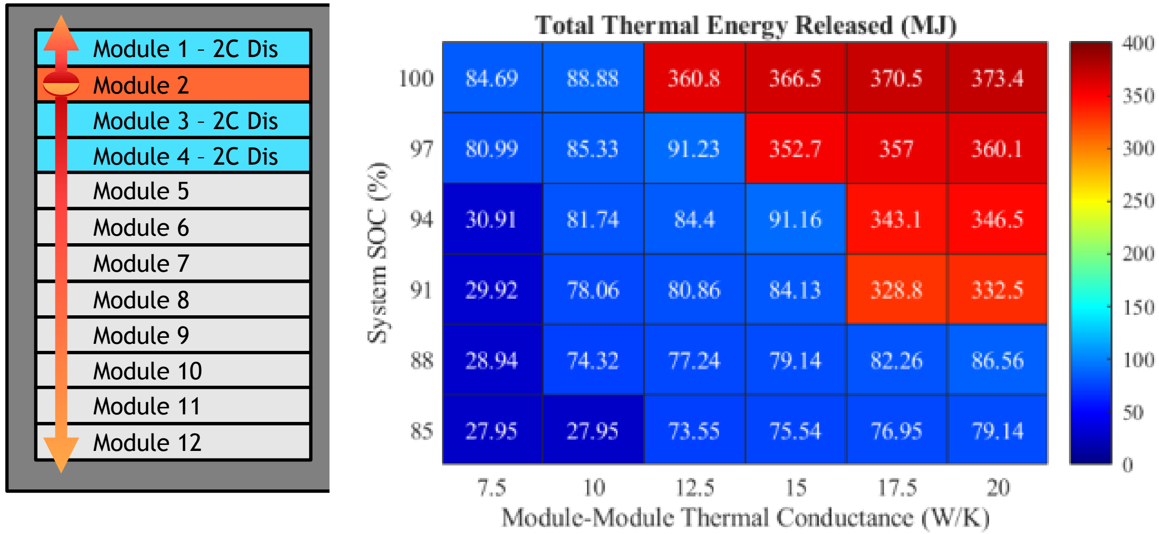
Intervention in 1st Adjacent Module



Intervention in 2nd Adjacent Module



Intervention in 1st and 2nd Adjacent Modules



Final Thoughts

New power conversion architectures provide new options for addressing existing problems

- The principal benefit of advanced power conversion architectures is **finer control over the energy within the system**
- We will need new power conversion architectures for other reasons, so we might as well use them to improve safety and reliability
- The ability to exert more control over energy resources is a good match for safety and reliability challenges, which essentially involve unintentional/uncontrolled release of energy

Simulation studies show feasibility of an active electrical response to thermal runaway

- Depleting modules along the pathways taken by thermal energy obstructs module-to-module propagation
- This response mechanism delays, and in some cases fully arrests, propagation of thermal runaway through the system
- Efficacy of response depends on:
  - Rate at which energy can be removed
  - SOC at time of failure
  - Thermal conductivity between modules and ambient environment

Important questions remain

- Does it really work? No substitute for hardware results
- How does the behavior of propagating thermal runaway scale up from cell to module?

Acknowledgements

Thanks For Your Attention

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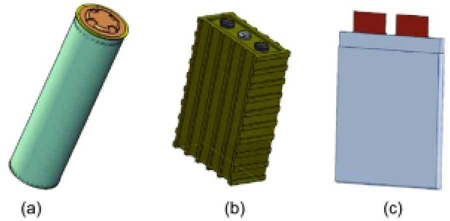
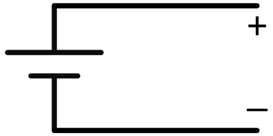
Backup Slides
Beyond This Point

Energy Storage Resources



Cells [8] a) Cylindrical, b) Prismatic, c) Pouch

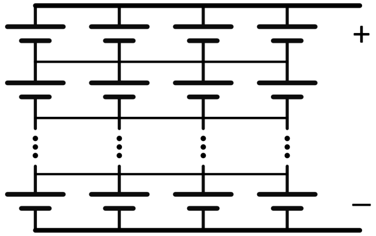


Cell – The irreducible unit of energy storage

Typ. Cell Voltage: 1V – 4V, depends on chemistry

Typ. Cell Capacity: 1Ah – 100Ah, varies greatly with cell format


Module/Pack/Subassembly



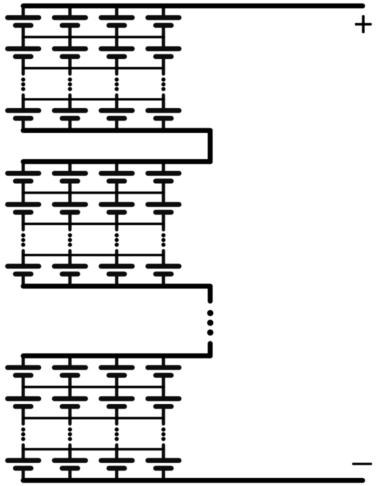
Module – An assembly of cells in series and parallel combinations

Usually includes sensors for monitoring, balancing electronics, and protection devices

Typ. Module Voltage: 48V – 100V

Typ. Module Capacity: 1kWh – 10kWh


Rack/System



System – An assembly of modules

Modules usually series-connected within an individual rack

Racks typically connected in parallel to increase system energy capacity

Typ. Rack Voltage: 700V – 1500V

Typ. Rack Capacity: 50kWh – 500kWh

The ***system*** is controlled by the PCS as a single unit, with one charging/discharging current and one voltage presented to the DC link

Behavior of Practical Batteries

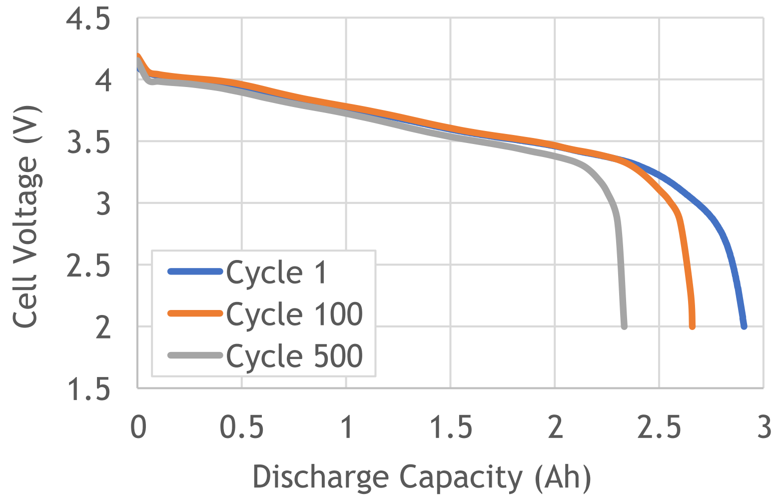
Cells are not ideal voltage sources

Cell voltage varies with:
- State of charge
- Charge/discharge operation and rate
- Internal parameters (e.g. capacity, internal resistance)

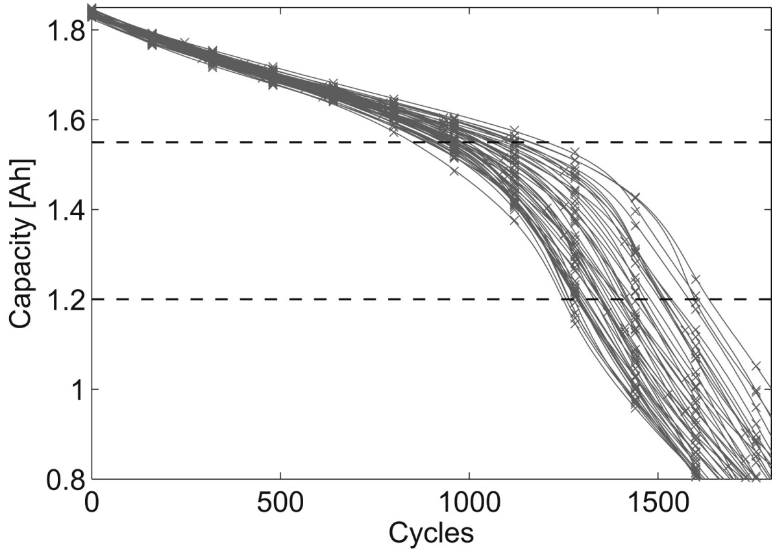
Internal parameters of a batch of "identical" cells exposed to the same operating conditions diverge over time

In a series-connected configuration, system-level performance is limited by the weakest cell in the circuit

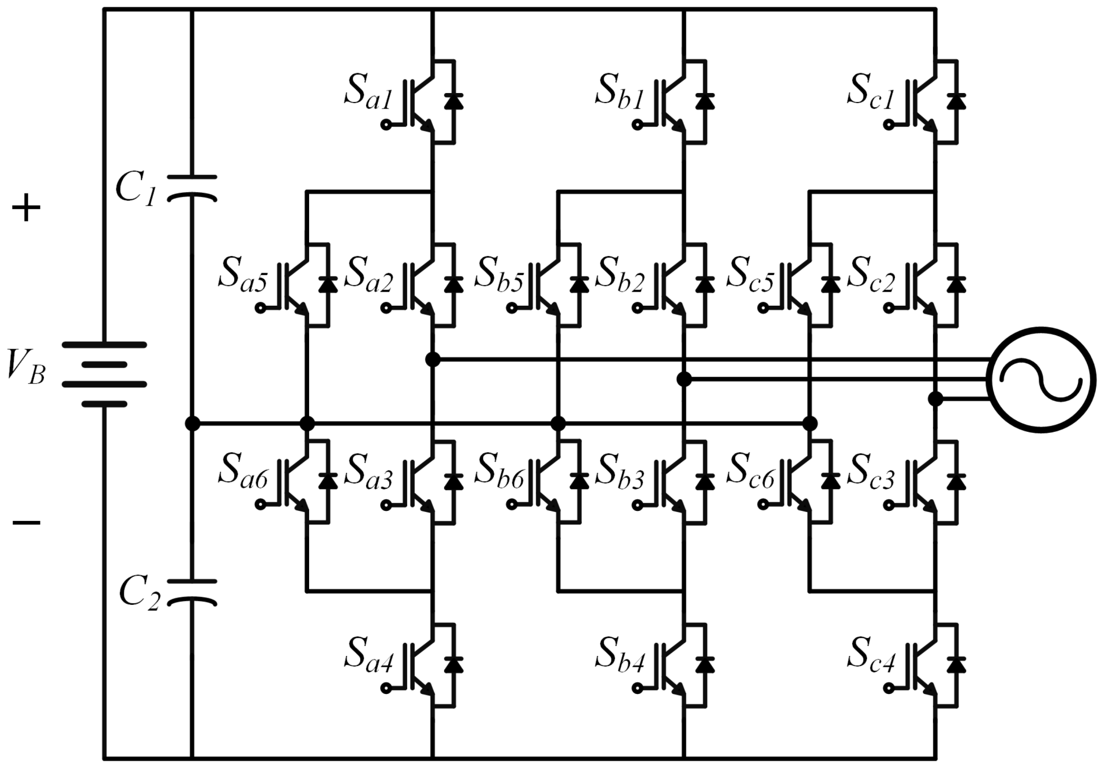
Voltage Variation in 3Ah Li-Ion Cell Over 500 Cycles



Capacity Degradation in 48 Cells Cycled Under Identical Aging Conditions [8]

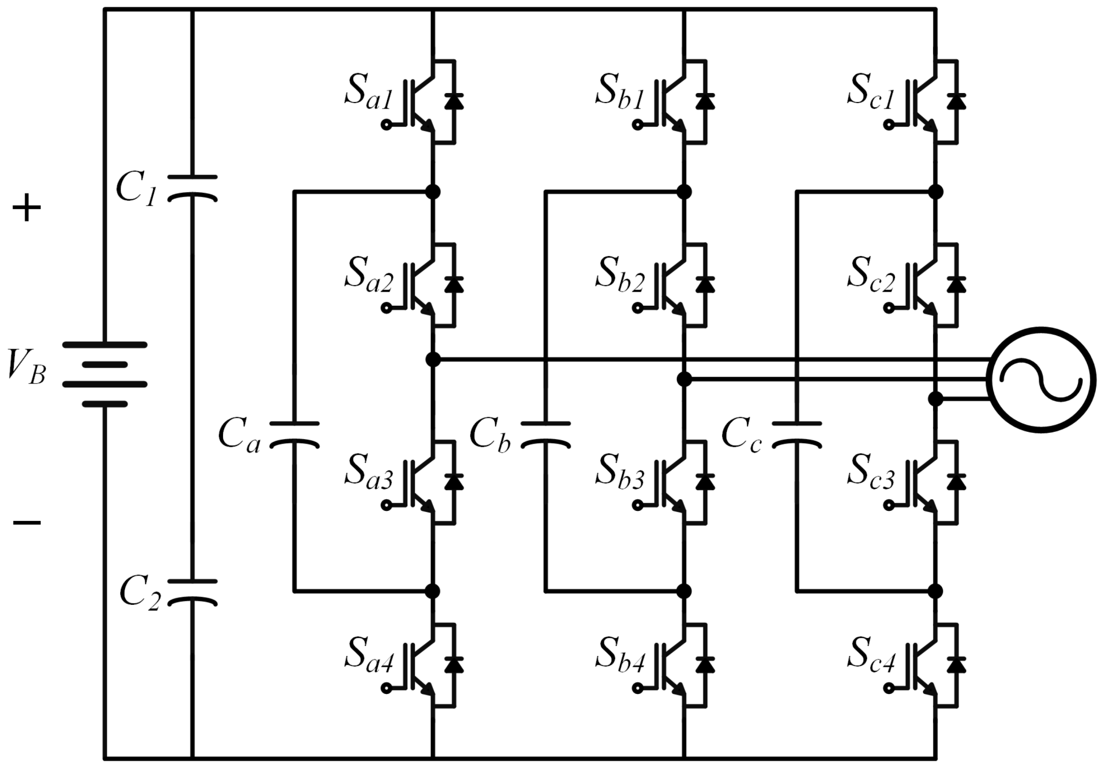


Mature DC-AC Topologies From MV Drive Applications



Neutral Point Clamped Multilevel Inverter

Example: ABB ACS6000A
3.3kV, 36MVA, IGCT semiconductors



Flying Capacitor Multilevel Inverter

Example: ALSTOM ALSPA VDM6000
3.3kV, 4.6MVA, IGBT semiconductors

Breaking the DC-Link Voltage Constraint

Pros:

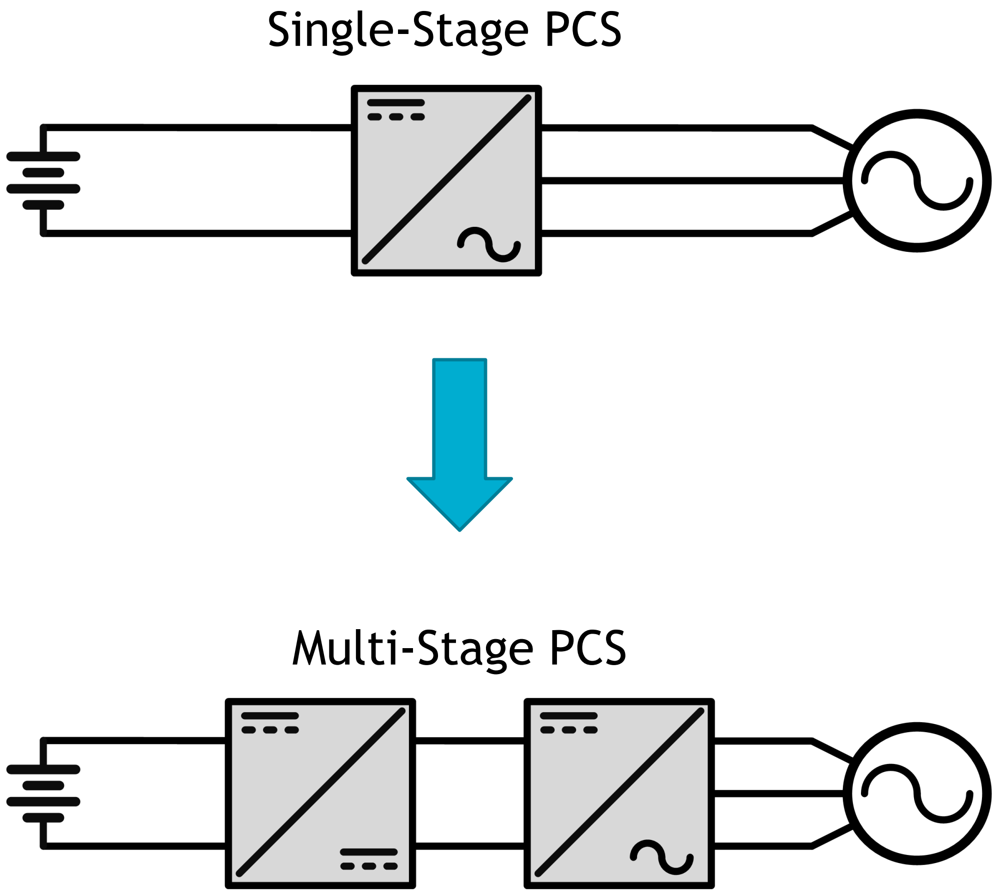
- Controlled DC link voltage
- Better semiconductor utilization in inverter
- Lower voltage battery system is safer, has reduced balancing losses

  OR
- Boosted DC link allows inverter to use higher working voltages, leverage benefits of new semiconductor devices and multi-level inverter topologies

Cons:

- Increased cost and complexity
- Increased power conversion loss
- Storage devices still controlled as a single unit

Scalability? Reliability?



Multi-Stage PCS – Parallel Case

Controlled DC-link provides a common point of connection for multiple parallel DC-DC converters

Battery system broken into individual subassemblies, power conversion and control moved from system-level to module-level

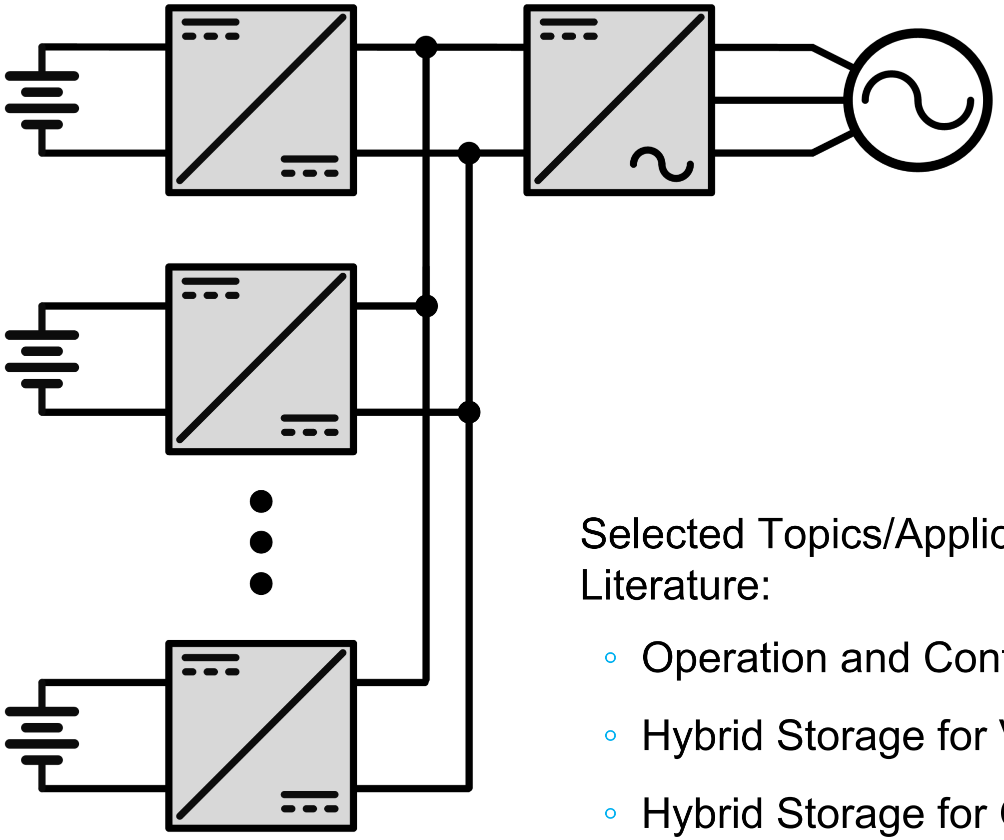
Storage device parameters need only be matched within a subassembly

Subassemblies may have different states of health, may come from different manufacturers, may be entirely different chemistries or storage technologies (hybrid storage)

Increased reliability through fault-tolerance, elimination for single points of failure

Hot-swappable storage/converter modules for uninterruptible operation at system-level

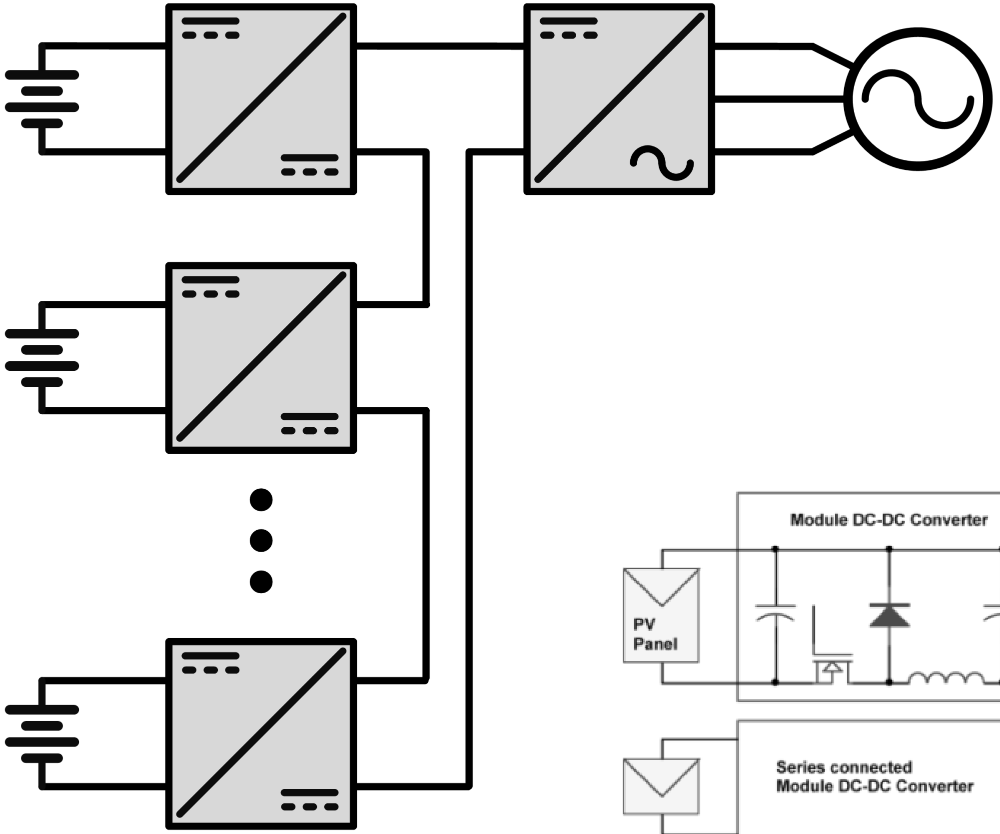
Scalability still limited by DC-DC converter voltage gain



Selected Topics/Applications in Literature:

- Operation and Control [10]
- Hybrid Storage for Vehicles [11]
- Hybrid Storage for Grid [12]
- Second Life Battery Systems [13]

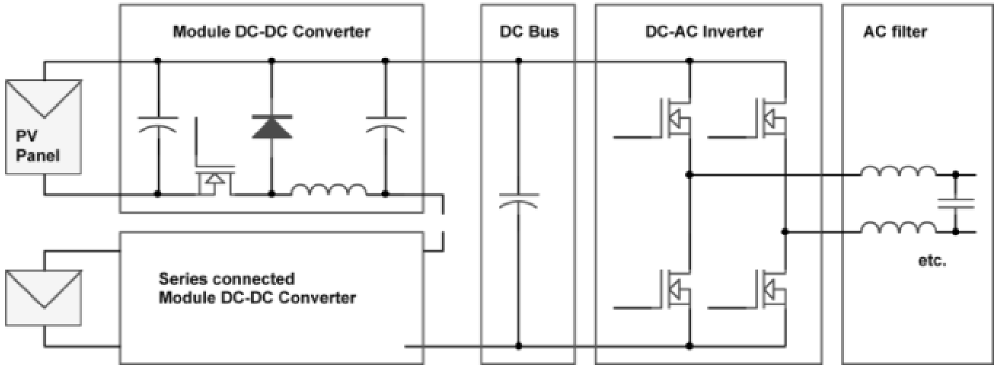
Multi-Stage PCS – Series Case

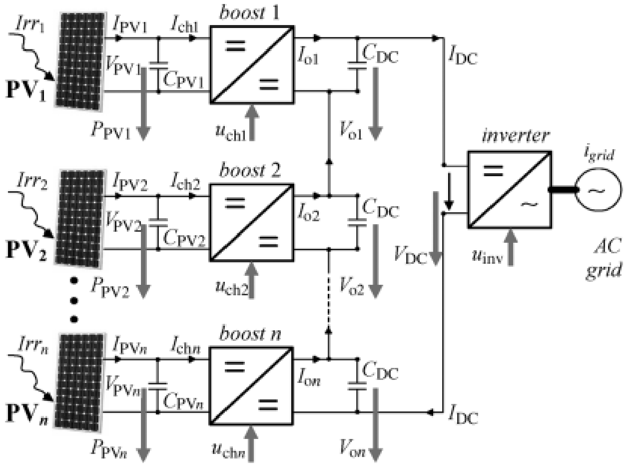


Higher DC link voltages built by series-connected DC-DC converter modules with even modest voltage gain

Retains most advantages of parallel case at the cost of higher control complexity: stability [14], voltage balancing [15]

Technical challenges related to module bypassing





Previously proposed for PV applications, e.g. [16] (left) and [17] (right), where similar voltage scale challenges exist

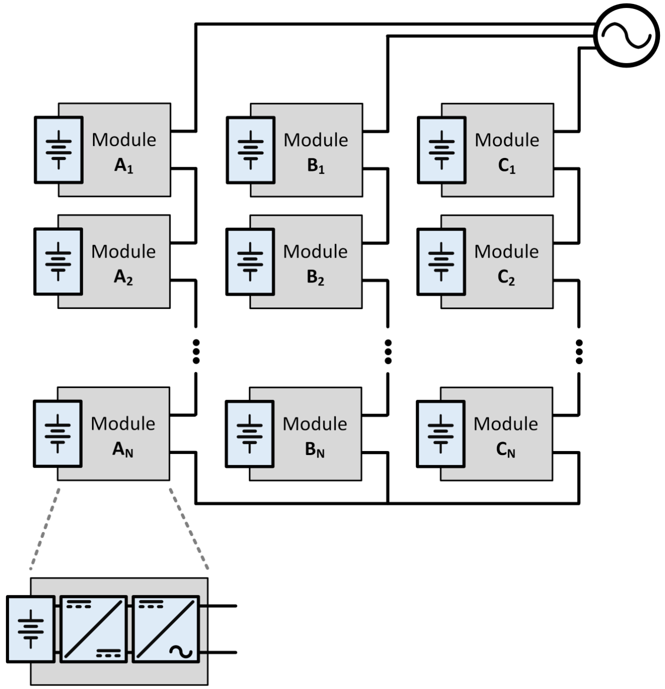
Large-Scale Storage Installations

Looking Forward: What does a GW-scale storage installation look like?

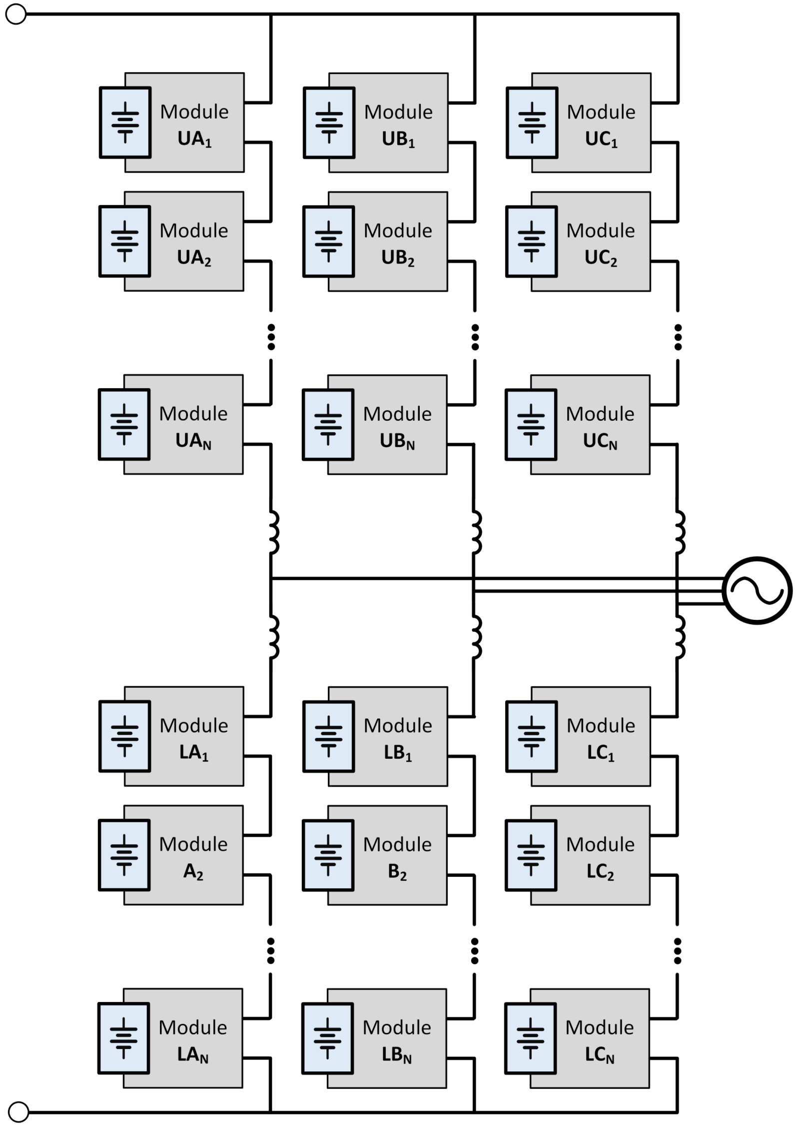
- Modular, scalable
- Fault tolerant, uninterruptible
- Storage technology agnostic
- Constructed from highly optimized power electronic building blocks
- Dual purpose – integrated into HVDC transmission or MVDC distribution infrastructure

Selected References on Integrated Storage:

- Operation and Control of CHB [18]
- Reliability Analysis of CHB [19]
- Operation and Control of MMC [20]
- Fault Tolerance of MMC [21]
- Reliability of MMC w/ Different Storage Device Configurations [22]



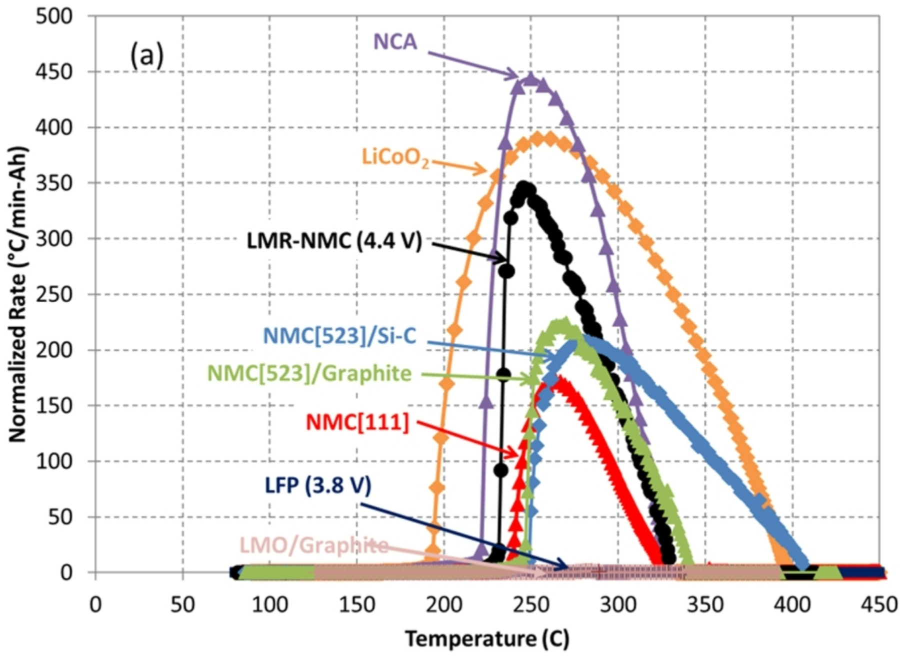
Cascaded H-Bridge Converter (CHB)



Modular Multilevel Converter (MMC)

Improving Battery Storage System Safety

Cell (Cathode) Chemistry	Common Name	Specific Energy	Typ. Max Discharge	Cycle Life	Notes
Lithium Cobalt Oxide	LCO	150-200Wh/kg	≤1C	500-1000	Cobalt is problematic
Lithium Manganese Oxide	LMO	100-150Wh/kg	≤10C	300-700	
Lithium Nickel Manganese Cobalt Oxide	NMC	150-220Wh/kg	≤2C	1000-2000	Currently the dominant chemistry
Lithium Iron Phosphate	LFP	90-120Wh/kg	≤25C	2000+	Lower heat release rate during thermal runaway
Lithium Nickel Cobalt Aluminum Oxide	NCA	200-260Wh/kg	≤1C	~500	Popular choice for EV powertrain applications

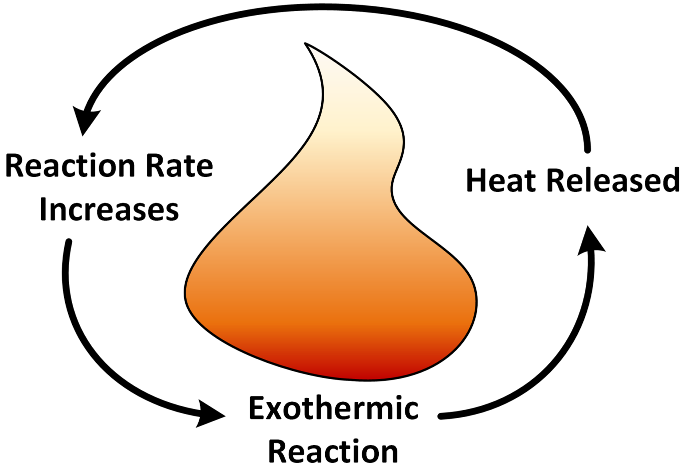


Lamb et al., *J. Electrochem Soc.*, 2021

Li-Ion dominates growth in energy storage across all applications

Excellent performance attributes, ability to achieve both high energy density and high power density

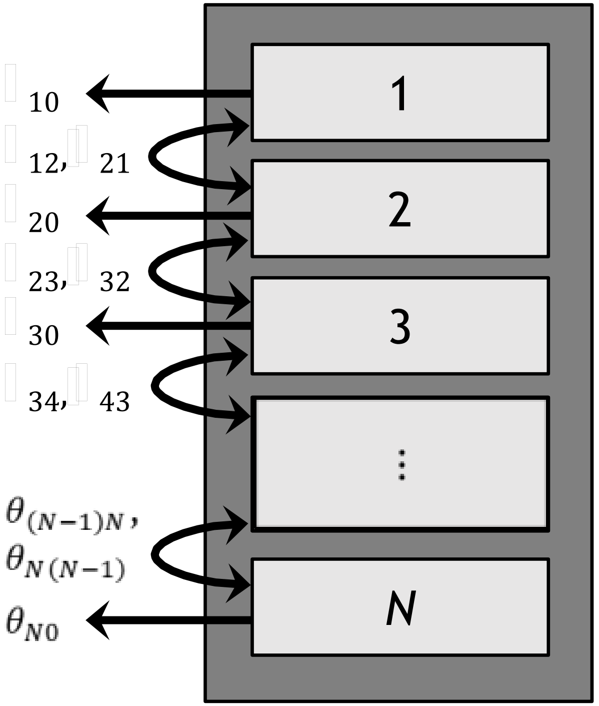
Key challenge for Li-Ion batteries: tendency to explode

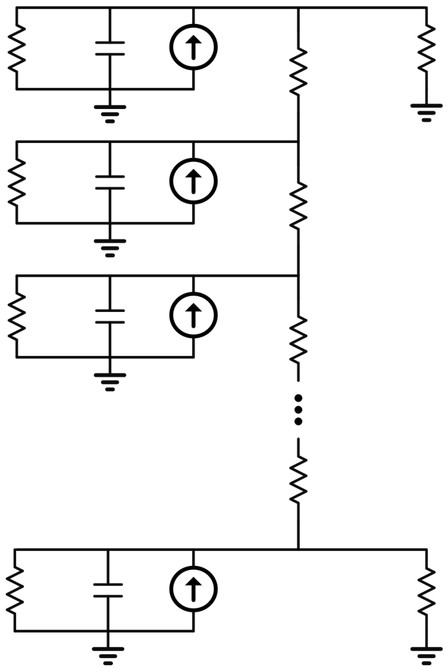


System-Level Simulation Studies

System Under Consideration

- 160kW/80kWh system organized into 12x rack-mount modules
- Each module consists of storage devices and a DC-DC converter, modules connect in parallel to common DC bus
- Storage modules
  - Rated power/energy 13.2kW/6.6kWh
  - Module capacity 128Ah, nominal voltage 52V
  - Capable of 2C continuous discharge
  - Consist of 28x NMC cells in 2P-14S configuration
- DC-DC converters
  - Modeled as bidirectional buck converters for simplicity
  - Power/voltage ratings matched to storage modules
  - Converters fail when temperatures exceed 100° C





Modeling Thermal Behavior

- Thermal runaway triggered at module-level when temperature exceeds a predetermined threshold (200° C in current implementation)
- Amount of energy released and rate of energy release is a function of module SOC at time of failure
- Heat transfer between modules modeled with a linear thermal network

$$\Theta = \begin{bmatrix} \theta_{10} & \theta_{12} & 0 & \cdots & 0 \\ \theta_{21} & \theta_{20} & \theta_{23} & \cdots & 0 \\ 0 & \theta_{32} & \theta_{30} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \theta_{N0} \end{bmatrix}$$

Modeling Simplifications:

- Thermal conductance to ambient higher for edge modules, but otherwise equal for all modules: $\theta_{n0} = \theta_{m0} < \theta_{10}, \theta_{N0}$
- Thermal conductance is symmetric between all adjacent modules: $\theta_{nm} = \theta_{mn}$