Approved, DCN# 2026-7-17-2514- 07/19/2026

Platform Energy Digital Twin Testbed for Prognostic Health Management and Battle Damage Assessment of Naval Power Systems

Dr. Kerry Sado

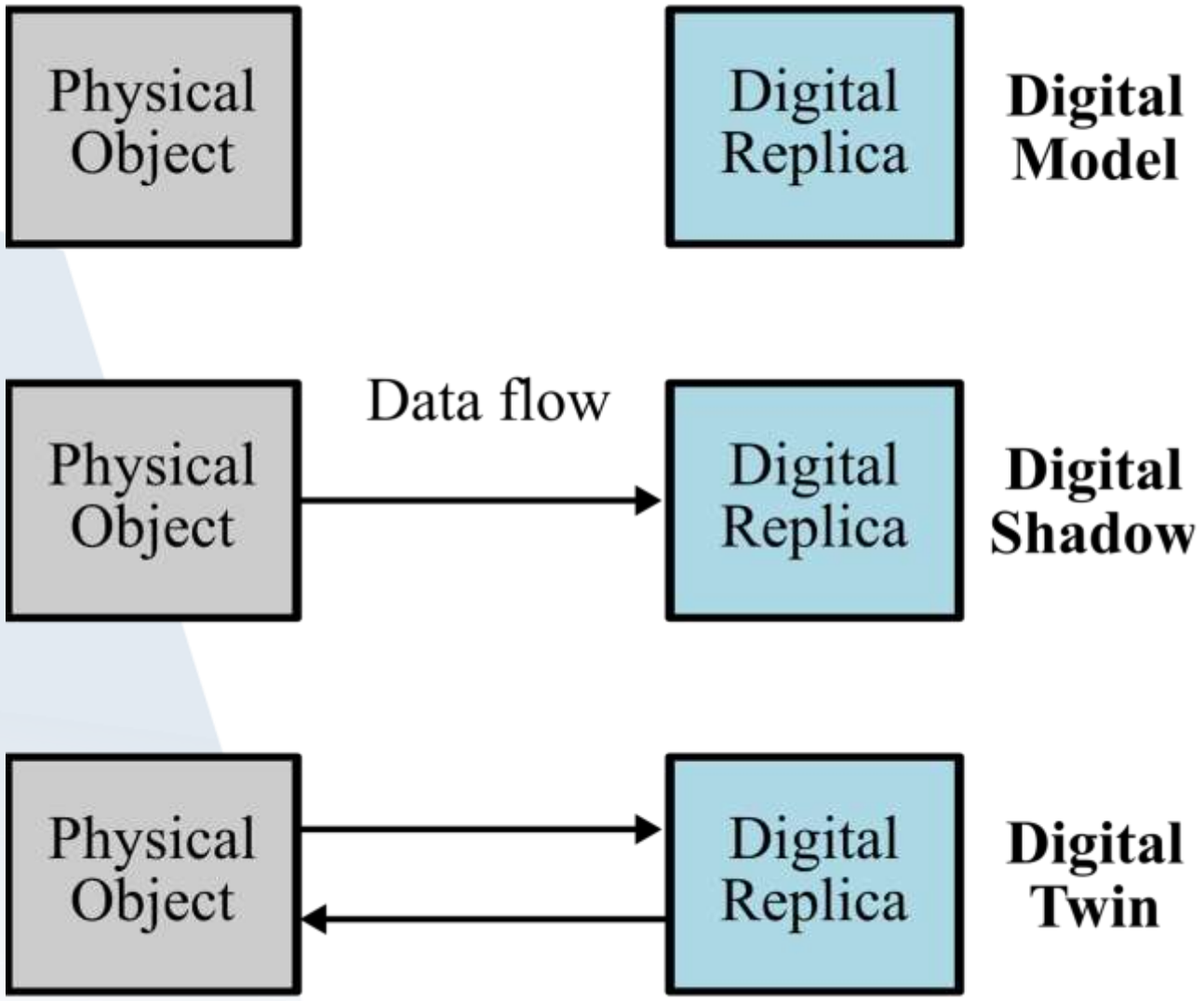
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Definitions

- **Digital Model:**
  - No data flow and replication of condition
- **Digital Shadow:**
  - Data exchange is unidirectional
- **Digital Twin:**
  - Data exchange must be bidirectional and enables control modification



K. Sado, J. Peskar, A. R. J. Downey, H. L. Ginn, R. Dougal and K. Booth, "Query-and-Response Digital Twin Framework Using a Multidomain, Multifunction Image Folio," in IEEE Transactions on Transportation Electrification, vol. 10, no. 4, pp. 7873-7885, Dec. 2024, doi: 10.1109/TTE.2024.3425276.

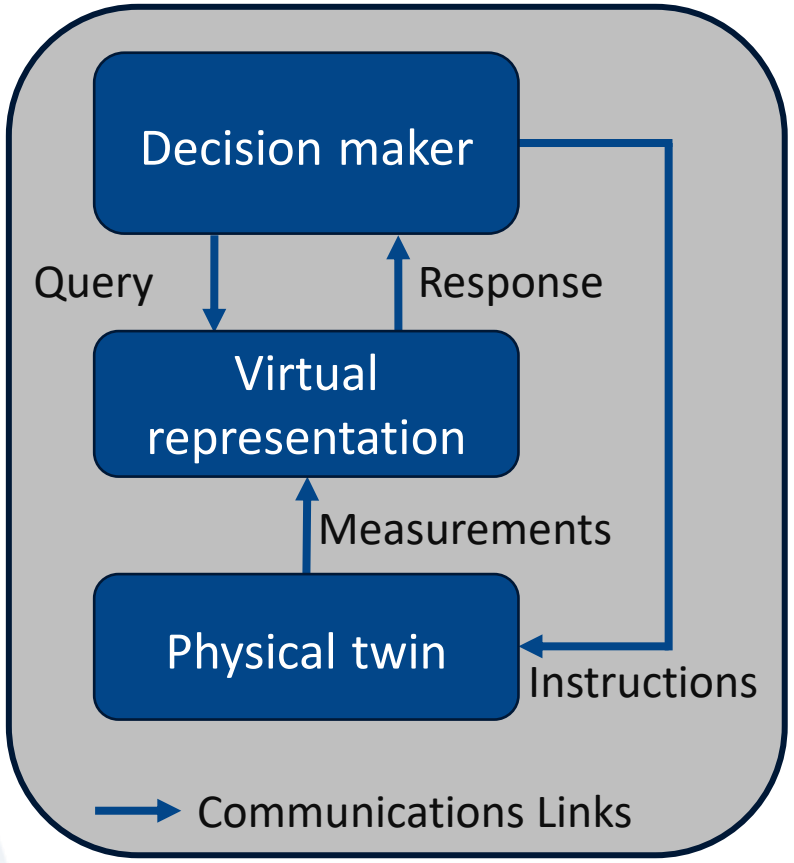
Digital Twin Framework

Decision Maker:

- A control algorithm, an AI, a human-in-the-loop, or a combination of these elements.
- Is the outermost control loop for the system.
- Develops the goal or query for the DT to study.

Query:

- Set of instructions sent by the decision maker to a virtual representation.
- Includes parameters or conditions that the DT uses to forecast behaviors to provide decision aids based on the decision maker's objectives.
- Could be predefined or asked in real-time.



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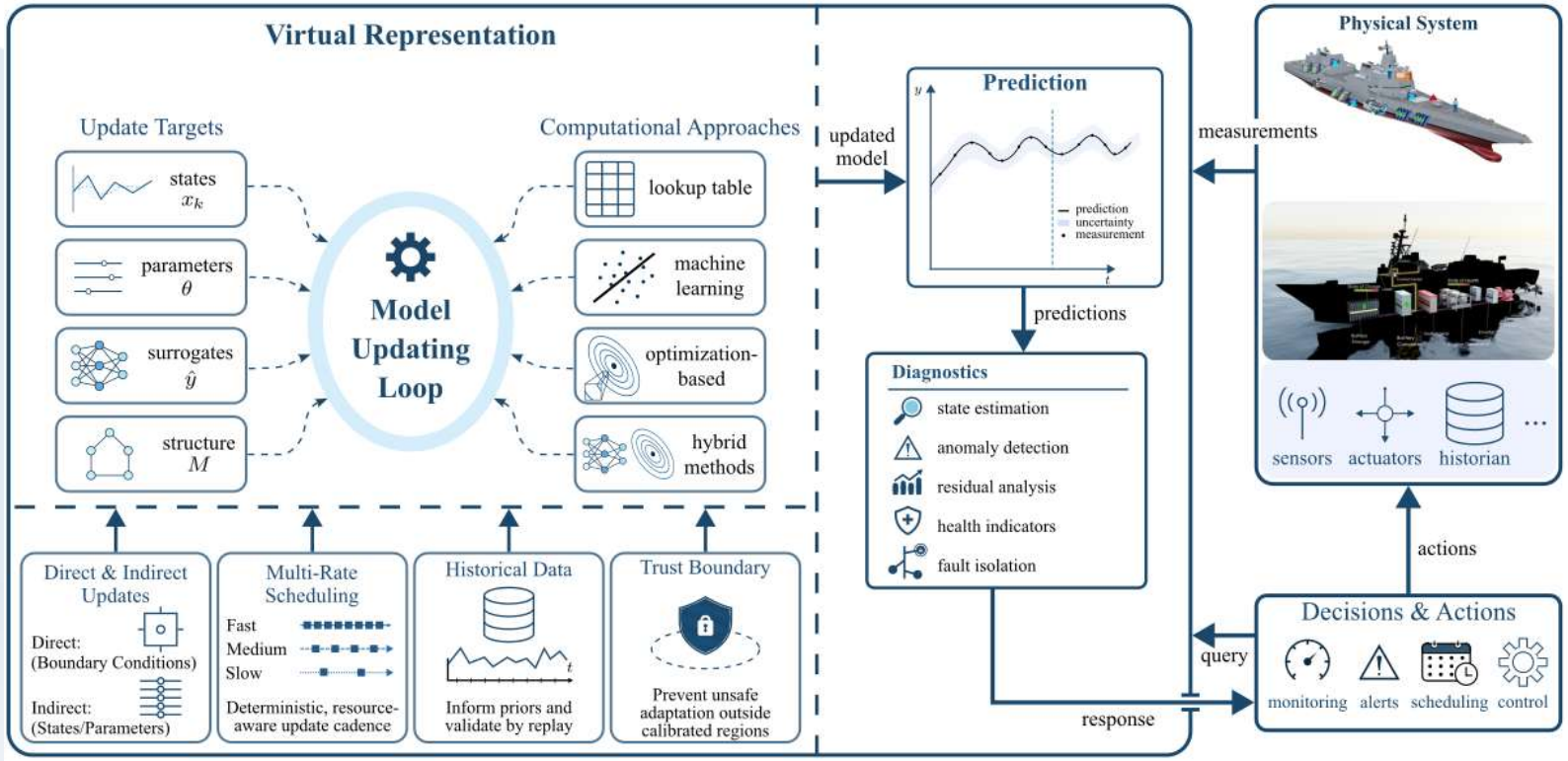
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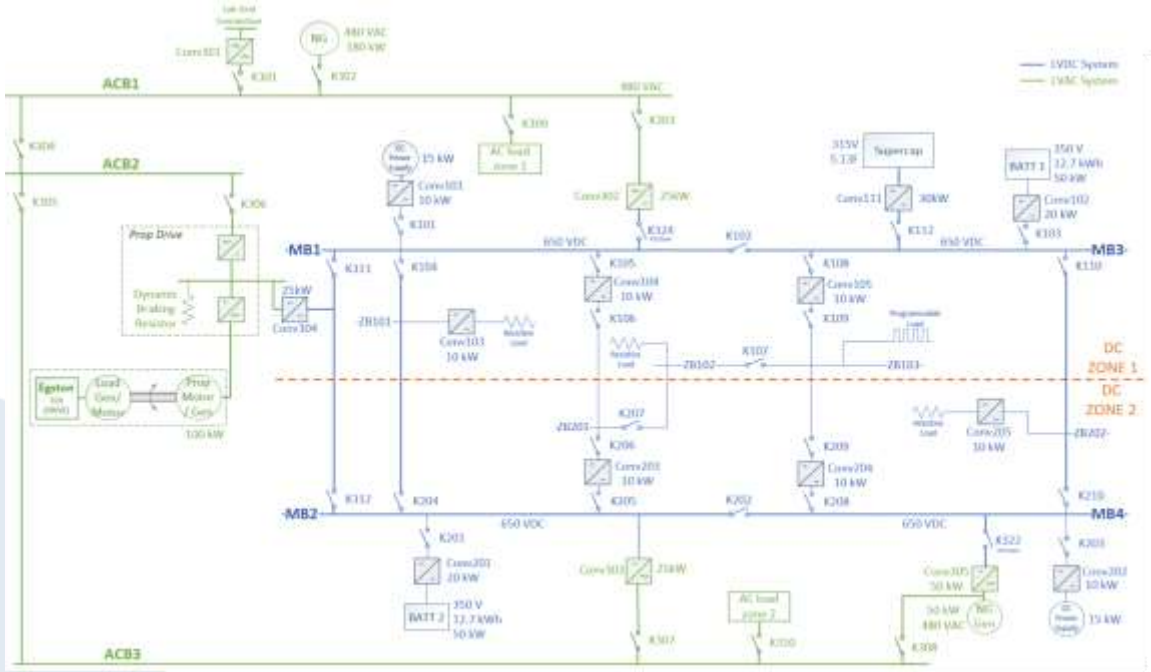
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SCEPTER Hardware

- **(a)**: Detailed one-line diagram of scaled naval power and energy system
- **(b)**: Image of the corresponding laboratory hardware



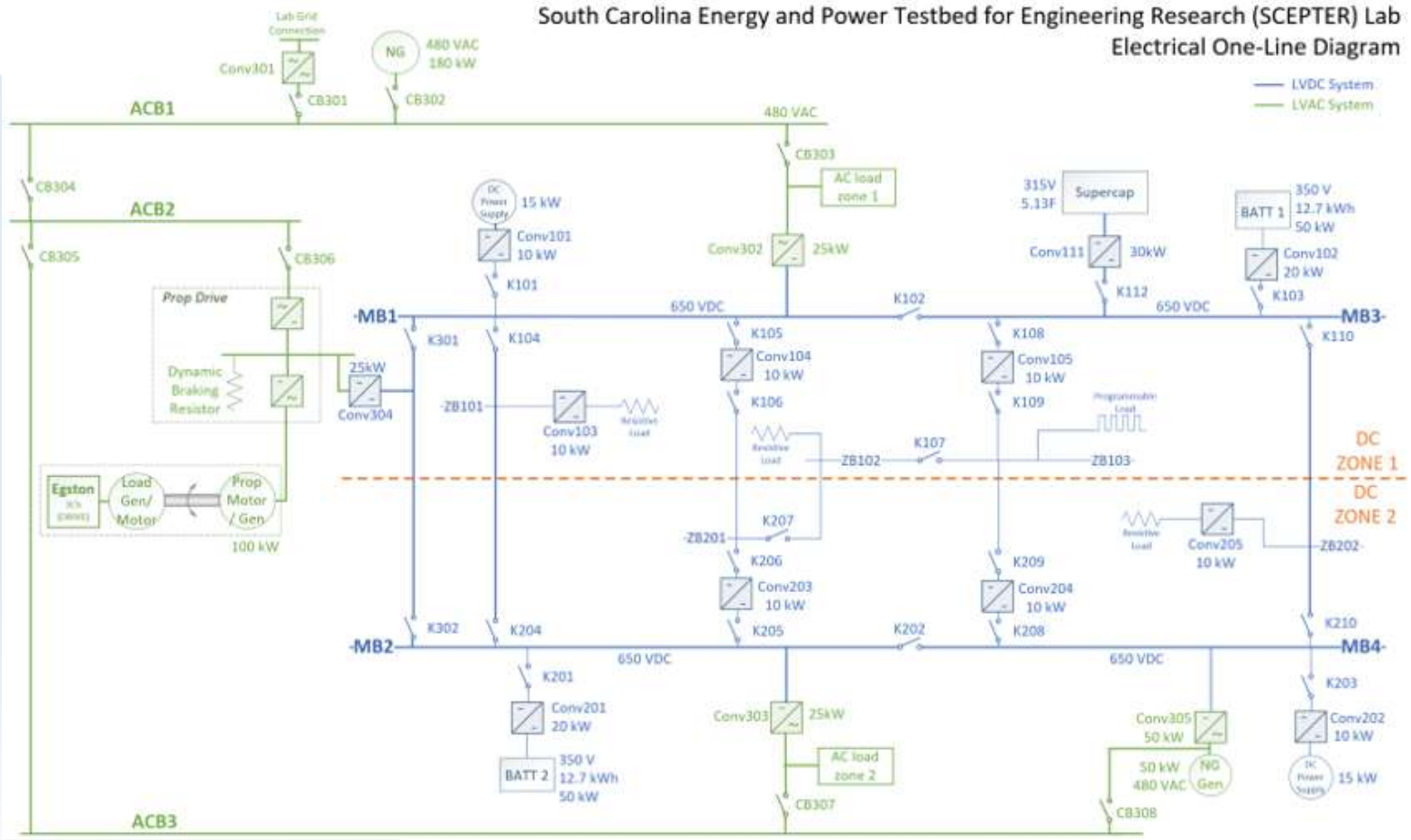
(a)



(b)

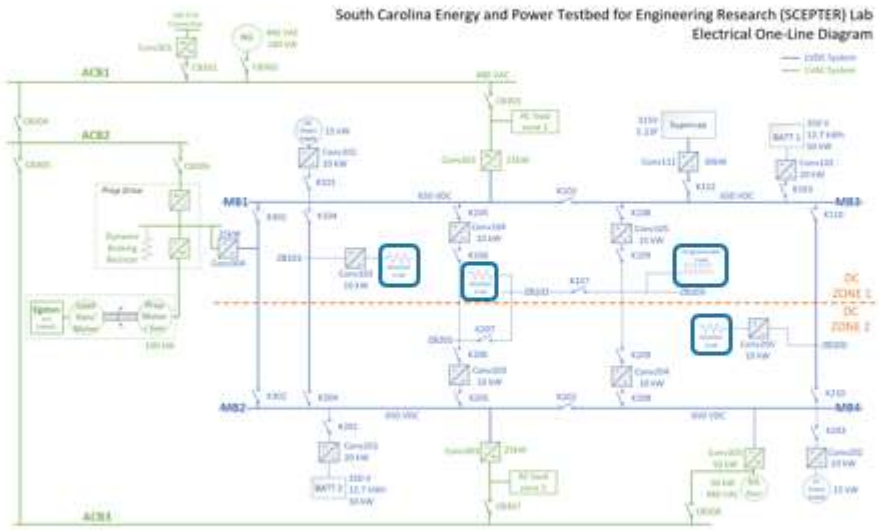
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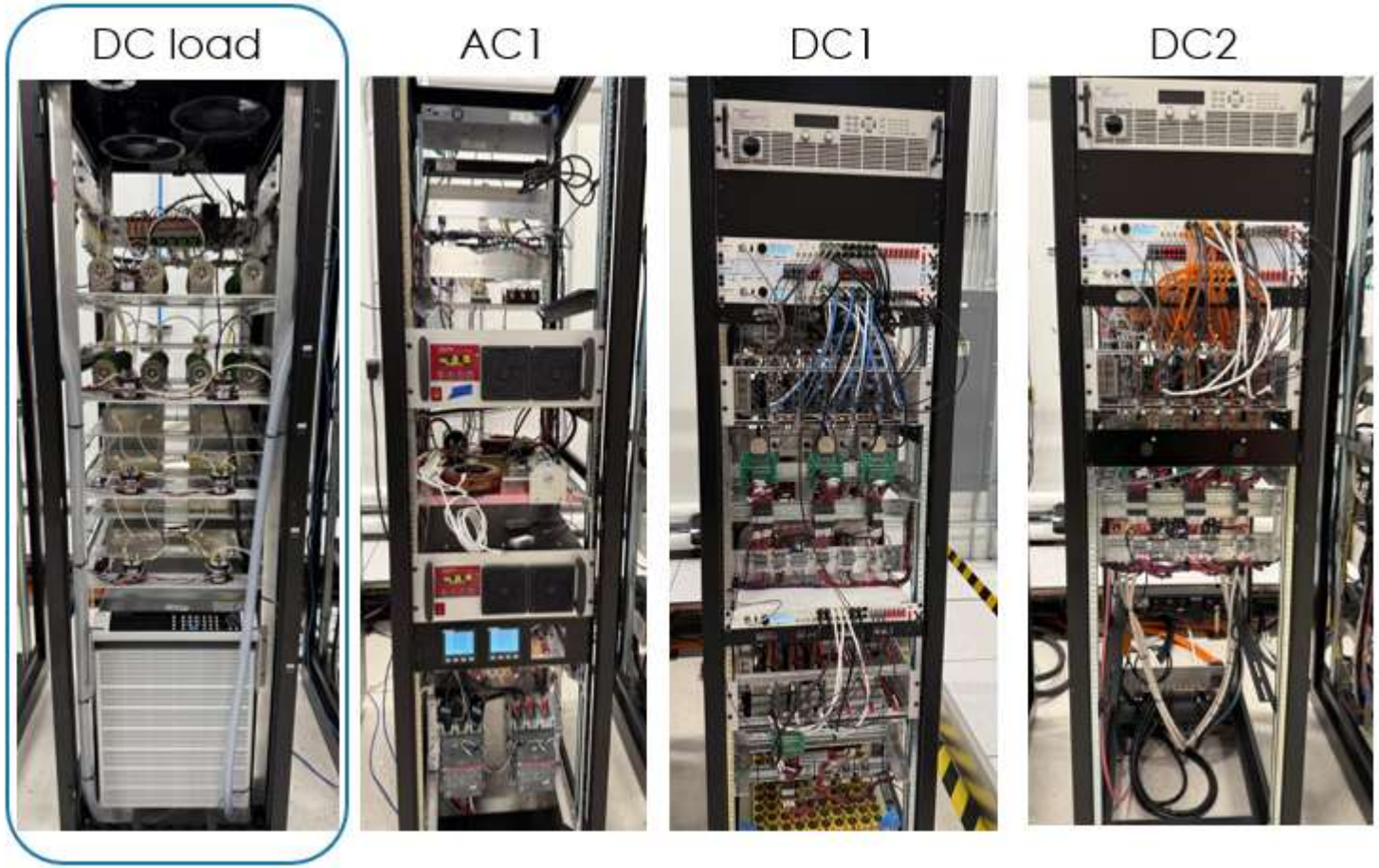
- Scaling ratios:
  - 1:30 V
  - 1:30 I
  - 1:1000 P
- Zonal architecture with three AC buses, four DC main buses
- Bidirectional converters, PHIL interfaces
- Evaluate DT performance for different applications (naval systems, EVs, microgrids, etc.)



SCEPTER Hardware

Rack mounted hardware is sectioned into zones based on one-line location

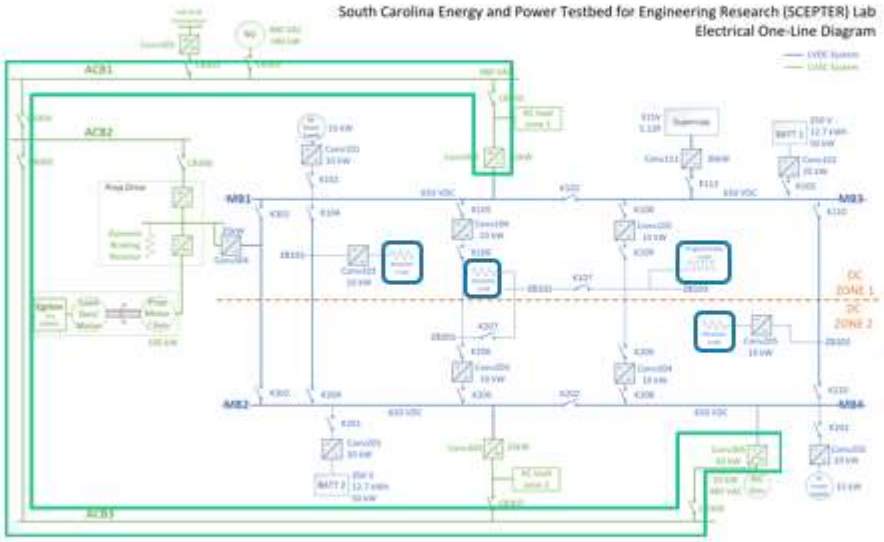


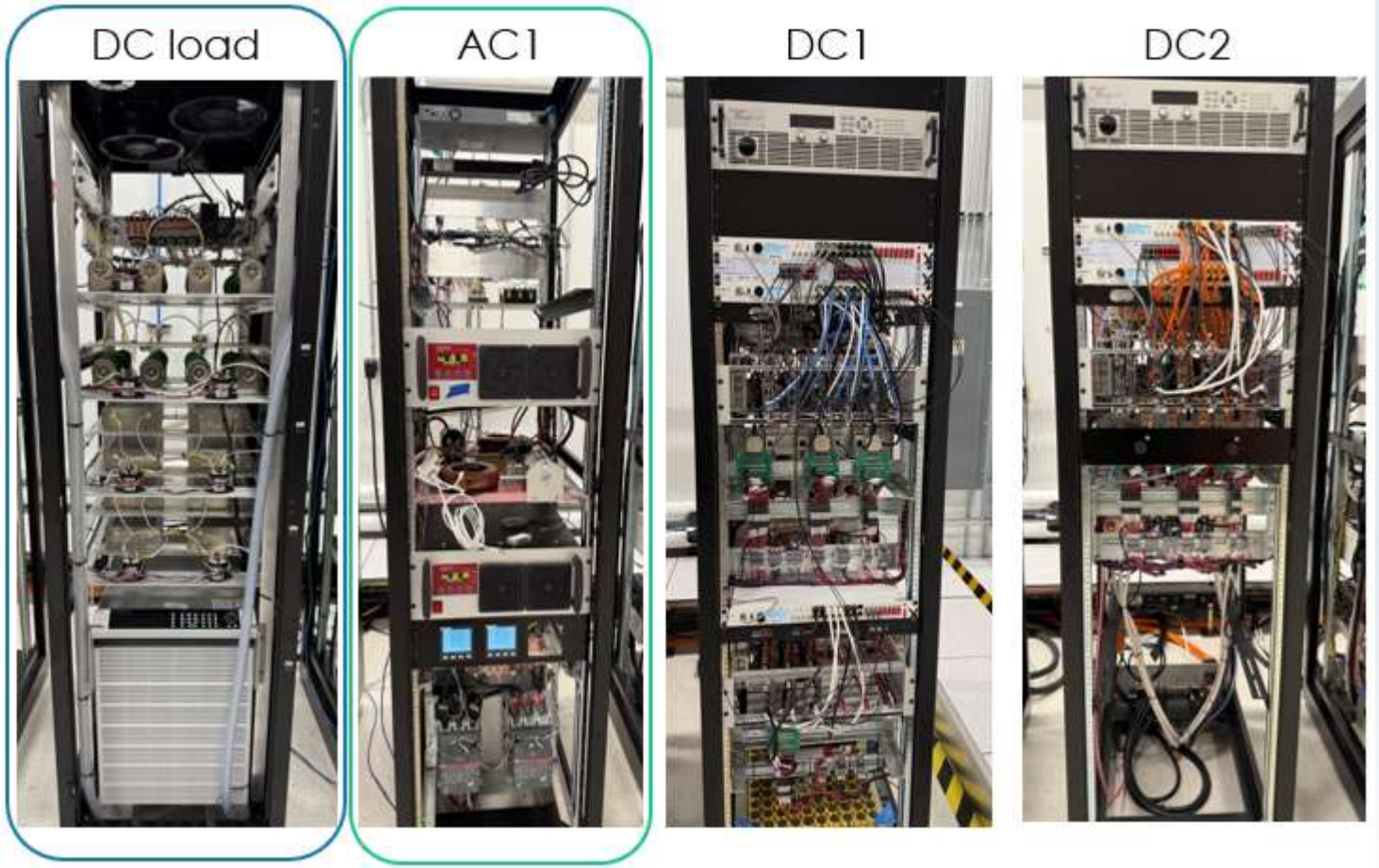


K. Sado et al., "Digital Twin Testbed for Dynamic Naval Power and Energy System Studies," 2025 IEEE Electric Ship Technologies Symposium (ESTS), Alexandria, VA, USA, 2025, pp. 452-457, doi: 10.1109/ESTS62818.2025.11152417.

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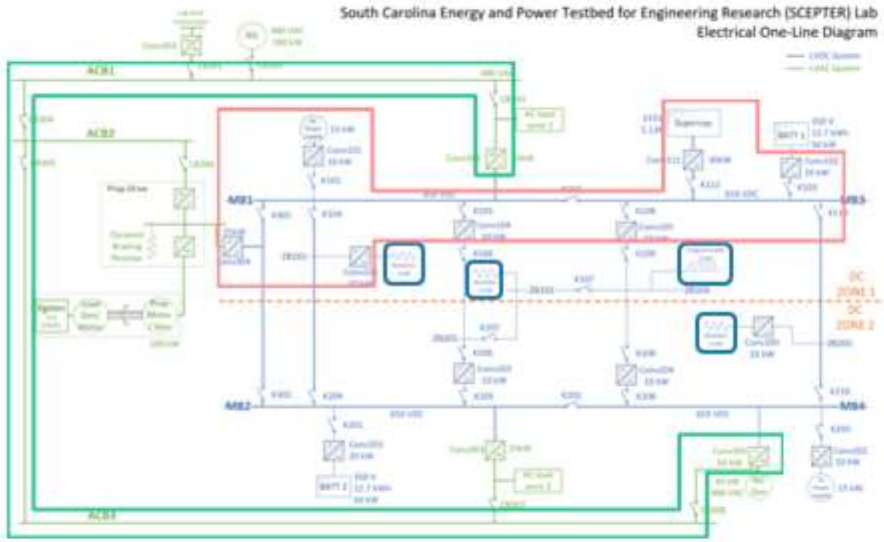
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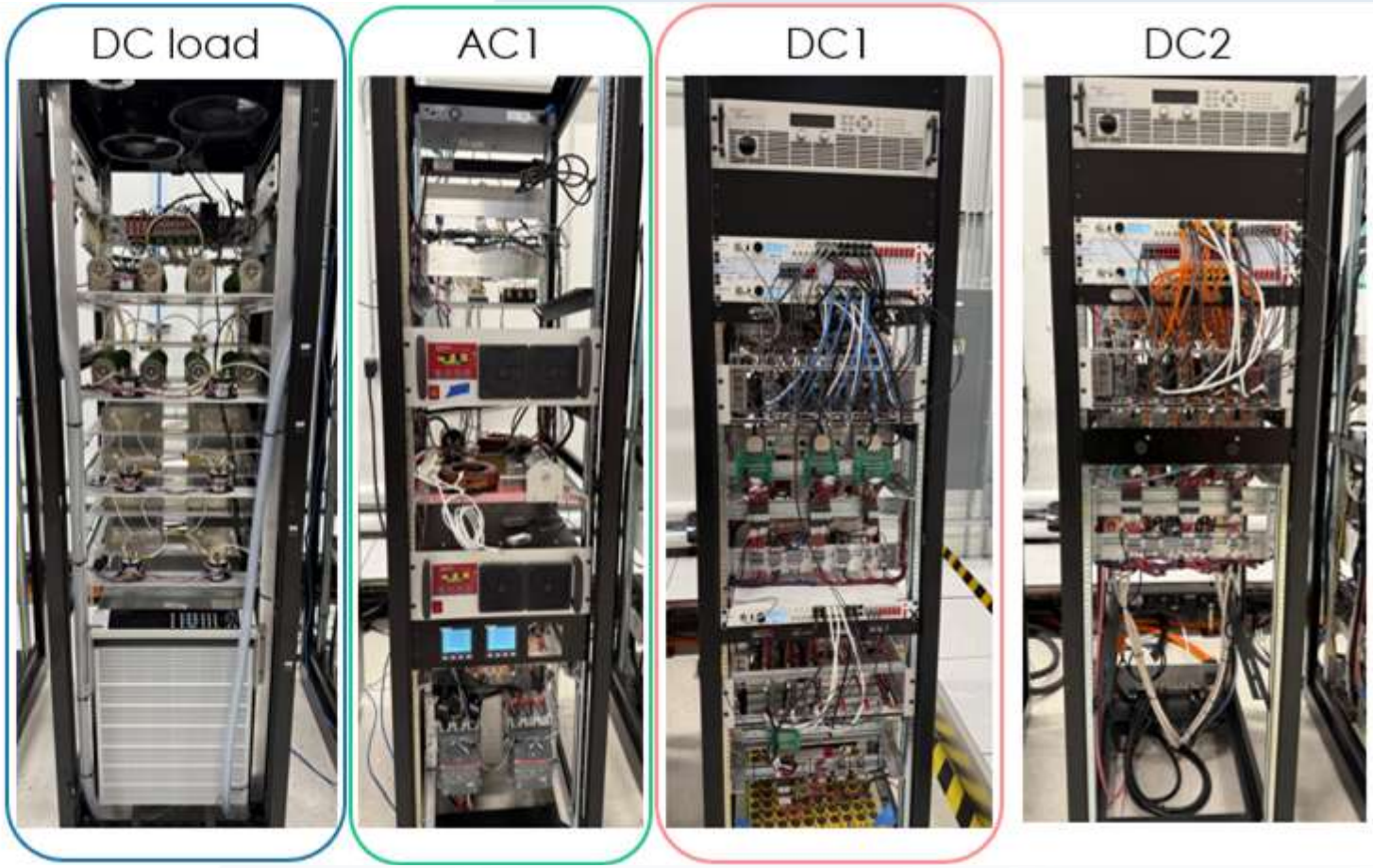




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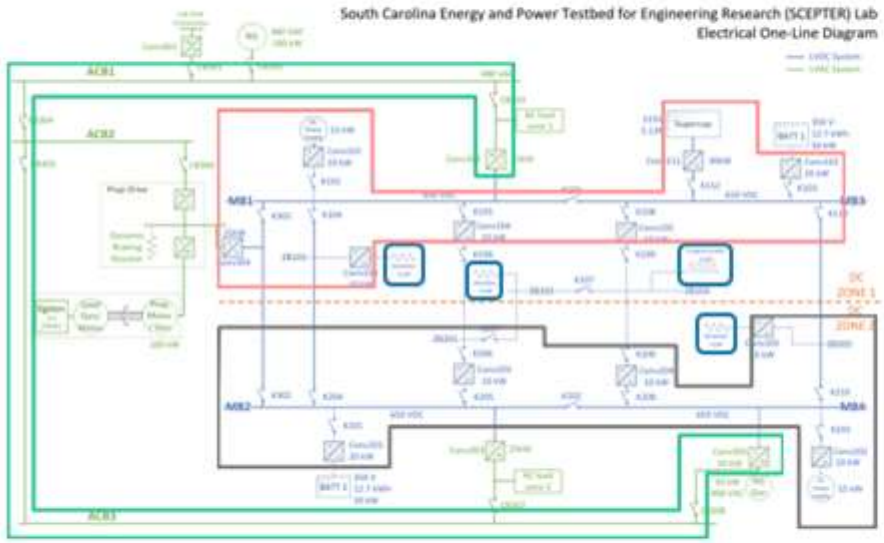
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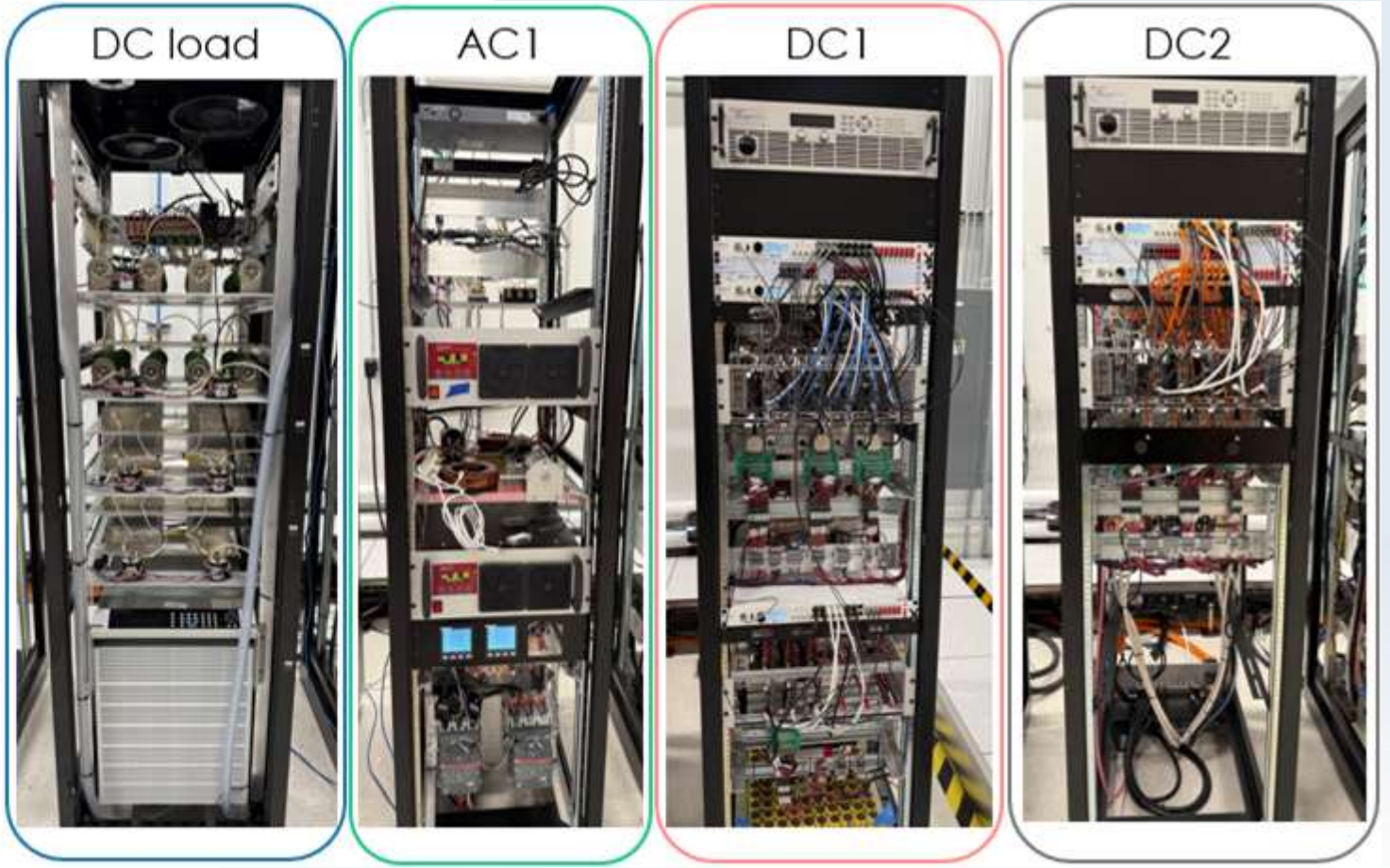




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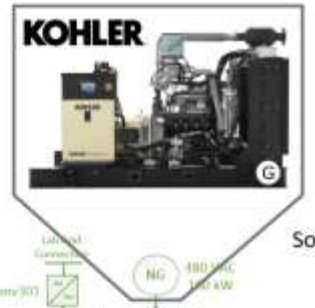


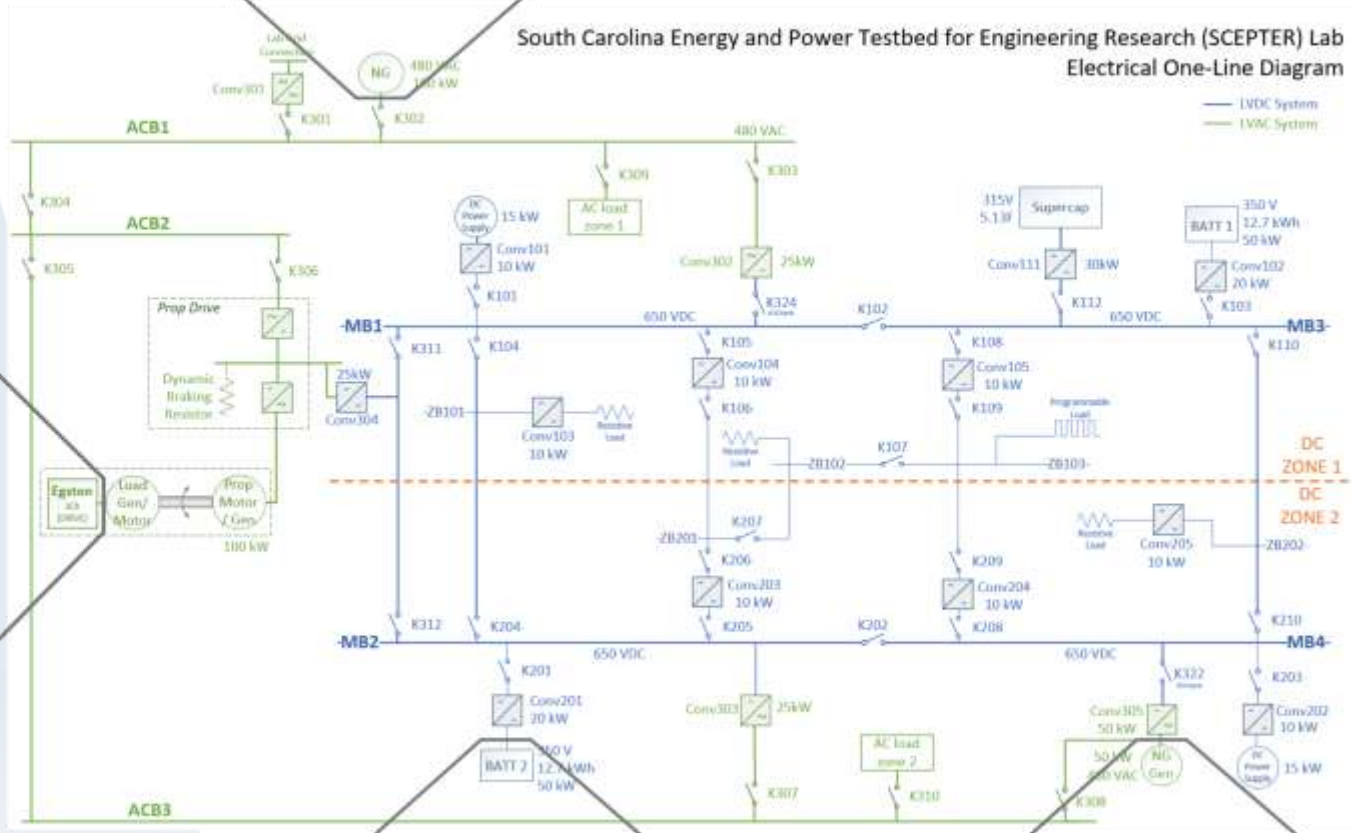


SCEPTER Hardware

- Larger equipment is housed separately from the rack-mounted modules
  - Natural gas generators
  - AC load banks
  - Battery storage
  - EGSTON power amplifiers
  - Chiller





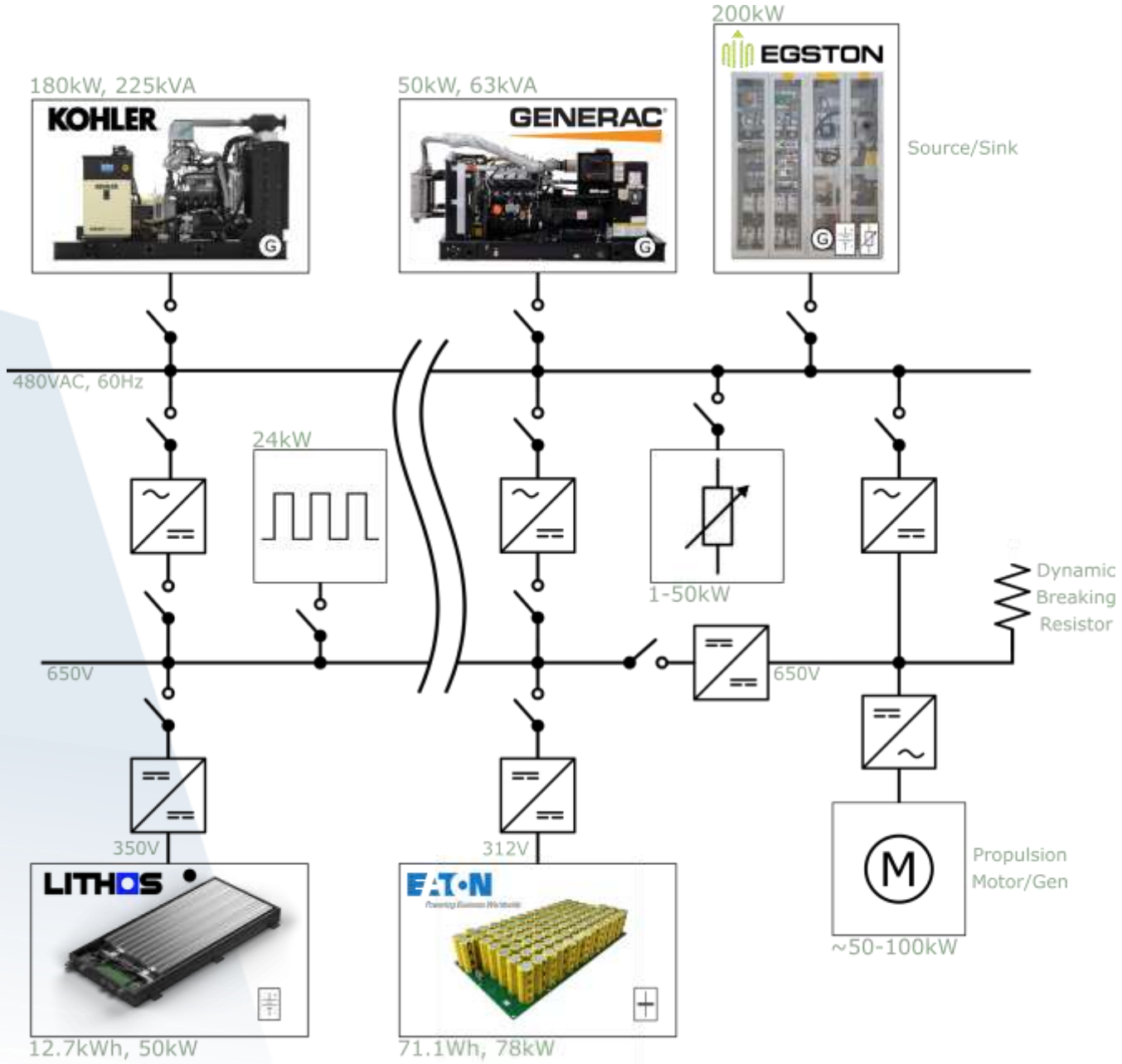






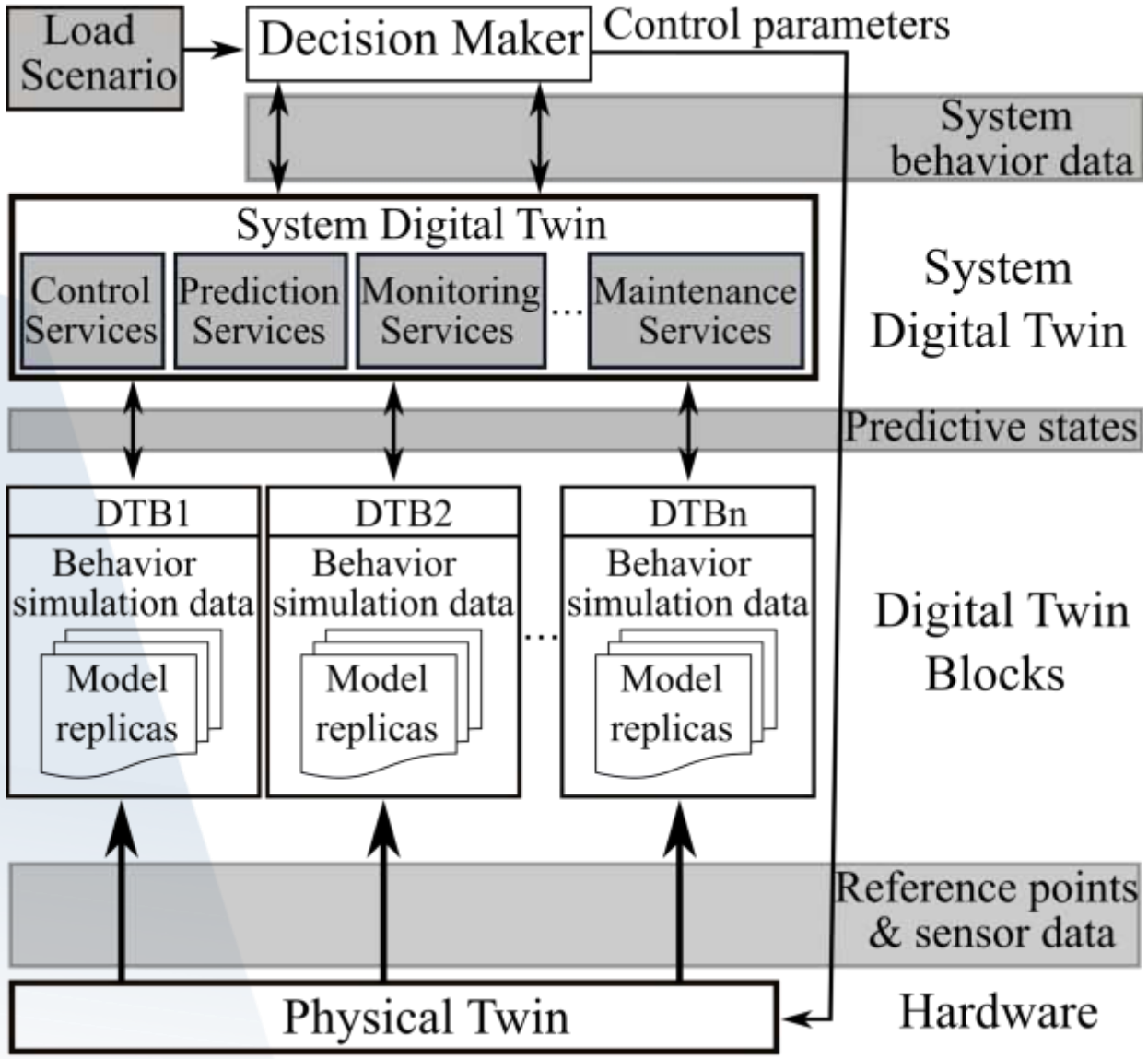
Energy Storage & Flexibility

- Energy storage systems:
  - Li-ion batteries
  - Super-capacitor
- Programmable and resistive loads to emulate scaled-down shipboard loads
- Enables exploration of power distribution methods for various conditions



Digital Twin Architecture

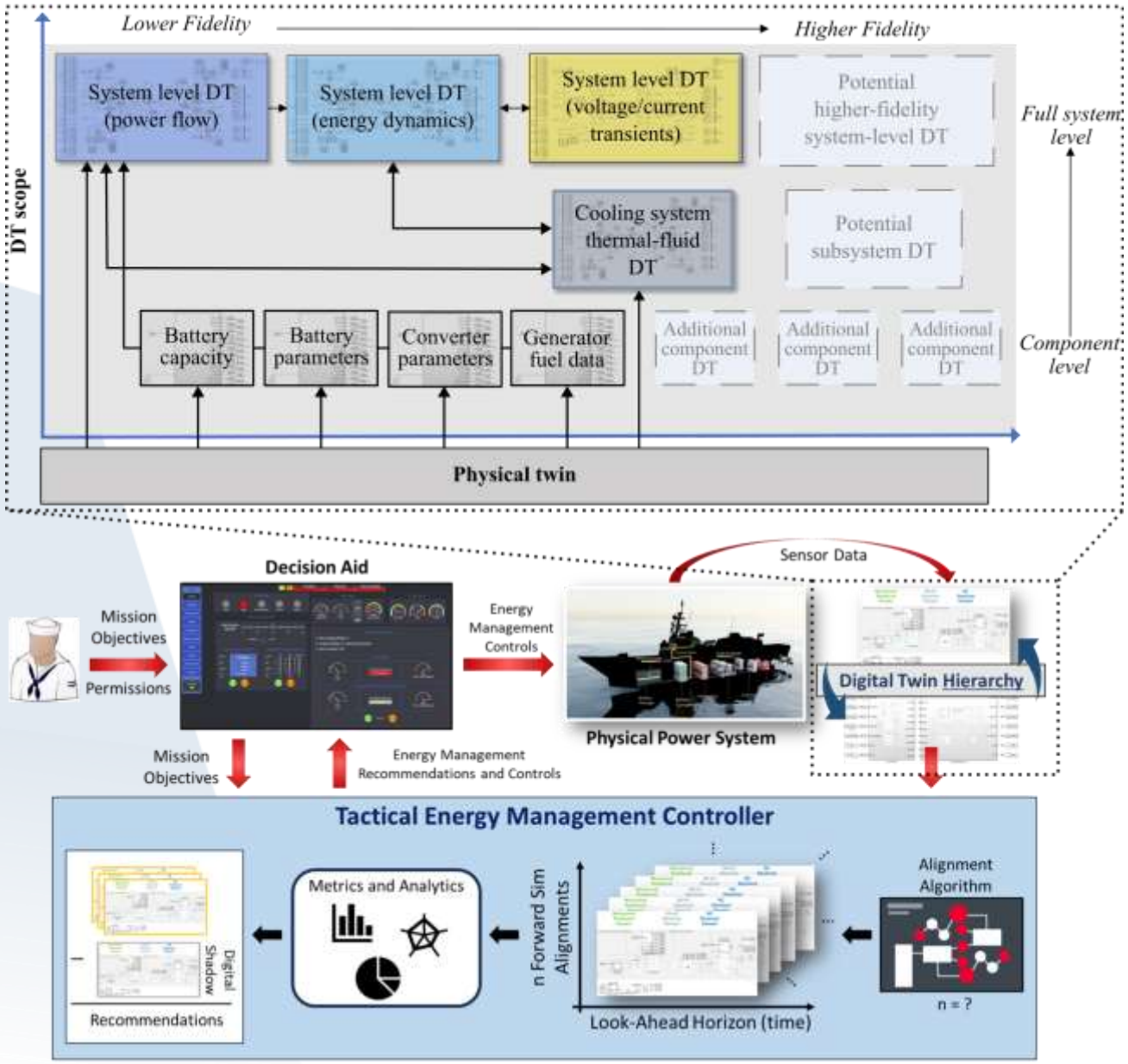
- Multiple fidelity levels to balance computational efficiency and accuracy
- Fast system-level model developed to capture dynamics of larger components (buses, converters, etc.)



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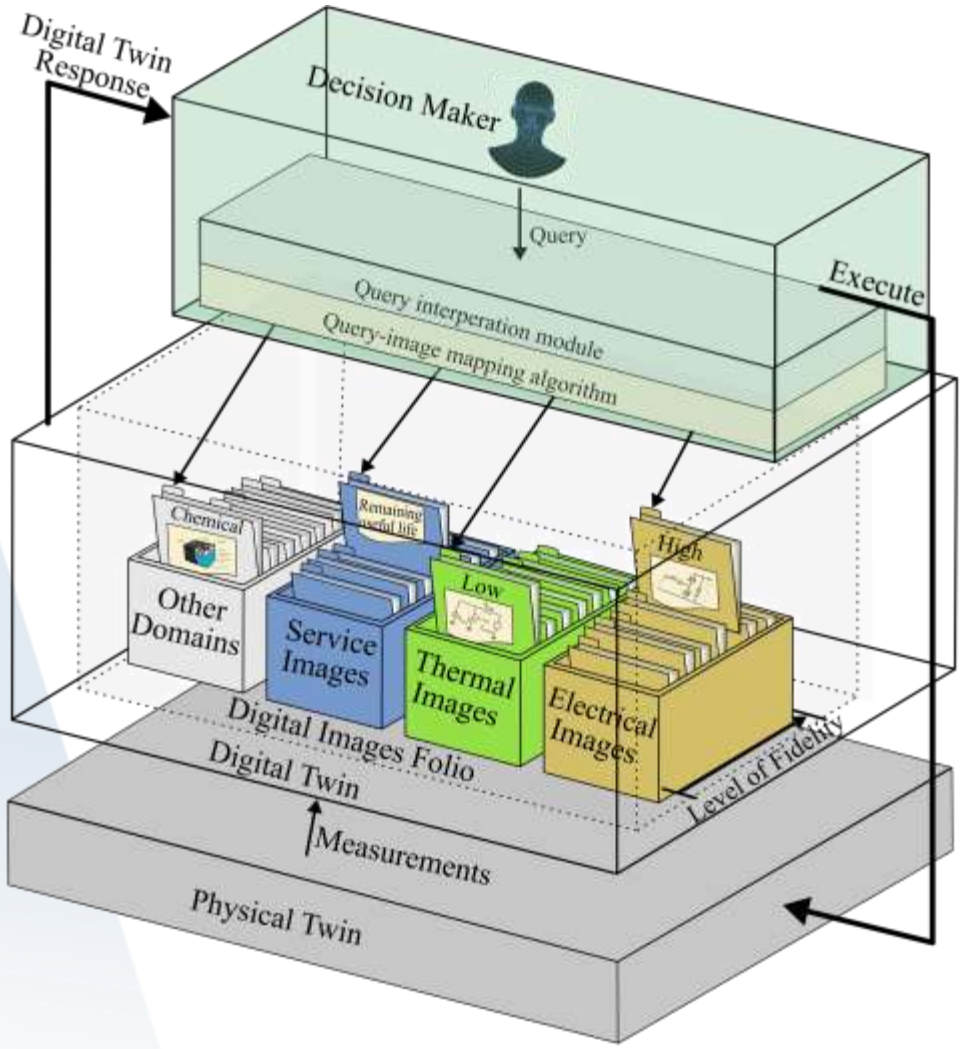
Digital Twin Architecture

- Physical Twin mapped to:
  - System-level twins
    - Power Flow
    - Energy Dynamics
    - Voltage/Current Transients
  - Component-level twins
    - Battery
    - Converter
    - Generator
    - Cooling-system



Query-image Mapping

- Dependency mapping.
- Composite query handling.
- Activation

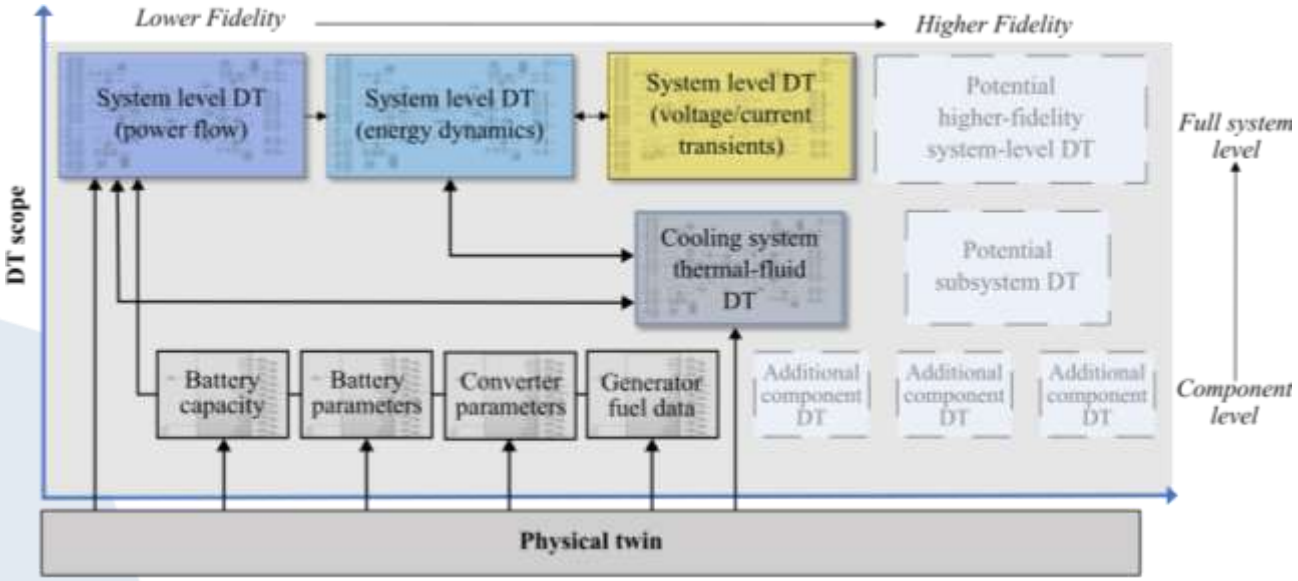


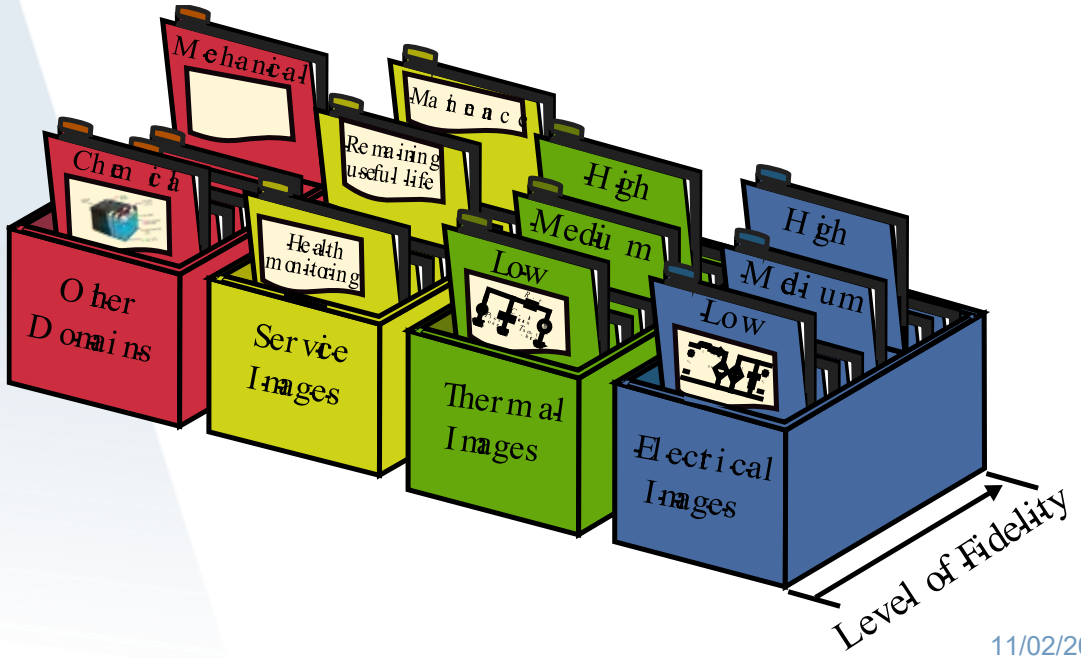
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Digital Twin Architecture

Varying fidelities, the architecture supports simulations across multi-physics domains

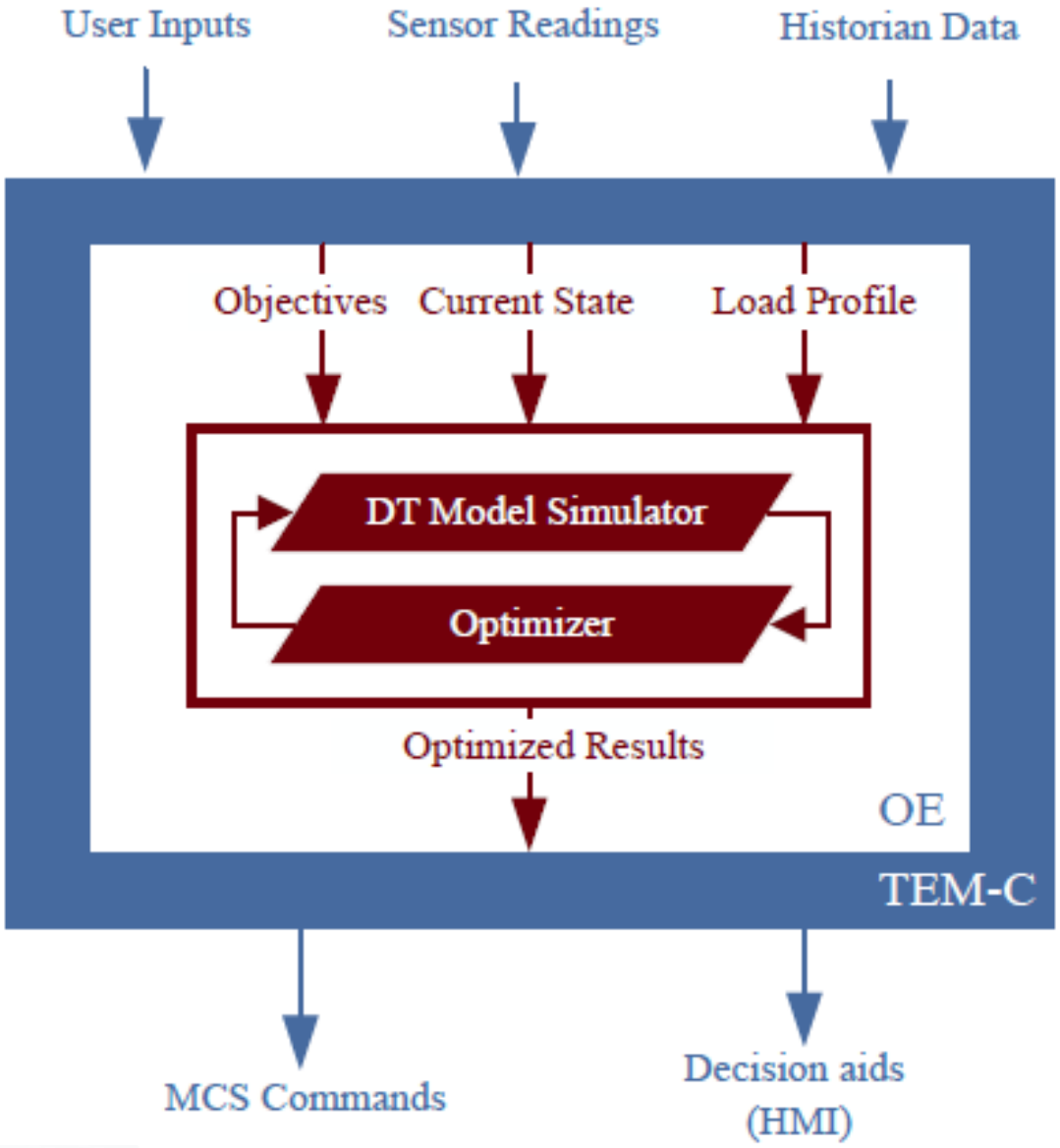
- Component-level DTs provide detailed insights into hardware performance
- Metrics such as degradation, remaining useful life, and efficiency variations are captured
- Insights inform decision-makers, enabling proactive adjustments and ensuring optimal performance





Tactical Energy Management Controller (TEM-C) & Optimization Engine (OE)

- DT Simulations deliver critical insights into system state
- TEM-C merges DT outputs, sensor data, and commands into decision aids for dynamic control adjustments
- OE runs DT-driven look-ahead simulations to craft and assess diverse control strategies
- Together, the TEM-C and OE enable real-time optimization, proactive fault management, and adaptive resource allocation for resilient naval power



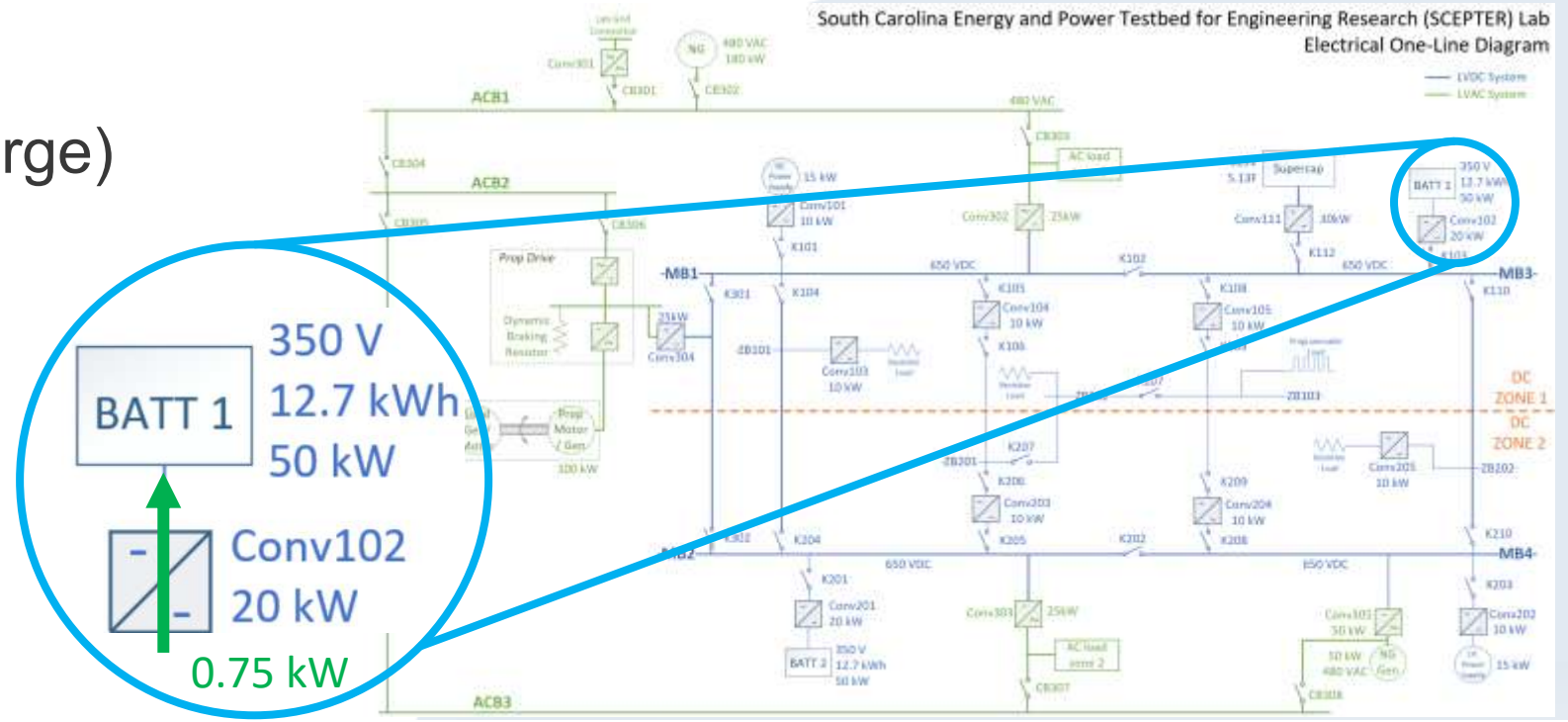
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Case Study 1

- Operator informs TEM-C that ship is to transition to the battle posture within 30 minutes
- TEM-C uses live DT states, forecasted loads, and posture rules
- The OE simulates generator ramp rates, storage availability, and load priorities to select the best alignment
- The alignment is transmitted to the TEM-C and can be automatically implemented through system controls or presented as decision aids to the user

Optimization Recommendations

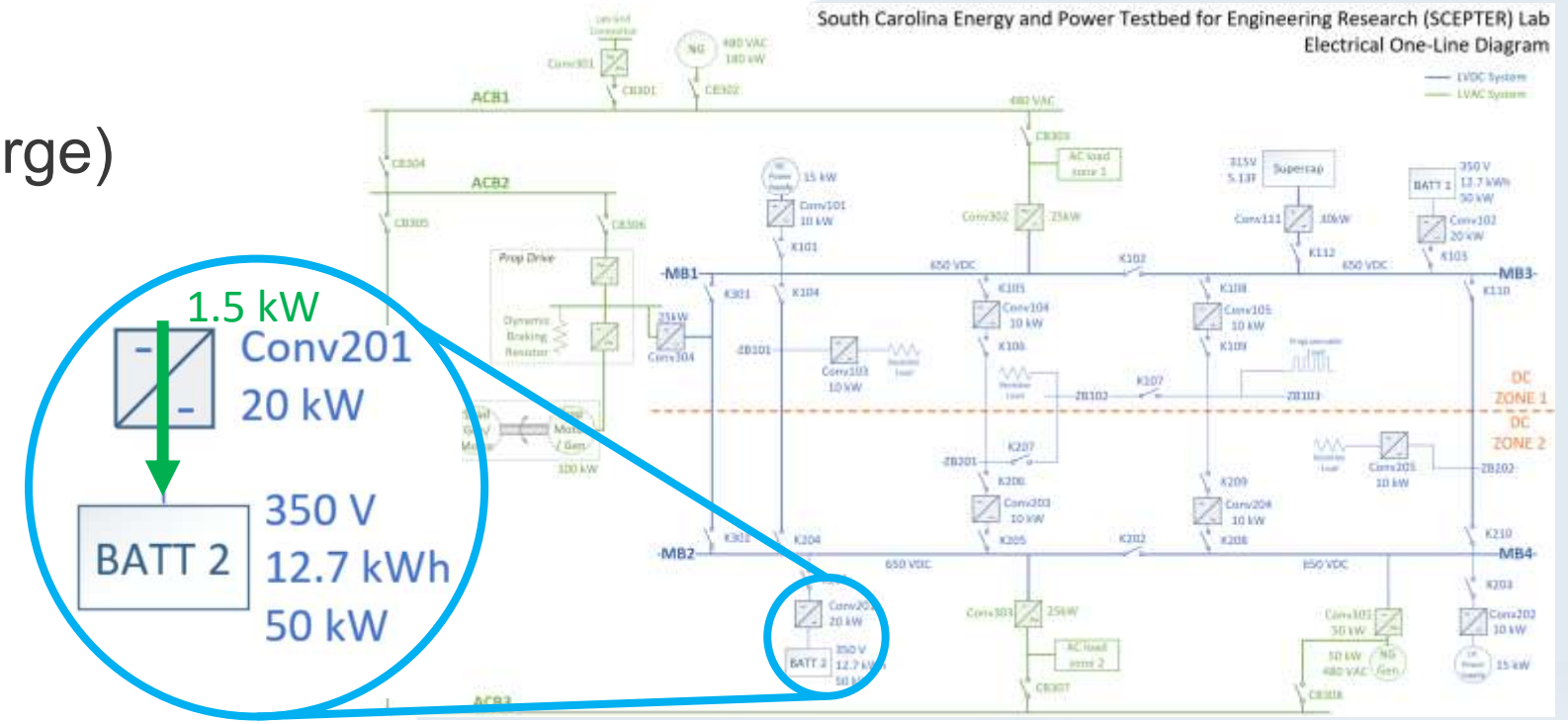
- Enable Batteries 1-2 (charge)
- Start Generator 2
- Close CB 109



Component	Cruise Mode	Battle Mode	Rationale
Battery 1	Off	Enabled, Charging 0.75 kW	SOC & Future Pulse Load Support
Battery 2	Off	Enabled, Charging 1.5 kW	SOC & Future Pulse Load Support
Generator 1	Enabled, Grid Support	Enabled, Grid Support	n/a
Generator 2	Disabled, Grid Support	Enabled, Grid Support	Anticipated threat and battle posture necessitate power redundancy
Bus Contactors	Nominal Alignment	Close CB109	Connect pulse load to bus

Optimization Recommendations

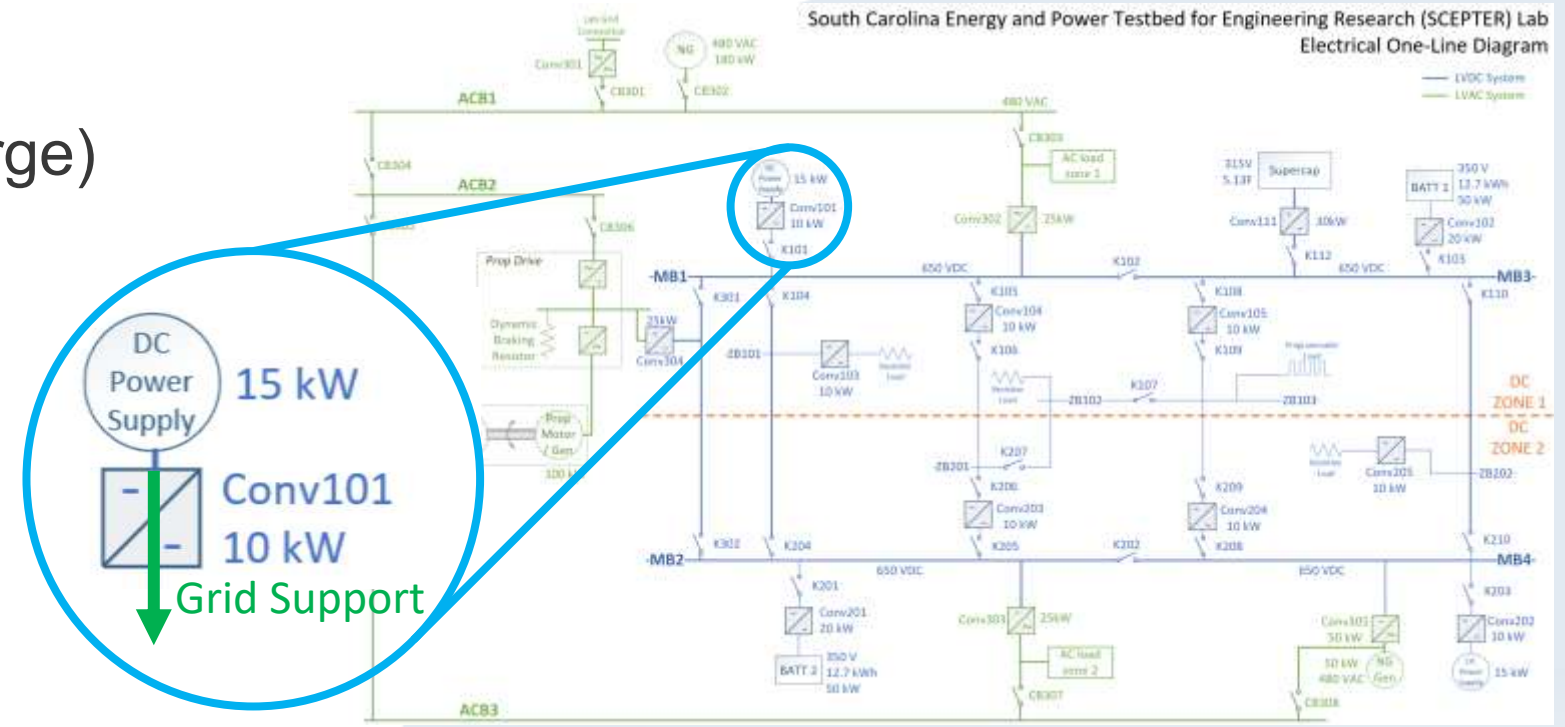
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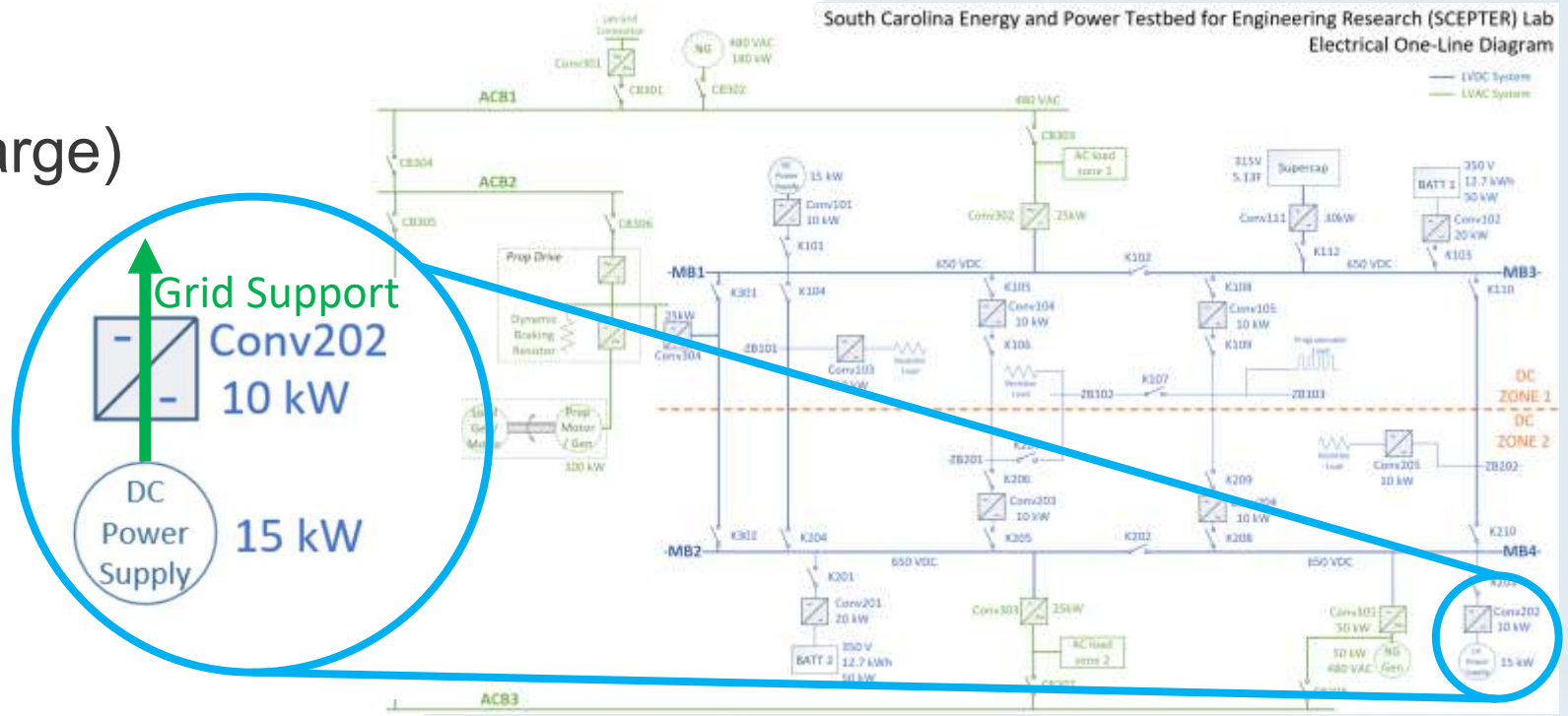
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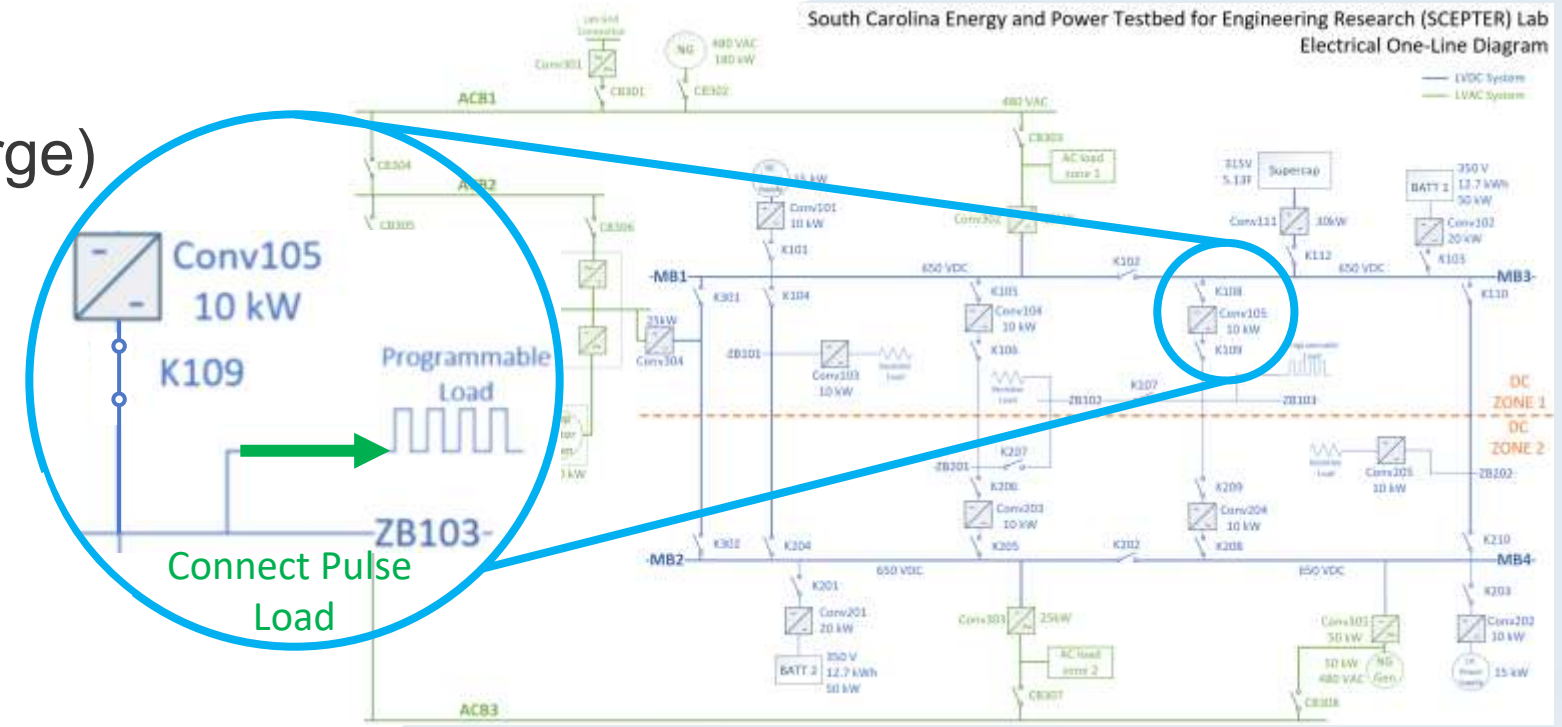
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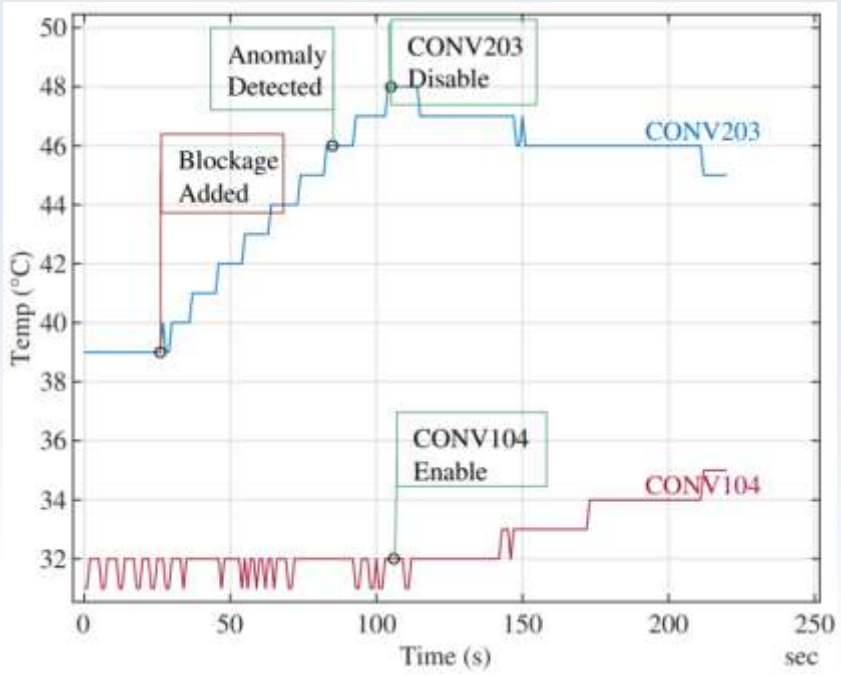
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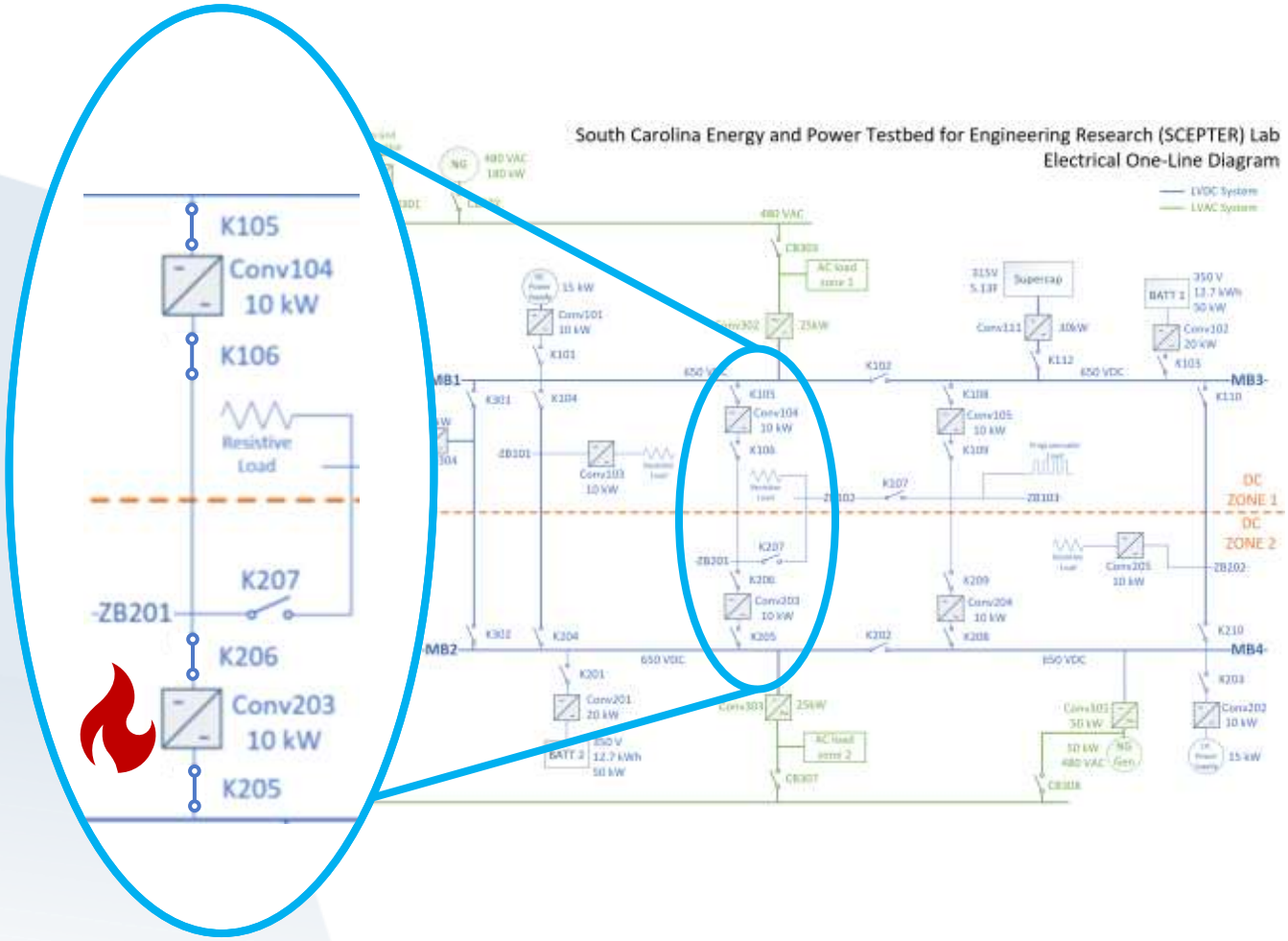
Case Study 2

- A cooling Blockage is applied in Converter 203
- DT detects the blockage 59 s after onset due to difference between measured and estimated temperatures
- After a threshold is reached, an alert is sent to the TEM-C allowing for the best course of action to be determined
- DT provides key state estimations if no actions were taken

Adaptive Response

- Isolate Converter 203
- Enable Converter 104
- Maintain load support





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System-Level Digital Twins

- Power-flow twin
  - Steady-state DC power flow model to rapidly evaluate bus voltages and power dispatch under a candidate alignment configuration
  - Used by the OE for alignment enumeration and screening during posture-based pre-alignment
- Fast System Model
  - Captures dynamic energy behavior of electrical buses, converters, and energy storage
  - Uses averaged models for converters and equivalent circuits for batteries and super-capacitor
  - Runs faster than real time (60-second look-ahead horizon in less than one second)
- Voltage/Current Transient Twin
  - High fidelity transient twin capturing converter switching ripple and fault transients
  - Used post-fault to evaluate the stability of proposed reconfiguration actions before dispatch to the physical twin

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Component-Level Twins

- Capture the detailed electro-thermal and aging behavior of key assets, exposing internal states not directly measurable by physical sensors
- **Battery Capacity and Parameter Twin**
  - Implements a second-order equivalent circuit model with an online parameter identification routine
  - Kalman filter fuses measured terminal volage and current with the model prediction to produce updated estimates of the open-circuit voltage, internal resistance, and diffusion impedances
  - From the identified parameters, the twin estimates the SoC, state of health, and RUL based on a cycle-counting degradation model calibrated against manufacturer aging data

Converter Electro-Thermal Twin Details

- Converter twin models the electro-thermal behavior of the water-cooled DC/DC converters throughout the testbed
- The twin operates two parallel sub-models for anomaly detection: a Real-Time Transient Model that captures dynamic thermal responses including thermal mass effects, and a steady-state temperature model that predicts the expected equilibrium temperature for the current load and coolant conditions
- Five temperature-based triggers are evaluated continuously:

T1. Absolute deviation (primary): a blockage is flagged if $|T_{\mathrm{PT}}(t) - T_{\mathrm{DT}}(t)| > \varepsilon_{\mathrm{T}_1}$, where T_{PT} is the measured physical twin temperature and T_{DT} is the DT prediction.

T2. Absolute deviation (redundant): a higher threshold $\varepsilon_{T_2} > \varepsilon_{T_1}$ provides a second confirmation, reducing false positives from transient load changes.

false positives from transient load changes.

T3. Rate-of-change: abnormal temperature gradients are detected by monitoring dT/dt and comparing it to the expected gradient under nominal conditions; a blockage is suspected if

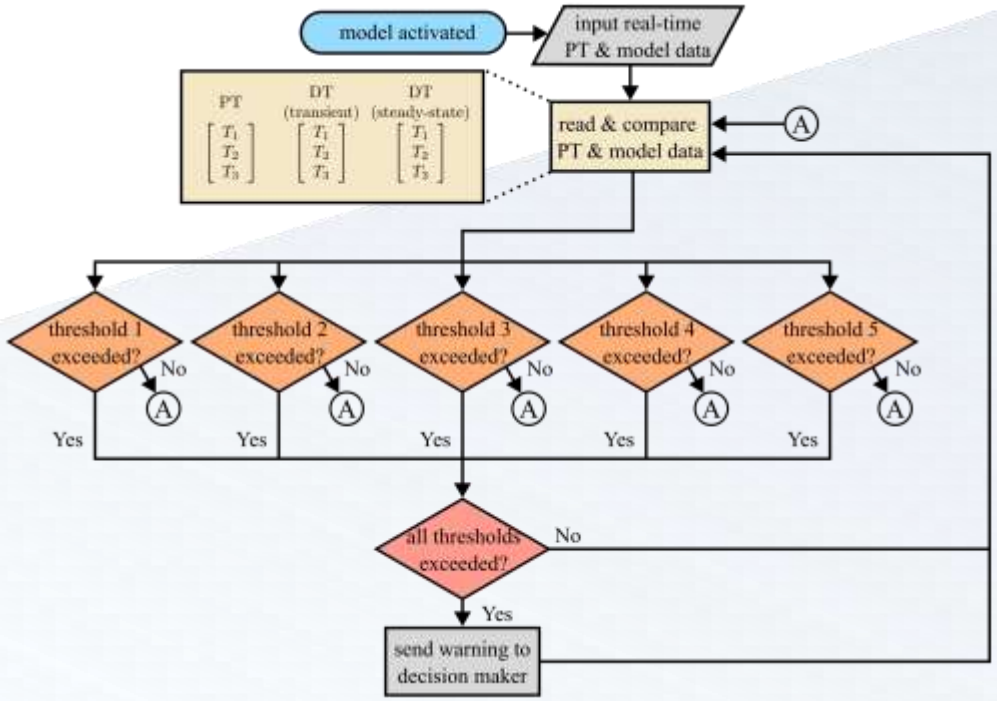
$$\left| \frac{dT}{dt} - \left[\frac{dT}{dt} \right]_{norm} \right| > \varepsilon_{\dot{T}}$$

T4. Steady-state deviation: persistent deviation of T_{PT} from the DT steady-state prediction T_{ss} beyond threshold $\varepsilon_{\mathrm{ss}}$ signals a cooling inefficiency: $|T_{\mathrm{PT}}(t) - T_{\mathrm{ss}}| > \varepsilon_{\mathrm{ss}}$.

T5. Cross-loop comparison: a blockage in one coolant loop redirects flow to adjacent loops, causing a detectable temperature drop in neighboring converters. The DT monitors for this signature to localize the blockage.

Converter Electro-Thermal Twin Details

- Flow chart detailing the anomaly detection logic of the DT system



Josiah N. Worch, Kerry Sado, Austin R. J. Downey, Jamil Khan, and Enrico Santi. Digital twin-based real-time blockage detection for liquid-cooled power electronic systems. IEEE Access, 14:62856– 62870, 2026

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Inter-Layer Data Exchange

- Data exchange is orchestrated between system-level and component-level twins through a query-response mechanism in which system-level twin requests refined estimates from component twins only when needed, managing computational cost while preserving accuracy
- The query carriers the component's current load condition and recent history; the component twin returns updated state estimates and prognostic indicators
- This on-demand coupling allows component twins to operate at their natural time scales independently of the system-level twin cycle time

TEM-C

- OE is software architecture that enables rapid prototyping and comparison of approaches
- Interface is defined by: (i) a system state vector, (ii) a predicted load profile over the look-ahead horizon, (iii) and objective function, and (iv) a set of constraints
- Algorithms currently implemented include gradient-based line search, genetic algorithms, particle swarm optimization, and a physics-based reduced-order search
- The problem can be defined as $\hat{\boldsymbol{\alpha}} = \arg\min_{\boldsymbol{\alpha}\in A} J(\boldsymbol{\alpha}, \boldsymbol{X}, L \mid s.t. \text{ constraints satisfied})$ where $\hat{\boldsymbol{\alpha}}$ is the optimal control alignment which is constrained to a feasible set A, J is the ship readiness objective function, $\boldsymbol{X}$ is the current state of the system, and L is the anticipated load profile
- For posture pre-alignment, genetic algorithm using FSM evaluates alignment configurations over 30 min look-ahead horizon to maximize a mission-readiness objective
- For fault response optimization, OE runs enumeration of reconfiguration options using power flow and transient DTs to identify the option to meet load demands while minimizing thermal stress

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HMI

- The Human-Machine Interface (HMI) presents operator decision aids: prioritized reconfiguration recommendations, prognostic indicators (time to failure, time to maintenance), system health dashboards, and look-ahead energy trajectories
- TEM-C nominally operates in a human-in-the-loop mode, requiring operator acceptance before MCS commands are dispatched, while autonomous mode is available if response times must be shorter than human reaction time

Thank you

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This work was supported by the Office of Naval Research under contracts No. N00014-23-C1012 and No. N00014-24-C-1301. The views expressed are those of the authors and do not reflect the official policy or position of the Department of War or the U.S. Government.