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

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ABSTRACT

Modern naval platforms are increasingly dependent on tightly coupled electric power and propulsion systems whose availability directly constrains mission effectiveness. Platform digital twins (PDTs) can help sustain warfighting readiness when extended into the use phase of the platform lifecycle, rather than being limited to design and acquisition. This paper presents a platform energy digital twin testbed realized on the South Carolina Energy and Power Testbed for Engineering Research (SCEPTER), a hardware microgrid scaling a notional 80 MW, 20 kV all electric naval combatant at approximately 1:30 in voltage and current and 1:1000 in power while preserving zonal architecture. A hierarchical PDT architecture spans system-level twins (power flow, energy dynamics, voltage/current transients) and component-level twins (electro-thermal and aging models), orchestrated by a Tactical Energy Management Controller (TEM-C) with a simulation-based Optimization Engine (OE). Two experimental case studies are demonstrated: (1) posture-based pre-alignment for a cruise-to-battle transition, and (2) digital twin-enabled fault detection, prognosis, and survivability-oriented reconfiguration following a converter cooling blockage casualty. Results show that physics-model-fused anomaly detection triggers approximately 59 seconds after blockage induction, providing sufficient warning for TEM-C directed load transfer that preserves mission loads and mitigates thermal escalation.

1.0 INTRODUCTION

Integrated naval power and energy systems (NPES) are transitioning toward all-electric ship architectures in which propulsion, combat systems, directed-energy weapons, and hotel loads share a common electrical distribution network. This convergence creates both opportunities and challenges: coordinated energy management can enhance mission effectiveness and fuel efficiency, but tightly coupled systems are also more susceptible to cascading failures when any subsystem is degraded. Prognostic health management (PHM) and battle damage assessment (BDA) are therefore critical capabilities for maintaining warfighting readiness, and both depend on accurate, real-time knowledge of component state that physical sensors alone cannot provide. Digital twins (DTs) have emerged as a foundational technology for bridging this sensing gap. A DT is a virtual, continuously updated representation of a physical asset that integrates real-time sensor data, physics-based models, and operational context to predict future behavior, detect anomalies, estimate remaining useful life (RUL), and support decision-making [1, 2]. The concept has roots in early hardware twins (physical replicas developed for the USS Nautilus SSN-571 powerplant in 1954 and the Nuclear Ship Savannah in 1959) and was central to the Apollo XIII recovery in 1970. Modern DTs extend these ideas with data-driven models, cyber-physical synchronization, and autonomous optimization, enabling a shift from reactive maintenance to predictive and prescriptive operations [3]. In naval and maritime contexts, DTs have shown value for real-time simulation of shipboard power systems, optimization of energy distribution, and prediction of system behavior under varying conditions [4,5]. The need for scalable, multi-fidelity architectures that combine physics-based

and data-driven models, support RUL estimation, and integrate with maintenance planning has been well documented [6–9]. However, validated testbeds that demonstrate end-to-end platform DT (PDT) workflows encompassing anomaly detection, prognosis, and survivability-oriented reconfiguration under experimentally induced casualty conditions remain limited. This paper addresses that gap by presenting the South Carolina Energy and Power Testbed for Engineering Research (SCEPTER) platform energy digital twin testbed and experimentally demonstrating two PDT use cases aligned with the AVT-SAS-HFM-SET-421 research topics: posture-based pre-alignment for cruise-to-battle transitions, and PHM/BDA for a converter cooling blockage casualty. The primary contributions are:

(1) A Power-Hardware-in-the-Loop (PHIL)-enabled platform energy digital twin testbed representative of a modern NPES;

(2) A hierarchical, multi-fidelity PDT architecture integrated with a Tactical Energy Management Controller (TEM-C) and Optimization Engine (OE) suitable for continuous, posture aware operation; and

(3) Experimentally validated PHM/BDA use cases demonstrating prognostic fault detection, time-to-failure estimation, and survivability-oriented reconfiguration.

1.1 Related Work

Research on DT-driven PHM frameworks has highlighted the need for scalable architectures that combine physics-based and data-driven models and support RUL estimation. Toothman et al. [6] established a modular DT framework for PHM applicable across industrial assets. Xiao et al. [7] extended this to a broad class of industrial assets with emphasis on data fusion and predictive maintenance scheduling. Fang et al. [8] surveyed next-generation PHM technologies, highlighting the role of DTs in integrating multi-physics sensing with machine learning for enhanced fault diagnostics. Penteado et al. [9] reviewed DT applications in asset prognosis and health management with a focus on industrial operations. For NPES, Cronin et al. [10] developed the Fast System Level Model, a faster-than-real-time DT for look-ahead simulation and control parameter optimization. Sado et al. [11] introduced a hierarchical DT architecture for multi-physics integration, [12] provided a query-and-response inter-layer communication framework, and [13] presented an integrated NPES digital twin testbed for optimization, anomaly detection, and reconfiguration. For cooling-system PHM, Worch et al. [14] developed a DT framework for real-time blockage detection and autonomous recovery in liquid-cooled power electronics—the component-level model underlying the case study in Section 5.2. In broader maritime digitalization, Majidi Nezhad et al. [5] and Madusanka et al. [4] surveyed marine energy DT approaches, identifying zonal electric architectures and high-energy mission loads as key drivers for real-time DT-enabled energy management.

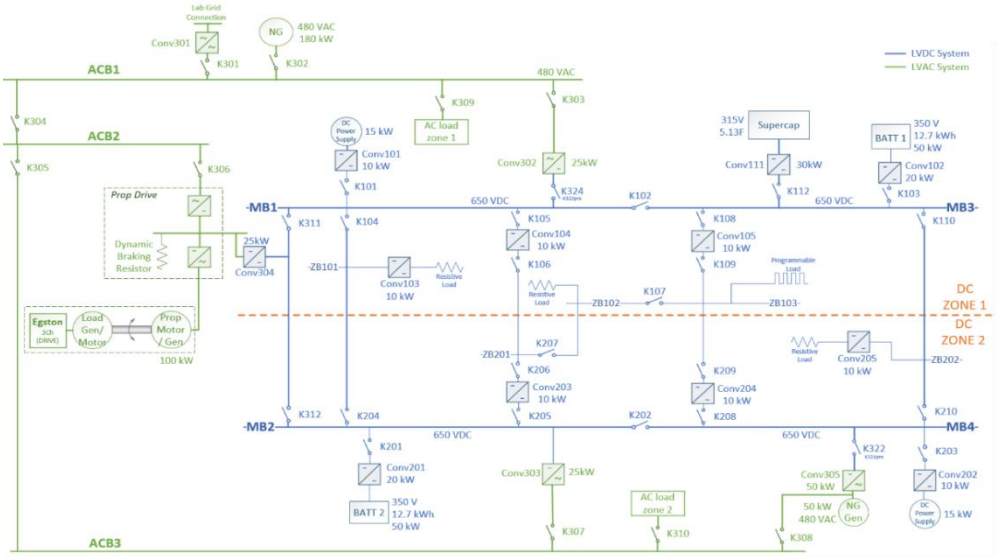
2.0 SCEPTER PLATFORM ENERGY TESTBED

The South Carolina Energy and Power Testbed for Engineering Research (SCEPTER) is a scaled hardware microgrid designed to replicate the electrical architecture of a notional 80 MW, 20 kV all-electric naval combatant. Scaling factors of approximately 1:30 for voltage and current and 1:1000 for power produce a laboratory-scale environment that preserves the zonal topology, control interactions, and energy management challenges of a full-scale NPES, while remaining compatible with commercially available power electronics and instrumentation.

2.1 Power Architecture and Zones

As shown in Figure 1, the physical twin comprises three AC buses (ACB1–ACB3) and four DC main buses (MB1–MB4), interconnected through bidirectional converters rated from 10 kW to 50 kW at 650 VDC. Two natural gas generators emulate ship service generation: Generator 1 connects to ACB1 supplying up to 100

kW, and Generator 2 feeds ACB3 at 50 kW. A laboratory grid connection at ACB1 provides an additional generation path for reconfiguration experiments. Zonal DC buses (ZB101–ZB202) distribute power to loads within each zone. Zone 1 and Zone 2 correspond to distinct damage control zones on the notional vessel, each served by dedicated DC main buses and bidirectional converters. This location-based zonal design ensures that faults or casualties in one zone can be electrically isolated, supporting the survivability and recoverability



(a)



(b)

Figure 1: SCEPTER hardware testbed: (a) one-line diagram of the scaled naval power and energy system; and (b) an image of the corresponding laboratory hardware.

objectives central to BDA workflows.

2.2 Energy Storage and Loads

Two lithium-ion battery banks (BATT 1 and BATT 2, each 350 V, 12.7 kWh, 50 kW) are connected to MB3 and MB2 respectively, emulating shipboard energy storage for load leveling, pulse-load support, and emergency ride-through. A 315 V supercapacitor bank (5.13 F) connected to MB3 provides high-power

density energy buffering for rapid transient demands. Loads include programmable DC constant-power loads, resistive loads, a propulsion drive capable of motoring and generating modes, and an Egston three-channel programmable AC source that emulates propulsion motor dynamics. AC loads in Zones 1 and 2 represent hotel and combat-systems loads. PHIL interfaces allow laboratory hardware to be exercised under emulated ship conditions while remaining tightly coupled to the digital twin. PHIL enables real-world hardware components, such as propulsion motors or energy storage, to receive real-time set-points from the TEM-C, creating a closed-loop physical–digital system.

2.3 Instrumentation and Real-Time Computing

System-wide sensing is implemented through voltage, current, temperature, and state-of-charge sensors distributed across all buses, converters, batteries, and load nodes. Data is aggregated on a National Instruments CompactRIO real-time controller that implements low-level control logic, protection functions, and data acquisition at rates up to 1 kHz. Data is archived to a server accessible by the TEM-C for DT state initialization and trending. The physical twin communicates with the digital twin hierarchy via a Machinery Control System (MCS) interface that accepts set-points from the TEM-C and returns measured states to the DT framework.

3.0 PLATFORM DIGITAL TWIN ARCHITECTURE

The PDT architecture is hierarchical and multi-fidelity, spanning component-level and system level twins with varying time scales and modeling approaches, following the frameworks of [11, 12] and extended here for PHM and BDA integration. Figure 2 illustrates the full hierarchy mapping the physical twin to digital twin layers and the TEM-C decision layer.

3.1 System-Level Digital Twins

Three system-level twins operate at increasing fidelity.

3.1.1 Power-Flow Twin

A steady-state DC power flow model rapidly evaluates bus voltages and power dispatch under a candidate alignment configuration. This model is used by the OE for alignment enumeration and screening during posture-based pre-alignment.

3.1.2 Fast System Model

The Fast System Model (FSM) is developed in MATLAB/Simulink and captures the dynamic energy behavior of electrical buses, bidirectional converters, and energy storage [10]. The FSM uses averaged switching models for power converters and equivalent-circuit models for batteries and the supercapacitor, enabling it to run faster than real time: a 60-second look-ahead horizon completes in less than one second of wall-clock time on the TEM-C computing platform. The

FSM accepts as inputs the current system state (bus voltages, state of charge (SoC), generator set-points, switch positions) and a predicted load profile, and returns bus voltages, power flows, energy storage trajectories, and component thermal estimates over the look-ahead horizon.

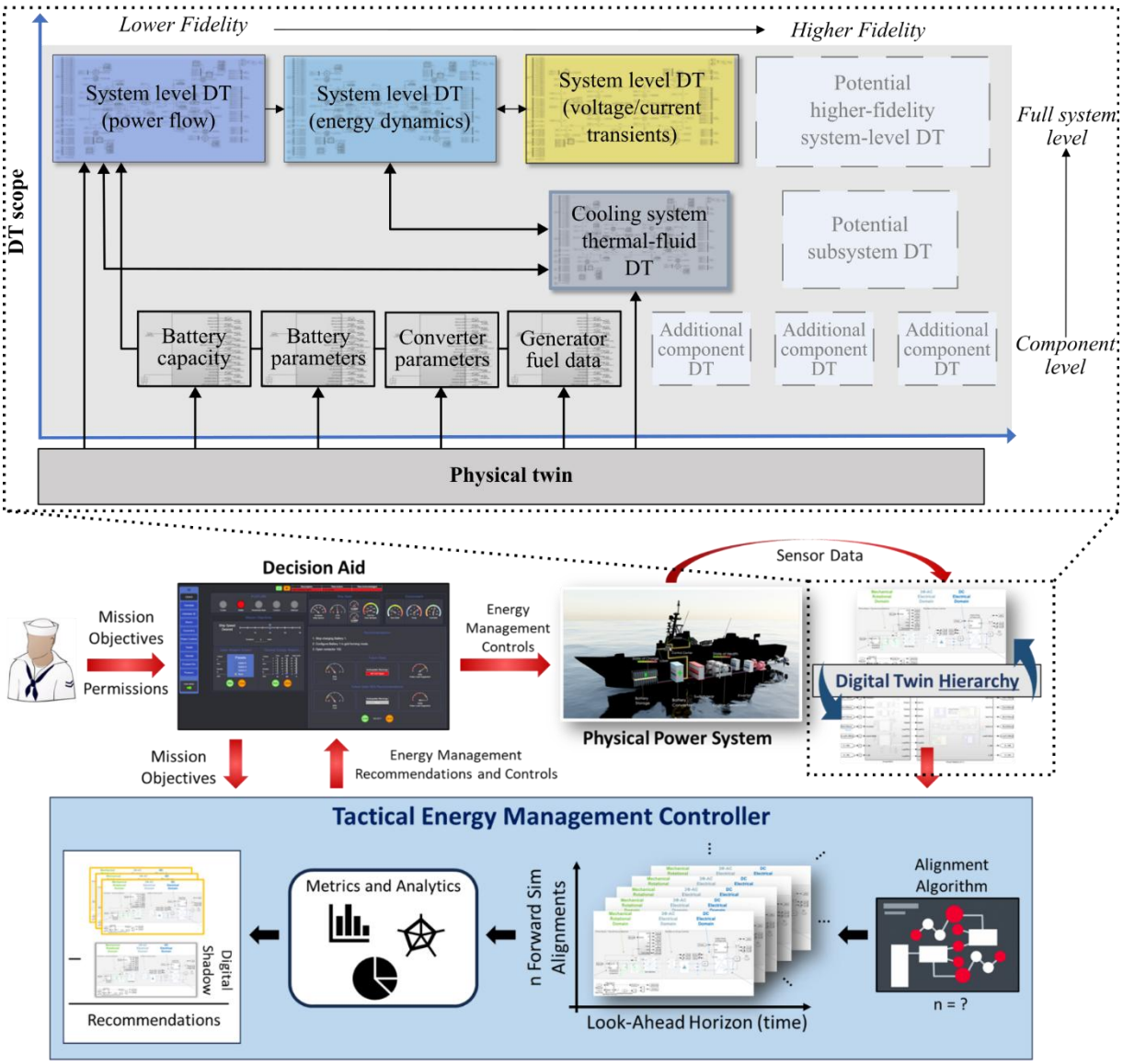


Figure 2: Hierarchical platform energy digital twin architecture mapping the physical twin to system-level twins (power flow, energy dynamics, voltage/current transients) and component-level twins (battery, converter, generator, and cooling-system models) across a range of model fidelities, together with the Tactical Energy Management Controller (TEM-C) and Optimization Engine (OE).

3.1.3 Voltage/Current Transient Twin

A high-fidelity transient twin captures converter switching ripple and fault transients. This twin is used post-fault to evaluate the stability of proposed reconfiguration actions before dispatch to the physical twin, preventing inadvertent instability from TEM-C-commanded reconfigurations during casualty response.

3.2 Component-Level Digital Twins

Component-level twins capture the detailed electro-thermal and aging behavior of key assets, exposing internal states not directly measurable by physical sensors.

3.2.1 Battery Capacity and Parameter Twin

The battery twin implements a second-order equivalent circuit model with an online parameter identification routine. At each time step, a Kalman filter fuses the measured terminal voltage 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 (SoH), and RUL based on a cycle-counting degradation model calibrated against manufacturer aging data.

3.2.2 Converter Electro-Thermal Twin

The converter twin models the electro-thermal behavior of the water-cooled DC/DC converters throughout the testbed. The thermal sub-model follows the framework of [14], governing heat flow using Fourier's law of conduction:

$$q = -k\nabla T \tag{1}$$

and Newton's law of cooling for convective heat transfer between the converter baseplate, coolant, and ambient:

$$q = h_c A \Delta T \tag{2}$$

where q is the heat flux (W m^{-2}), k is the thermal conductivity (W m^{-1} K^{-1}), h_c is the convective heat transfer coefficient (W m^{-2} K^{-1}), A is the heat transfer area (m^2), and ΔT is the temperature difference across the boundary (K). Component specifications from manufacturer datasheets, pipe dimensions and material properties, and coolant flow rate inform the model parameters.

The twin operates two parallel sub-models for anomaly detection: a Real-Time Transient Model (RTTM) 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 [14]. Figure 3 presents the anomaly detection logic as a flow chart. Five temperature-based triggers are evaluated continuously:

T1. Absolute deviation (primary): a blockage is flagged if $|T_{\mathrm{PT}}(t) - T_{\mathrm{DT}}(t)| > \varepsilon_{T_1}$, 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.

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

$$\left|\frac{dT}{dt} - \left[\frac{dT}{dt}\right]_{norm}\right| > \varepsilon_{\dot{T}} \tag{3}$$

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.

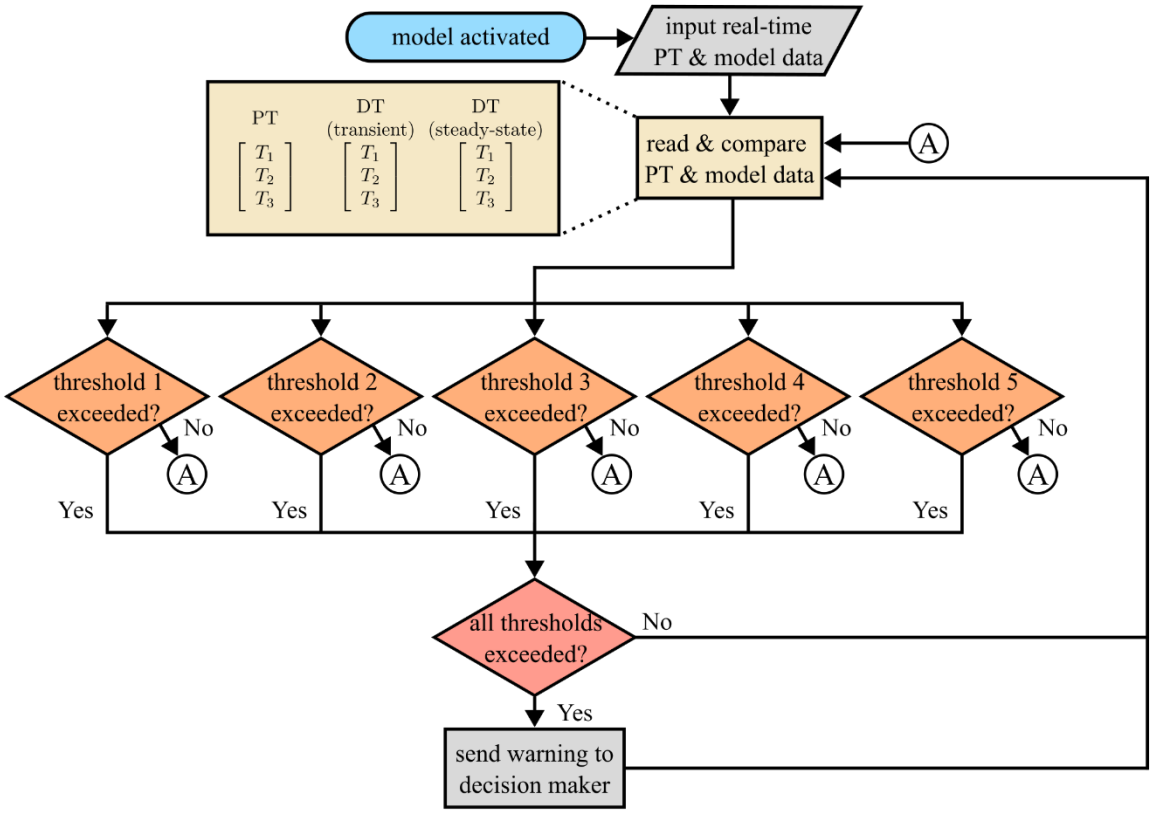


Figure 3: Flow chart detailing the anomaly detection logic of the DT system [14].

3.3 Inter-Layer Data Exchange

Data exchange between system-level and component-level twins is orchestrated through a query–response mechanism [12] in which the system-level twin requests refined estimates from component twins only when needed for the current decision cycle, managing computational cost while preserving accuracy. The query carries 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 (milliseconds to minutes) independently of the system-level twin cycle time.

4.0 TACTICAL ENERGY MANAGEMENT CONTROLLER

Decision-making is centralized in the Tactical Energy Management Controller (TEM-C), which integrates real-time sensor telemetry, historian data, operator intent (posture declarations), digital twin predictions, and component health indicators to generate decision aids and, when authorized, dispatch control actions. The TEM-C is conceptually aligned with the "platform digital twin" role articulated in the AVT-SAS-HFM-SET-421 call.

4.1 Optimization Engine

The Optimization Engine (OE) is a software architecture that is agnostic to optimization algorithm and model type, enabling rapid prototyping and comparison of approaches. The OE interface is defined by: (i) a system state vector, (ii) a predicted load profile over the look-ahead horizon, (iii) an 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 stated as

$$\widehat{\boldsymbol{\alpha}} = \arg\min_{\boldsymbol{\alpha}\in A} J(\boldsymbol{\alpha}, \boldsymbol{X}, L \mid s.t. \text{ constraints satisfied}) , \tag{4}$$

where $\widehat{\boldsymbol{\alpha}}$ 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, a genetic algorithm using the FSM evaluates discrete alignment configurations over a 30-minute look-ahead horizon to maximize a mission-readiness objective subject to SoC limits, generator ramp constraints, and component health thresholds. For fault-response optimization, the OE runs a constrained enumeration of reconfiguration options using the power-flow and transient DTs to identify the option that best preserves critical load power while minimizing thermal stress on degraded components.

4.2 Human-Machine Interface

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. The 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.

5.0 EXPERIMENTAL RESULTS

Two experimental case studies are presented. Case Study 1 demonstrates simulation-based optimization for posture-based pre-alignment. Case Study 2 demonstrates digital twin-enabled PHM and BDA for a converter cooling blockage casualty. Both studies are conducted on the SCEPTER hardware testbed with the full TEM-C/OE software stack.

5.1 Case Study 1: Posture-Based Pre-Alignment

Posture represents the readiness of a ship to achieve mission objectives through available power and supporting systems; alignment refers to the specific set-points of power system resources at a given moment. Posture-based pre-alignment proactively adjusts alignment before mission changes occur, reducing disruption and improving preparedness.

Table 1: DT-informed posture-based pre-alignment recommendations.

Component	Cruise Mode	Battle Mode	Rationale	DT Trigger
Battery 1	Off	Charging 0.75 kW	Buffer anticipated pulse load; maintain SoC margin	SoC + Load Profile
Battery 2	Off	Charging 1.5 kW	Additional energy reserve for extended engagement	Load Forecast
Generator 1	Enabled	Enabled	Primary Generation; continuous operation	N/A
Generator 2	Disabled	Enabled	Redundancy and capacity for battle-posture power surge	Threat + Posture
CB109 (Pulse Load)	Open	Closed	Connect high-energy weapon bus before transition	Mission Objective

5.1.1 Scenario Description

The testbed is operating in cruise mode: Generator 1 supplies power, Generator 2 is off, Batteries 1 and 2 are off, and bus contactors hold their nominal alignment. The operator informs the TEM-C that within 30 minutes the ship will transition to battle posture, requiring extensive manoeuvring and activation of high-energy weapon loads. Without pre-alignment, the abrupt load increase risks voltage sags, generator overload, and transient instability.

5.1.2 Optimization and Results

The TEM-C calls the OE, which runs a genetic algorithm using the FSM over a 30-minute look-ahead horizon. The objective function maximizes a composite mission-readiness score rewarding available battery SoC margin, generator headroom, and voltage stability, subject to generator ramp rate constraints, battery SoC bounds (20%–90%), and converter thermal limits.

The recommended alignment is summarized in Table 1. The DT predicted that without pre-alignment, the generator would experience approximately 15% overload for 8 seconds at transition and bus voltage would sag by up to 7%. With pre-alignment, the FSM predicts a smooth transition with generator loading remaining within 85% of rated capacity and bus voltage deviation below 3%.

Experimental measurements confirmed that the cruise-to-battle transition was accomplished without generator overload or load interruption, consistent with the FSM prediction.

5.2 Case Study 2: PHM and BDA for Converter Cooling Blockage

This case study demonstrates the full PHM/BDA workflow: anomaly detection, prognosis, TEMC-directed reconfiguration, and post-casualty state update. The scenario targets converter cooling blockage (a local casualty that can escalate into a wider power system threat if unmanaged).

5.2.1 Fault Scenario and Detection

CONV203, a 10 kW water-cooled DC/DC converter supplying zonal bus ZB201, is operating at approximately 55% load. A partial blockage is introduced into its coolant loop by partially obstructing the inlet fitting. The component-level electro-thermal twin continuously predicts converter temperature given the current electrical load, measured coolant inlet temperature, and nominal coolant flow rate using Equations (1) and (2) [14]. The physical twin provides the measured device temperature via an embedded thermistor at the converter baseplate.

After blockage introduction, the measured temperature T_{PT} diverges from the DT prediction T_{DT} as reduced coolant flow impairs heat dissipation. The DT evaluates the five blockage detection triggers on each control cycle. Trigger T1 (absolute deviation ε_{T_1} = 2 °C) and Trigger T3 (rate-of-change, Equation (3)) are the first to fire, followed by Trigger T5 (cross-loop: the temperature of neighboring CONV104 shows a slight decrease consistent with redistributed coolant flow).

As shown in Figure 4, approximately 59 seconds after blockage initiation, the composite trigger condition is satisfied, and the PDT declares an incipient thermal anomaly in CONV203. At detection, T_{PT} is approximately 3.5 °C above the DT prediction and rising. The twin simultaneously estimates the time-to-overtemperature limit (defined as 70 °C) at approximately 4.5 minutes under continued loading with no corrective action.

5.2.2 Prognostic Package and TEM-C Response

The PDT passes the following prognostic package to the TEM-C: (i) anomaly confidence level (all five triggers satisfied); (ii) estimated cooling effectiveness (≈35% of nominal, inferred from the ratio of actual to predicted temperature rise); (iii) estimated time-to-overtemperature of 4.5 minutes under current loading; and (iv) a list of candidate alternate converters with sufficient capacity to absorb the CONV203 load.

The TEM-C activates the OE, which evaluates candidate reconfiguration options using the power-flow and transient DTs to verify bus voltage stability. The recommended strategy is to: (a) reduce CONV203 load to 20% over 10 seconds via ramp command; (b) enable CONV104 (a 10 kW converter in Zone 1) and ramp it to full load; and (c) issue a maintenance alert for a cooling system inspection of CONV203.

5.2.3 Experimental Outcome

The operator accepted the TEM-C recommendation. As shown in Figure 4, CONV104 was brought to full load while CONV203 was ramped down and isolated. CONV203's temperature stabilized and began to decrease following load removal. CONV104 reached a steady-state temperature of approximately 44 °C, well within its thermal limit. Bus ZB201's voltage remained within specification throughout the transfer, and downstream loads were uninterrupted.

After reconfiguration, the updated network and operating conditions were propagated to the system-level FSM twin, which marked CONV203 as degraded and isolated. The TEM-C re-ran the OE to optimize dispatch for

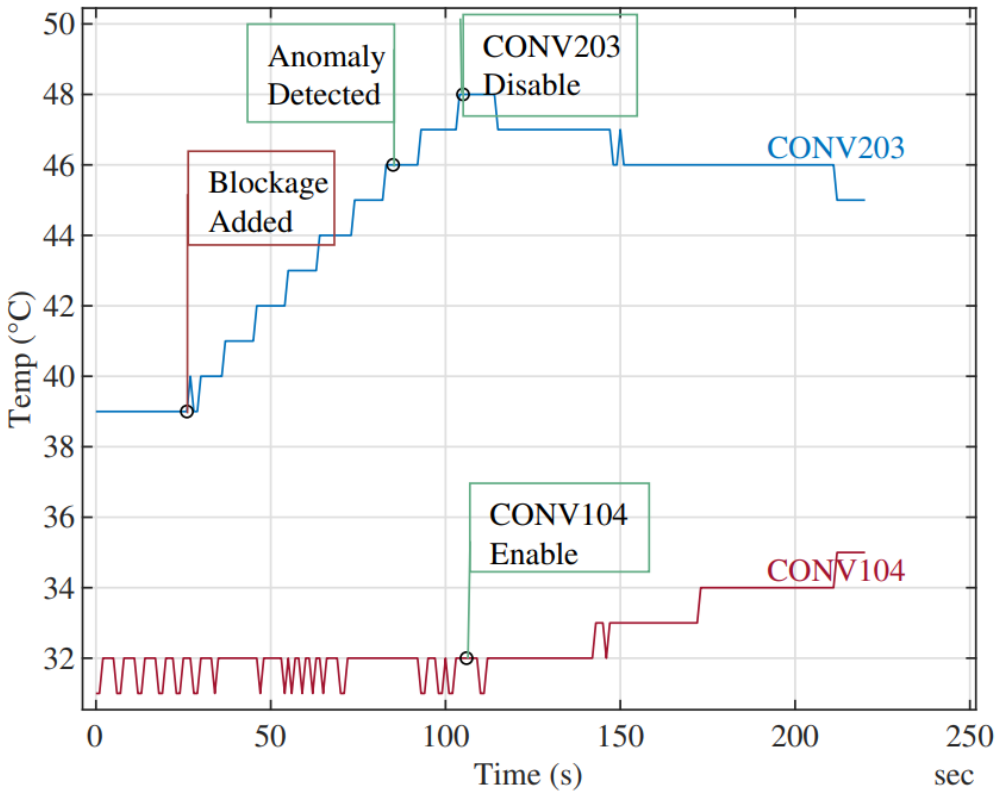


Figure 4: Converter cooling blockage experiment results showing measured temperatures of CONV203 and CONV104. CONV203, which initially supplies the load, experiences a cooling-path blockage; the anomaly is detected approximately 59s after blockage initiation. CONV104, initially off, is brought online per TEM-C/OE recommendations and supports the load, mitigating thermal escalation.

the remaining mission profile with one converter offline, closing the BDA loop: anomaly detection, prognostic isolation, reconfiguration, residual capability assessment, and updated operational planning.

6.0 DISCUSSION

The two case studies collectively illustrate how the SCEPTER testbed addresses the four topic areas of the AVT-SAS-HFM-SET-421 call.

PDT Architectures. The testbed demonstrates a multi-fidelity, multi-domain PDT with physically realized PHIL interfaces, a capability that purely software-based testbeds cannot provide. The hierarchical architecture concentrates computational resources where precision is most needed: the transient DT is invoked only to validate safety-critical reconfigurations, while the FSM handles continuous look-ahead optimization.

Optimized Control of Systems. The TEM-C/OE framework produces actionable alignment recommendations on operationally relevant time scales: minutes for posture pre-alignment and seconds for casualty response. The algorithm-agnostic OE ensures that improvements in optimization methods can be incorporated without restructuring the broader framework.

PHM. Integration of the physics-based electro-thermal twin with the five-trigger blockage detection methodology of [14] demonstrates that component-level DTs detect anomalies earlier and with greater specificity than threshold monitoring of raw sensor data alone. The cross-loop comparison trigger exploits the

global knowledge available to the DT to identify signatures that no single local sensor can detect. The time-to-overtemperature prognosis provides the TEM-C with a decision-relevant metric that quantifies urgency without requiring thermal expertise.

BDA and Platform Recoverability. The post-reconfiguration state update and residual capability assessment show how a PDT can support damage-control situational awareness. Rather than manually assessing sustainable loads with one converter offline, the TEM-C re-optimizes dispatch and presents a capability-reduced but operationally viable alignment.

Current limitations include the single-zone casualty scope and the assumption of a human-in-the-loop acceptance step. Future work will extend to multi-zone simultaneous casualties, develop autonomous response modes for time-critical scenarios, and expand the component twin library.

7.0 CONCLUSIONS

This paper presented the SCEPTER platform energy digital twin testbed and two experimental use cases relevant to AVT-SAS-HFM-SET-421. The testbed emulates an 80 MW, 20 kV all-electric naval combatant at laboratory scale using a PHIL-enabled hardware microgrid and hierarchical DT architecture spanning system-level power-flow, energy-dynamic, and transient twins, plus component-level electro-thermal, aging, and fuel twins. The TEM-C combines DT predictions, sensor data, and operator intent to generate decision aids and dispatch controls through a model-agnostic Optimization Engine.

Experimental results demonstrated:

(1) **Posture-based pre-alignment:** DT-informed genetic algorithm optimization produced an actionable generator, storage, and contactor configuration that smoothed the cruise-to-battle transition without overload or interruption; and

(2) **PHM/BDA – converter cooling blockage:** physics-model-fused anomaly detection triggered at 59 seconds post-blockage, time-to-failure prognosis quantified urgency, and TEMC-directed load transfer was completed without interruption to the downstream load.

These results support the conclusion that platform energy digital twins operating in the use phase of the ship lifecycle can improve operational availability, reduce unplanned maintenance, and optimize platform recovery from casualty scenarios. The SCEPTER testbed provides a validated, open-architecture environment for continued development and evaluation of PDT algorithms, architectures, and interfaces in support of NATO naval digital transformation objectives.

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