Real-Time Blockage Detection and Autonomous Recovery in Liquid-Cooled Systems Using Digital Twins

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***Abstract*—Water-cooled power electronics in autonomous naval applications require continuous and reliable thermal management to prevent component failure and maintain operational reliability. Blockages in coolant loops impede heat dissipation, reducing performance and potentially leading to failures during mission-critical operations. This paper presents a digital twin framework for real-time blockage detection and autonomous self-healing in water-cooled power electronics. The digital twin monitors thermal parameters, detects anomalies indicative of blockages, and initiates corrective actions by generating pulsed flow waves to dislodge obstructions. Simulation results demonstrate the effectiveness of the framework in early blockage detection and automated recovery, ensuring uninterrupted operation.**

***Index Terms*—Digital Twin, Blockage Detection, Cooling System, Power Electronics, Decision Making**

I. Introduction

Autonomous vehicles are increasingly utilized in industrial, military, and societal domains to minimize or eliminate human involvement in hazardous or suboptimal conditions. Examples include self-driving cars designed to assist impaired or injured individuals and naval vessels capable of operating without direct human oversight, reducing personnel risk during high-stakes missions. Fully autonomous systems rely on power electronics and embedded control architectures, requiring high power density and effective thermal management to prevent performance degradation and potential system failures.

Water-cooled power electronics are preferred over their air-cooled counterparts due to their superior heat dissipation capabilities [1]. However, liquid cooling systems are prone to blockages from sediment buildup, biofouling, and air pockets. Undetected blockages can lead to significant overheating, potentially causing power converter failures, battery thermal runaway, or complete system shutdown. In military applications, such failures may result in mission failure, data loss, or equipment damage. Traditional methods for detecting and mitigating coolant blockages, such as flow meters, pressure sensors, and manual inspections, are widely used [2]. However, many of these approaches are expensive and demand frequent maintenance. For instance, in-line flow meters can become obstructed as sediment accumulates over time. In contrast, Digital Twin (DT) technology offers a non-intrusive, real-time alternative, leveraging existing temperature data from power electronic modules to detect potential blockages. A DT is a virtual replica of a physical asset, integrating real-time sensor data, physics-based models, and artificial intelligence to enable simulation, prediction, and performance optimization [3], [4]. Synchronization between a DT and its physical counterpart facilitates real-time fault detection, predictive maintenance, and informed operational decision-making [5].

In water-cooled power electronics, DT implementations can continuously monitor temperature differentials, coolant flow patterns, and system power inputs to detect anomalies indicative of blockages. Liquid cooling is the predominant method for cooling electric vehicle (EV) components, owing to its high efficiency [6]. Recent studies have confirmed the effectiveness of thermal digital shadows in simulating and identifying coolant flow restrictions in electronic systems, highlighting their value for predictive maintenance [7]. Since temperature data from critical components is already collected in most power electronic converters, DT-based methods can identify cooling system blockages using only existing data acquisition. This approach eliminates the costs, maintenance demands, and obstruction risks associated with commercial flow meters, making reliance on existing data the primary advantage of DT-based blockage detection. Moreover, requiring no additional hardware, DT integration can be seamlessly implemented in existing systems at minimal cost.

Although research on blockage detection in electronic cooling systems for autonomous vehicles remains limited due to the field's recent emergence, pipeline blockage detection

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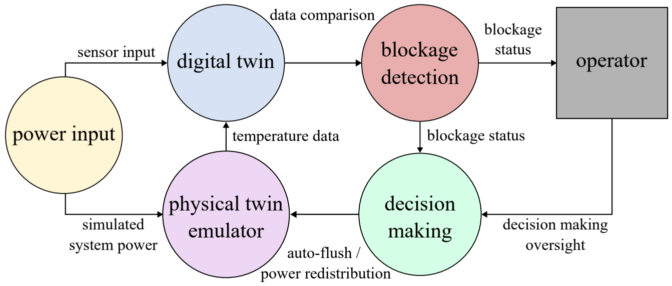

Fig. 1. General system operation allowing DT to provide input for blockage detection and decision making.

in broader contexts has been extensively explored. Previous studies have used temperature and energy data to pinpoint deviations from baseline conditions [8]. Other efforts have employed Acoustic Wave Propagation and hydrodynamic modeling to detect blockages in natural gas pipelines [9]. Similarly, acoustic reflectometry, employing microphones or hydrophones, has been applied to detect piping blockages by transmitting sound waves through the network [10]. Additionally, a steady-oscillatory flow frequency response approach has shown success in single-pipeline studies [11].

Despite these advances in related fields, the unique challenges of coolant blockages in autonomous vehicle cooling systems, particularly in high-stakes applications like naval operations, call for innovative, cost-effective solutions. This work addresses this gap by developing a digital twin capable of both detecting coolant blockages and initiating automated corrective actions, such as pulsed flow waves for obstruction removal and back-flushing for persistent blockages. Relying solely on existing temperature sensors, this approach is illustrated in Fig. 1. By enabling DT-based blockage detection and removal in liquid cooling systems without additional parts or material costs, these methods enhance the current state of thermal management for autonomous systems.

II. Proposed Digital Twin Architecture

The system under study consists of three parallel power converter modules delivering power to a DC bus, as shown in Fig. 2. Each module dissipates heat through a dedicated fluid path with inlet and outlet manifolds. This architecture supports the development of a digital twin designed to detect and mitigate coolant blockages in real time, leveraging existing temperature sensors as outlined in the introduction.

A. System Overview

Power converters, integral to autonomous systems like naval vessels and electric machinery, generate significant heat due to switching losses in semiconductor devices. These modules typically incorporate thermal sensors to safeguard against overheating-induced damage. Although temperature correlates directly with power load, as shown in Fig. 2, relying solely on absolute temperature to identify coolant blockages can lead to false alarms. For example, a rapid change in load can cause a sudden increase in temperature, mimicking the thermal signature of a blockage. For instance, a sudden load increase may

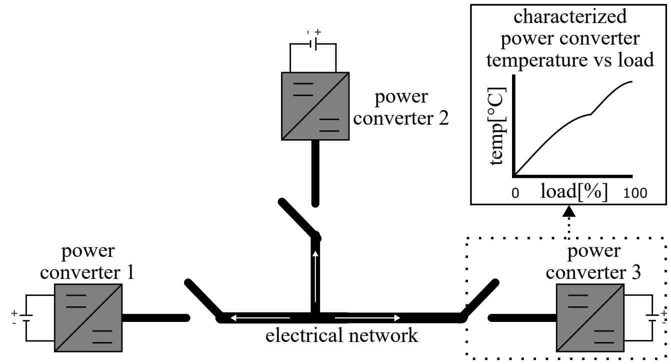

Fig. 2. Example power converter system showing relationship between power load and system temperature.

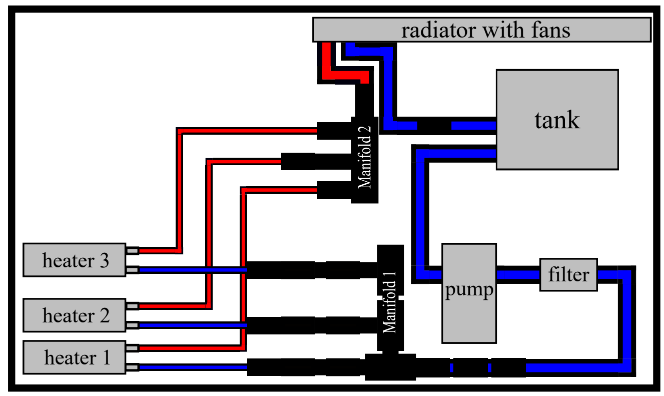

Fig. 3. Diagram of the physical system that the PT emulator is modeled after.

mimic the thermal signature of a blockage, triggering false alarms. Accurate detection thus requires integrating additional metrics, such as the rate of temperature change and power flow data beyond static temperature levels alone.

B. Digital Twin Development

Developing a DT requires the presence of a Physical Twin (PT) or an emulation of it to accurately replicate the physical system's behavior. A comprehensive understanding of the PT is essential to ensure fidelity between the virtual and physical models [12]. In this study, an emulation of the PT is used to represent the thermal loop of the system provided in Fig. 2. The digital twin replicates a typical power electronics cooling loop, consisting of a liquid pump, reservoir, three heating elements (simulating power converter heat), a filter, and a radiator, as shown in Fig. 3. Component specifications were obtained from manufacturer datasheets to ensure accurate modeling. Pipe material properties, dimensions, and lengths informed thermal simulation parameters. The system's behavior is governed by thermodynamic principles, particularly Fouriers law of conduction (1) and Newtons law of cooling (2), which supported modeling of thermal interactions among the coolant, power electronics, and radiator.

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

$$q = h_c \cdot A \cdot dT \tag{2}$$

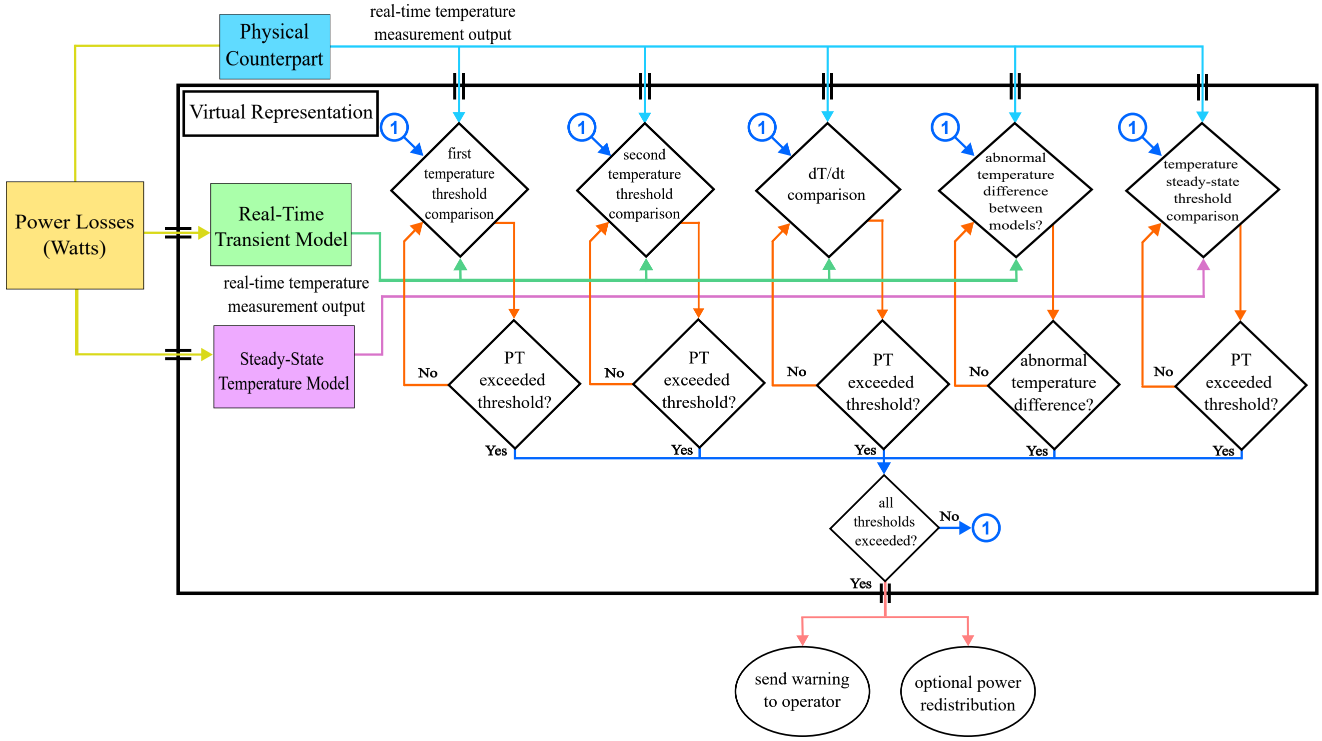

Fig. 4. Flowchart describing DT system operation focused on blockage detection comparison methods.

C. Blockage Detection Methodology

The DT integrates two models for blockage detection: a Real-Time Transient Model (RTTM) and a steady-state temperature model. RTTM captures transient thermal responses influenced by the system's thermal mass, while the steady-state model predicts expected temperatures under unblocked conditions. Together, these models enable robust detection through five temperature-based triggers, outlined in Fig. 4 and detailed below with their mathematical formulations.

1) **Temperature Difference Trigger 1:** This trigger detects discrepancies between the real-time temperature measured from the physical twin (T_{PT}) and the predicted temperature from the digital twin (T_{DT}). A blockage is flagged if the absolute difference exceeds a threshold (ϵ_{T1}), defined by system tolerances and typical operating variations:

$$|T_{\mathrm{PT}}(t) - T_{\mathrm{DT}}(t)| > \epsilon_{T1} \tag{3}$$

2) **Temperature Difference Trigger 2:** Similar to Trigger 1, this uses a higher threshold (ϵ_{T2}) for redundancy, reducing false positives:

$$|T_{\mathrm{PT}}(t) - T_{\mathrm{DT}}(t)| > \epsilon_{T2} \tag{4}$$

This dual-threshold approach enhances reliability by distinguishing blockages from minor fluctuations.

3) **Rate of Change Trigger ($\frac{dT}{dt}$):** Detects abnormal temperature gradients by continuously monitoring the rate of temperature change. The rate is calculated as:

$$\frac{dT}{dt} = \frac{T(t) - T(t - \Delta t)}{\Delta t} \tag{5}$$

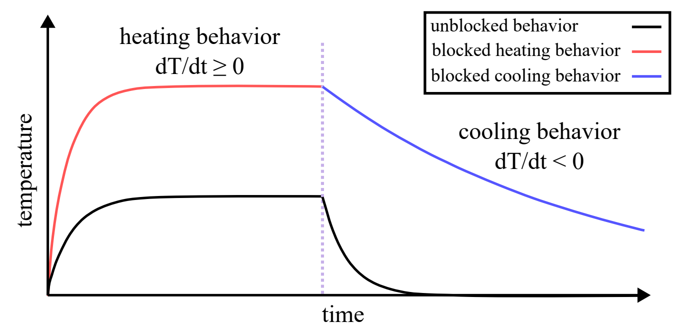

Fig. 5. Example change in temperature over time behavior for blocked and unblocked systems.

The DT compares this rate to the expected rate under normal conditions ($(\frac{dT}{dt})_{\mathrm{norm}}$). A blockage is suspected if:

$$\left| \frac{dT}{dt} - \left(\frac{dT}{dt}\right)_{\mathrm{norm}} \right| > \epsilon_{\frac{dT}{dt}} \tag{6}$$

Under normal conditions, temperature changes gradually with load variations. However, blockages cause a more abrupt rise, leading to a steeper $\frac{dT}{dt}$. Conversely, rapid load changes can mimic this behavior, which is why the trigger is used alongside power input data. Fig. 5 illustrates temperature profiles highlighting differences between blocked and unblocked scenarios.

4) **Steady-State Deviation Trigger:** The steady-state temperature T_{ss} predicted by the digital twin is compared to the measured temperature. A significant deviation signals a blockage:

$$|T_{\mathrm{PT}}(t) - T_{\mathrm{ss}}| > \epsilon_{\mathrm{ss}} \tag{7}$$

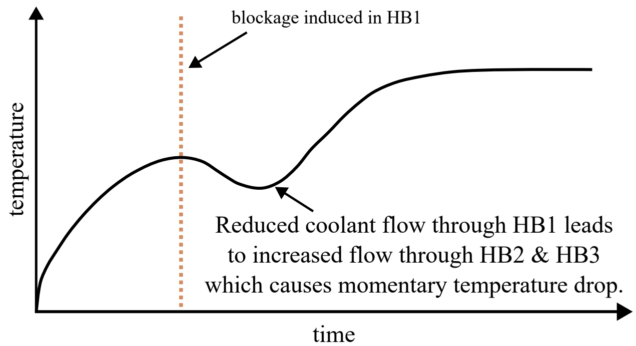

Fig. 6. Example abnormal behavior due to blocked coolant flow.

In steady-state, temperatures should stabilize. Persistent deviations indicate cooling inefficiencies, often caused by blockages.

5) **Cross-Loop Comparison Trigger:** Monitors neighboring coolant loops for abnormal cooling trends indicating increased flow caused by upstream blockages. When a blockage forms in a coolant loop, flow through the affected heat sink decreases, causing adjacent heat sinks to experience increased coolant flow. This results in a temporary temperature drop in neighboring components, serving as an indicator of obstruction. Fig. 6 shows a blockage in heater block 1 (HB1), where elevated coolant flow to HB2 and HB3 causes noticeable temperature reductions. The digital twin identifies this behavior by comparing real-time data with model predictions.

III. Simulation Results

The digital twin system was evaluated through a series of simulation tests using MATLAB Simscape to validate its capability in detecting coolant blockages under various scenarios. These simulations included both sudden and gradual blockage inductions, with and without power redistribution strategies. Detection performance was assessed using the five defined triggers, with particular focus on temperature deviations, rate of temperature change, and system response dynamics. The following subsections detail the scenarios, observed behaviors, and corresponding system responses.

A. Test 1a – Single Blockage without Power Redistribution

A sudden 95% blockage was introduced in the coolant loop of heater block 2 (HB2) to assess the digital twin's detection capabilities without compensatory measures.

Fig. 7 presents the temperature profiles of the heater blocks during the simulation. The blockage was detected approximately 10 minutes after induction when the temperature difference between the physical twin and the digital twin exceeded the predefined threshold (ϵ_T), with a recorded variance of approximately 3°C. The rate of temperature change $\left(\frac{dT}{dt}\right)$ also surpassed its threshold ($\epsilon_{\frac{dT}{dt}}$), further validating the detection. The temperature profile for HB2 exhibited a rapid rise post-blockage induction, reflecting the loss of effective cooling. Adjacent heat sinks displayed nominal temperature changes, as little redistribution of coolant flow occurred.

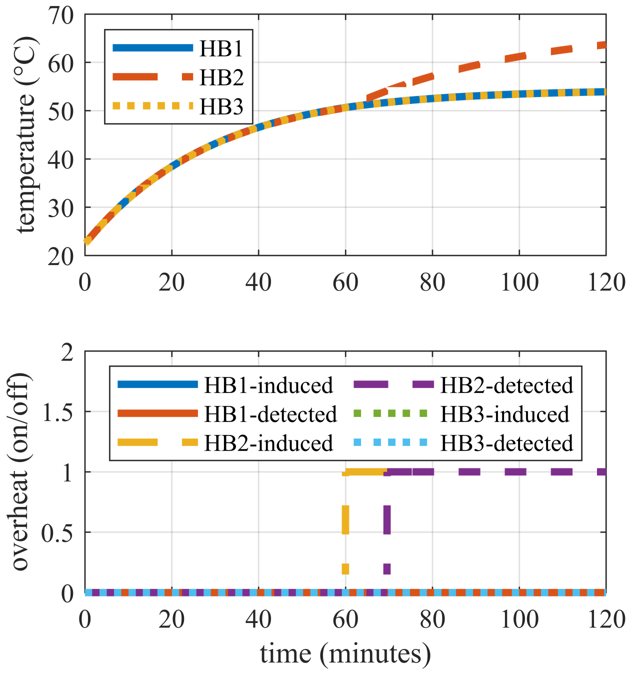

Fig. 7. Test 1a: Detection of a single blockage in HB2. The temperature deviation surpasses 3°C within 10 minutes. The rapid temperature increase in HB2 is indicative of blockage, confirmed by the rate of temperature change trigger.

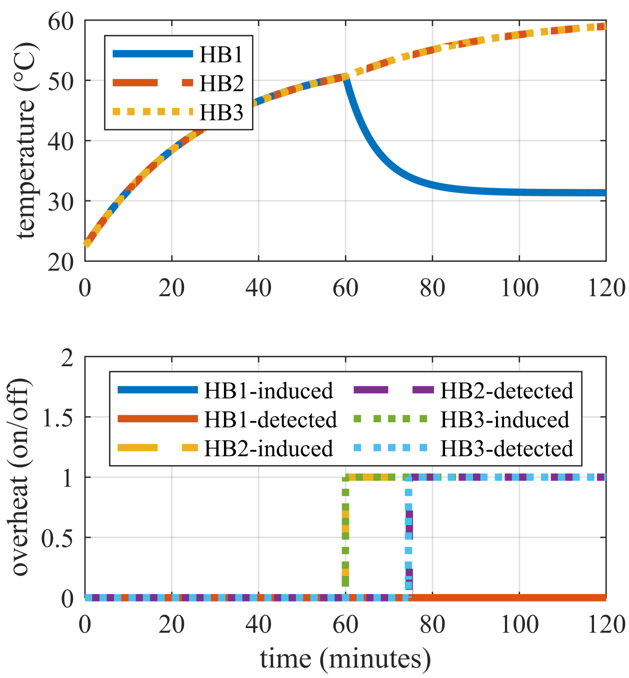

Fig. 8. Test 2a: Dual blockage detection in HB2 and HB3. Blocked sinks show sharp temperature increases, while HB1 exhibits cooling due to altered flow patterns.

B. Test 2a – Dual Blockage without Power Redistribution

Blockages of 95% were simultaneously introduced in heater blocks 2 and 3 (HB2 and HB3) to evaluate detection under compounded fault conditions. As shown in Fig 8, detection was achieved approximately 15 minutes after the blockage,

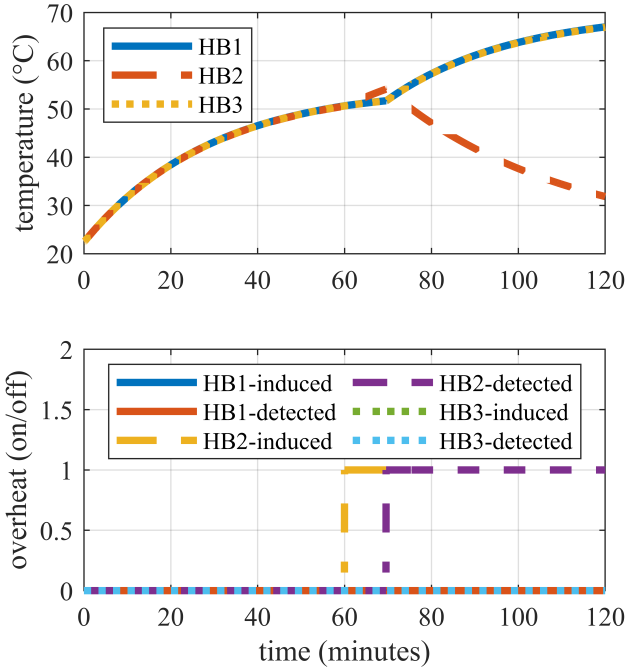

Fig. 9. Test 1b: Post-detection power redistribution mitigates temperature escalation in HB2 while ensuring continuous operation by transferring load to HB1 and HB3.

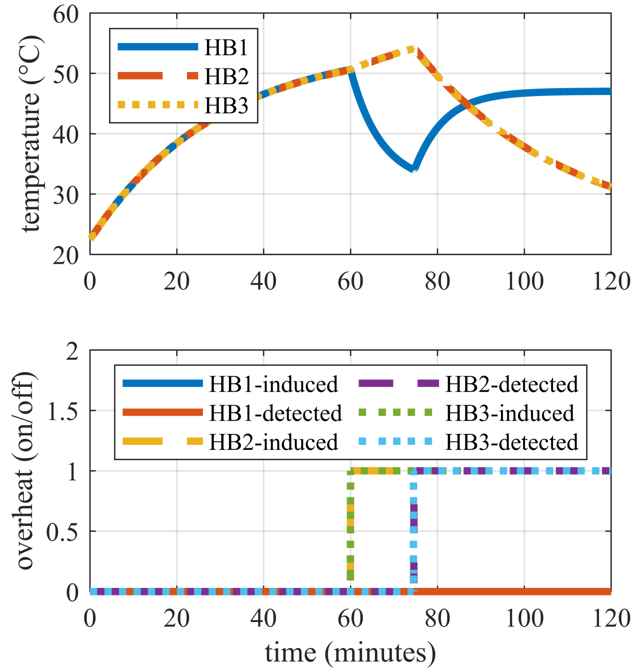

Fig. 10. Test 2b: Effective management of dual blockages via power redistribution, preventing temperature spikes and sustaining operational stability.

with a temperature deviation of about 5°C from the predicted DT values. The cross-loop comparison trigger detected abnormal temperature behavior in heater block 1 (HB1), which exhibited an unexpected cooling trend due to redirected coolant flow caused by the obstructions in HB2 and HB3. The simultaneous rise in HB2 and HB3 temperatures, alongside the decline in HB1 temperature, underscores the effectiveness of using multiple triggers for accurate blockage localization.

C. Test 1b – Single Blockage with Power Redistribution

This simulation repeated the conditions of Test 1a but introduced a power redistribution mechanism. Upon blockage detection in HB2, power was automatically rerouted to adjacent heater blocks to emulate load balancing in real-world applications. Fig. 9 illustrates the system's response to the detected blockage. Following detection, HB2's temperature decreased sharply as power input ceased. Conversely, HB1 and HB3 experienced controlled temperature increases due to the additional power load. The immediate response of the redistribution strategy demonstrates the digital twin's ability to maintain operational integrity despite localized faults. This test highlights the potential for integrating automated corrective actions alongside detection systems to minimize performance degradation.

D. Test 2b – Dual Blockage with Power Redistribution

Expanding upon Test 2a, this simulation examined dual blockages in HB2 and HB3 with the activation of power redistribution protocols. As shown in Fig. 10, the redistribution system effectively stabilized temperatures across all heater blocks. HB1 absorbed the redirected load, maintaining a safe operating temperature, while temperatures in the blocked sinks (HB2 and HB3) gradually decreased post-redistribution. These results demonstrate the digital twin's capability not only to detect multiple simultaneous faults but also to execute compensatory measures that preserve system functionality.

E. Test 3 – Gradual Blockage Induction (1-hour Span)

To evaluate sensitivity to slow-developing faults, a blockage in HB2 was induced gradually from 0% to 95% over a one-hour period. Fig. 11 highlights the early detection capability of the digital twin. The rate of temperature change $\left(\frac{dT}{dt}\right)$ exceeded its threshold before a significant rise in absolute temperature was observed. This preemptive detection allowed for timely intervention, demonstrating the system's robustness in identifying gradual degradation conditions.

Such early warnings are essential in operational environments where slow-developing faults may otherwise go unnoticed until critical thresholds are surpassed.

In summary, rapid blockage detection was achieved with sudden obstructions identified within 10–15 minutes post-induction using temperature difference and rate of change triggers. The system successfully preemptively detected slow-developing blockages, demonstrating predictive monitoring capabilities. Power redistribution mitigated operational disruptions, maintaining system integrity despite multiple simultaneous blockages. Early detection during prolonged operations enhanced mission assurance and reduced maintenance risks, highlighting the digital twin's reliability in various operational scenarios.

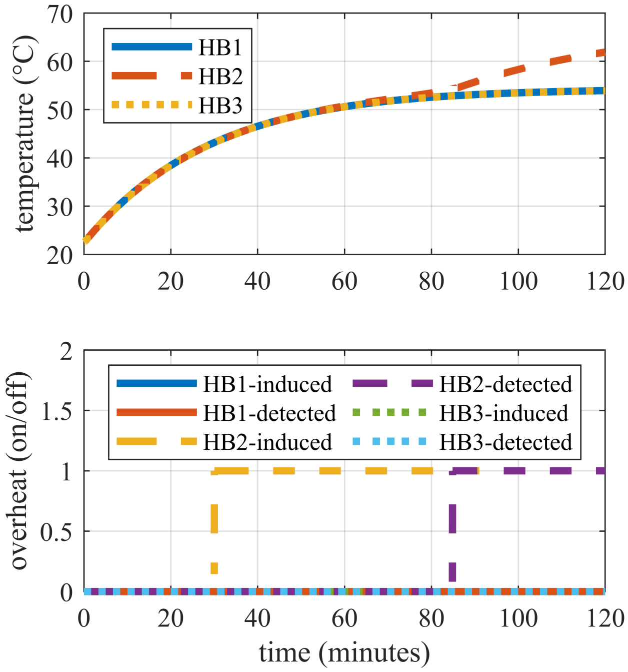

Fig. 11. Test 3: Detection of a gradually induced blockage before critical temperature levels are reached, showcasing the digital twin's predictive monitoring capabilities.

IV. Conclusion And Future Work

This paper presented a digital twin-based framework for real-time blockage detection and self-healing in water-cooled power electronic systems. By leveraging existing temperature sensors, the proposed approach eliminates the need for additional hardware, enabling seamless integration into existing platforms with minimal cost and complexity. Five detection triggers were employed to identify blockage events with high reliability. Simulation results demonstrated that the digital twin can detect sudden blockages within 10–15 minutes of occurrence, with temperature deviations as low as 3°C serving as early indicators. The system also effectively identified gradual blockages, enabling proactive maintenance before critical temperatures were reached.

Future work will focus on hardware-in-the-loop (HIL) validations, experimental implementation on physical systems, and further refinement of the self-healing mechanism through automated back-flushing and pulsed wave generation to dislodge obstructions.

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