

Demonstration of 17 Industry-Grade Controllers and Relays in a Typhoon Hardware-in-the-Loop Testbed for Microgrid and Grid Modernization Applications: A Case Study

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Abstract—Microgrids are increasingly recognized as self-sustaining backup power systems, making rigorous validation of microgrid models critical for ensuring reliable and resilient operation. This paper presents a case study of 11 distributed energy resources (DERs) plus 6 relays implemented in Typhoon Controller Hardware-in-the-Loop (CHIL) environment, demonstrating their parallel operation under both Islanded Mode (ISM) and Grid-Connected Mode (GCM). The study integrates 17 industry-grade controllers, including the Woodward Easygen generator controller, EPC inverter controller and SEL-751 relays, within multi-HIL framework. Results validate the successful implementation of droop-based control and grid-following operation for DERs, highlighting the capability of the multi-CHIL platform to safely validate control strategies and system performance in a low-risk environment. This work highlights the utilization of multi-HIL testing for the development, optimization, and verification of complex microgrid systems, leveraging the interconnection of multiple HIL devices and parallel operation to enhance computational capability for real-time validation of large-scale microgrids.

Index Terms—Controller Hardware-in-the-Loop, Droop, Micro-grid control, Woodward Diesel Generators controller, EPC power inverter controller.

I. INTRODUCTION

Microgrid modeling and simulations are crucial for real-world deployment. Most modeling and validation is performed using software virtual simulations, which rarely test controllers in real-time environments. Controller Hardware-in-the-Loop

(CHIL) provides a practical solution, enabling safe and realistic testing of industry-grade controllers, bridging the gap between virtual simulations and actual microgrid operation [1]. The CHIL environment enables low-risk testing of microgrid interconnections and functionality across multiple test scenarios, providing real-time validation of controllers without testing of high-risk real-world systems [2].

Various studies have demonstrated the use of real-time simulators and CHIL testbeds for validating microgrid controllers [3], [4]. The literature [5] presents a CHIL framework for a DC microgrid model using Typhoon HIL 402 and RTDS platforms. A CHIL framework using RSCAD/RTDS to simulate PV systems and boost converters is presented in [6]. In [7], Raspberry Pi controllers are integrated with OPAL-RT and RTDS to implement a CHIL framework for distributed microgrid control. The microgrid control application using Typhoon HIL 602+ with a DSP board as the controller is presented in [8]. Four bidirectional interlinking converters in a networked microgrid are modeled and tested using OPAL-RT HIL real-time simulation [9]. In [10], the CHIL-based validation of a non-standard tripping characteristic relay coordination scheme for microgrids using RTDS is presented. The implementation and CHIL testing of a microgrid control system using the OPAL-RT real-time simulator is presented in [11]. The design of a modular marine microgrid testbed using Typhoon CHIL for real-time validation and testing is presented in [12]. A CHIL test bench with constant POI power control in grid-connected mode (GCM) and fixed-frequency control in islanded mode (ISM) is developed in [13]. A CHIL testbed system with protection, dispatch, and transition functions for the microgrid is presented in [14]. The development of a universal CHIL platform for testing microgrid control is presented in [15]. The CHIL setup utilizing an FPGA-based controller for the Energy Storage System (ESS) has been presented in [16].

While most studies focus on CHIL testing of microgrids

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using individual HIL devices for specific setups, only a few investigate the parallel operation of multiple CHIL devices to establish a multi-HIL environment for comprehensive testing. The advantage of a multi-HIL setup lies in its ability to test larger systems in real time, where multiple distributed energy resources (DERs), industry-grade controllers, and system extensions can be simulated and tested in parallel using multiple CHIL platforms. The major challenges in multi-HIL simulation include communication time lag, signal transfer, system stabilization, and CPU core management, aspects that are not widely addressed in the existing literature. In this context, the paper presents a case study of microgrid operation utilizing 5 Typhoon HIL 606 devices operating in parallel, in conjunction with 11 industry-grade controllers and 6 SEL-751 relays tested for coordinated operation. To the best of the authors' knowledge, this paper presents the highest number of CHIL DERs in an integrated Typhoon-HIL testbed to date. The study demonstrates the integrated management of 11 DERs in both GCM and ISM, with five separate racks functioning simultaneously. Based on these capabilities, the main contributions of this paper are summarized as follows:

- Developing and implementing a Typhoon multi-CHIL microgrid model that integrates 11 DERs and 6 industry-grade SEL 751 relays.
- Implementing and validating proportionally optimized droop settings for industry-grade Woodward EasyGen 3500 DiG controllers and EPC inverters within a multi-HIL environment.
- Demonstrating and analyzing the operation of 11 DERs in parallel under both ISM and GCM within the Multi CHIL setup.

The remainder of this paper is organized as follows: Section II describes the Center for Microgrid Research's (CMR) Multi-CHIL test system, including the available controllers and devices. Section III provides a detailed discussion of the microgrid model, its droop control methodology, and implementation. Section IV presents the results of the parallel operation of multiple Typhoon HIL racks as real-time simulators in both GCM and ISM. In Section V, the conclusion is provided.

II. THE CMR TYPHOON MULTI-CHIL TESTBED SYSTEM

The CMR's Typhoon CHIL testbed system is the largest testbed within Typhoon's network of more than 600 global university partners and utility customers according to Matt Baker from Typhoon HIL, Inc. The system consists of 12

Typhoon HIL real-time simulator devices and 10 Typhoon HIL controller racks, integrated with industry-grade inverter and generator controllers, as well as relays for protection control. This configuration enables real-time simulation of multiple interconnected microgrids with different control schemes. Each Typhoon HIL unit models a microgrid or microgrid segment, enabling the validation of multiple DER controllers and microgrid control strategies in a realistic, hardware-integrated environment. The Typhoon Multi-CHIL testbed setup used in this work is shown in Fig. 1

The case study on parallel operation of multiple DERs in a multi-HIL environment utilizes key components from the CMR Typhoon Multi-CHIL facility, including Typhoon HIL real-time simulators, modular HIL I/O units, 7 Woodward EasyGen 3500 diesel generator controllers, 4 EPC Power inverter controllers, 6 SEL-751 protection relays, and associated interconnection hardware. The Woodward EasyGen 3500 controllers provide industry-grade diesel generator control functions such as droop control, active and reactive power regulation, and grid synchronization within the CHIL environment. The EPC Power inverter controllers implement inverter-specific characteristics, including droop and reference-following control. The SEL-751 relays enable real-time validation of protection functions to ensure reliable microgrid operation. These components are distributed across multiple HIL racks to form a comprehensive test system for evaluating parallel DER operation.

III. COORDINATED OPERATION OF MULTIPLE DERs ACROSS MULTIPLE REAL TIME SIMULATORS

The test system comprises 11 DER controllers distributed across multiple Typhoon HIL racks. Controllers from different CHIL devices are integrated into a single microgrid model capable of operating in both GCM and ISM. Individual microgrid sections are simulated on separate racks, while the complete microgrid is co-simulated across five Typhoon HIL units, forming a multi-CHIL environment. The interconnections among HIL racks and internal components are shown in Fig. 2. Table I summarizes the source modeling parameters used in the real-time simulation. All DiG units are controlled by Woodward EasyGen 3500 controllers rated at 62.5 kVA, and all inverters use EPC controllers rated at 125 kVA. For this study, identical line parameters are assumed throughout the microgrid.

The ESS inverter and DiG units operate under P-Q control in GCM and droop control in ISM. In GCM, both resources function as grid-following devices, while in ISM they operate as grid-forming sources. The P-f and Q-V droop control strategies are employed to regulate frequency and voltage, respectively. In ISM, both the frequency and voltage droop coefficients are set to 4% to enable proportional power sharing according to the resource ratings. The droop characteristics used to model the ISM behavior are given by (1) and (2), consistent with [17], [18].

$$f = f_{\text{ref}} - K_P(P - P_{\text{ref}}) \quad (1)$$

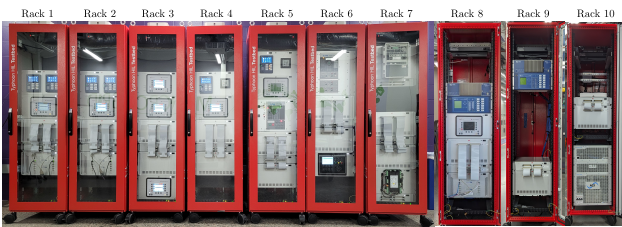


Fig. 1. CMR Typhoon Multi-CHIL testbed used in this case study

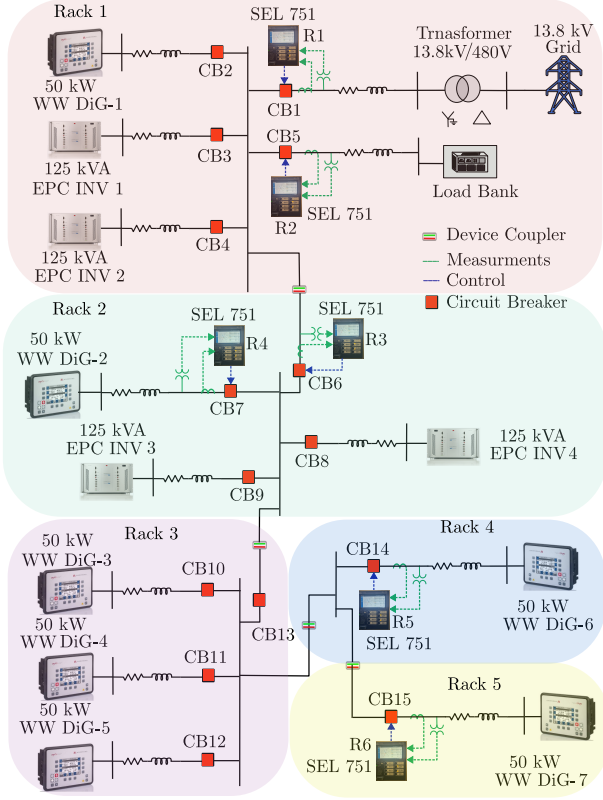


Fig. 2. Schematic of the Test System for Parallel Operation of 11 DERs Using Multi-CHIL and 6 relays

TABLE I
TYPHOON MULTI CHIL SYSTEM PARAMETERS

Source	Rating	Source	Rating
DiG 1	62.5 kVA	ESS 1	125 kVA
DiG 2	62.5 kVA	ESS 2	125 kVA
DiG 3	62.5 kVA	ESS 3	125 kVA
DiG 4	62.5 kVA	ESS 4	125 kVA
DiG 5	62.5 kVA	Utility grid	480 V/13.8 kV
DiG 6	62.5 kVA	Load Bank	750 kVA
DiG 7	62.5 kVA	Transformer	750 kVA
R_T	0 (p.u.)	X_T	0.06 (p.u.)
R_{Line}	0.01 (p.u.)	X_{Line}	0.03 (p.u.)

$$V = V_{ref} - K_Q(Q - Q_{ref}) \quad (2)$$

where f and V are the source output frequency (Hz) and voltage (V), respectively; f_{ref} and V_{ref} are the reference values; P and Q are the measured active (kW) and reactive (kVA) power outputs; P_{ref} and Q_{ref} are the no-load reference powers; and K_P and K_Q are the frequency and voltage droop coefficients. For the presented case study, K_P corresponding to a 4% frequency droop is calculated using (3) for the 125 kW ESS and (4) for the 50 kW DiG.

$$K_{P_{f_{ESS}}} = \frac{\Delta f_{max}}{P_{rated}} = \frac{0.04 \times 60}{125} = 0.0192 \text{ Hz/kVA} \quad (3)$$

$$K_{P_{f_{DiG}}} = \frac{\Delta f_{max}}{P_{rated}} = \frac{0.04 \times 60}{50} = 0.048 \text{ Hz/kVA} \quad (4)$$

Similar to the frequency droop, the value of K_Q , considering a 4% voltage droop, is calculated using (5) for a 125 kVA rated ESS, and using (6) for a 62.5 kVA rated DiG.

$$K_{Q_{V_{ESS}}} = \frac{\Delta V_{max}}{Q_{rated}} = \frac{0.04 \times 277}{125} = 0.0886 \text{ V/kVA} \quad (5)$$

$$K_{Q_{V_{DiG}}} = \frac{\Delta V_{max}}{Q_{rated}} = \frac{0.04 \times 277}{50} = 0.2216 \text{ V/kVA} \quad (6)$$

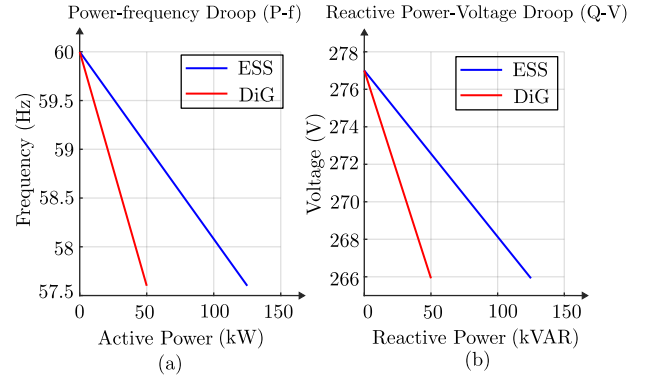


Fig. 3. P-f and Q-V droop characteristics of the ESS and DiG controller

The schematic representation of the ESS and DiG droop characteristics is shown in Fig. 3. Using these droop settings for all DERs, the microgrid is operated in islanded mode.

IV. TYPHOON MULTI-CHIL TEST CASES

A. ISM operation of 11 DERs on Multi CHIL platform

Fig. 4 illustrates the frequency response to active power variations during ISM operation. All eleven DERs are configured with 4% droop for both frequency and voltage control. The system load is increased from 200 kW to 400 kW in 50 kW steps and subsequently decreased back to 200 kW. The incremental load is proportionally shared among the DERs according to their ratings. Since the four ESS inverters have identical ratings of 125 kVA and the seven DiG units each have a rating of 50 kW with identical droop settings, each ESS and DiG contributes an equal share within its respective group. The increased load is shared between the ESS and DiG units in a 70:30 ratio, with the ESS units collectively supplying 70% and the DiG units supplying the remaining 30%, both distributed equally within each group. The results demonstrate stable parallel operation of all eleven DERs in ISM, with no oscillations or stability issues observed during load transitions.

Fig. 5 shows voltage response under varying reactive load conditions in ISM mode. All eleven DERs share the reactive power proportionally to their respective ratings, following the same 70:30 distribution ratio between the ESS and DiG units as in active power sharing. The reactive load is increased from

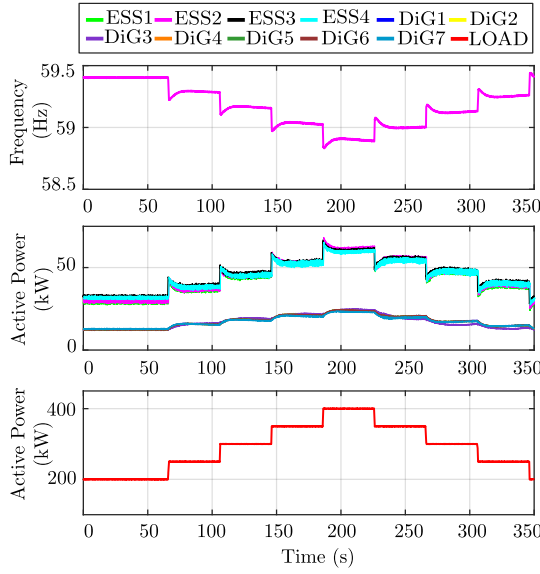


Fig. 4. (a) Frequency (b) DERs active power (c) Load active power in ISM

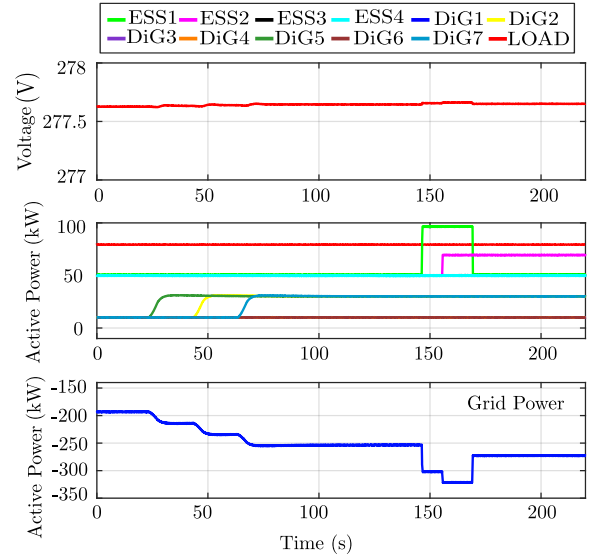


Fig. 6. (a) Voltage (b) Active power (c) Reactive power in GCM

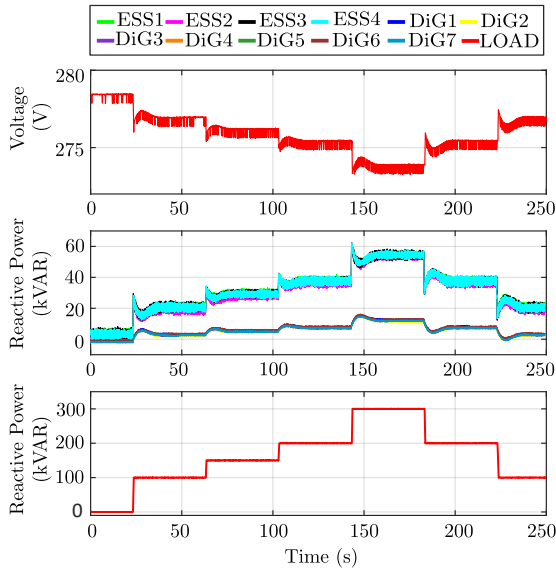


Fig. 5. (a) Voltage (b) DERs Reactive power (c) Load Reactive power in ISM

0 kVAR to 300 kVAR in increments of 100, 150, 200, and 300 kVAR, and subsequently decreased through 250 and 100 kVAR. As the reactive load increases, the system voltage exhibits a corresponding droop and returns to its nominal value as the load decreases. The legends at the top of the figure indicate the color codes representing the individual reactive power contributions of all eleven DERs, demonstrating proportional sharing and coordinated operation. The results confirm stable voltage regulation and effective reactive power management among all DERs during load variations.

B. GCM operation of 11 DERs on Multi CHIL platform

In GCM, all DERs operate under grid-following control using P-Q control to manage active and reactive power sharing

among the units. Fig. 6 shows the dynamic response of the DERs in GCM following changes in active power setpoints. To illustrate grid-following performance, the active power setpoints of selected DERs are varied while keeping the total load constant, with excess power exported to the grid. Initially, all DiGs operate at 10 kW, and the ESS units are set to 50 kW. As the setpoints of certain DiGs are adjusted, the grid power responds accordingly, with negative values indicating surplus power export. The grid frequency remains constant at 60 Hz during GCM operation. The results confirm coordinated power sharing among the DERs and effective grid interaction under GCM. Key challenges during the multi-HIL simulations include real-time model stabilization, efficient core management of HIL devices, coordination of droop settings, optimal time-slot utilization, and fine-tuning of parameters to ensure stable operation without controller tripping.

C. Scalability Analysis of Multi-CHIL Systems

Performance analysis is critical for multi-HIL operation, especially regarding communication latency and synchronization accuracy. The HIL-606 platform addresses these requirements using QSFP28 high-speed interfaces, enabling deterministic, low-latency data exchange between HIL units. QSFP28 supports 100 GbE through four parallel lanes operating up to 25–28 Gbps each, delivering an aggregate bandwidth of 100 Gbps. In HIL-606, this architecture operates at signaling frequencies up to 16 GHz and supports transfer rates of approximately 1000 variables per microsecond. This high-bandwidth, low-jitter communication minimizes transmission delays and ensures tight synchronization, making the platform well suited for multi-HIL real-time simulation and large-scale HIL co-simulation.

The computational load of the HIL devices is illustrated in Fig. 7. A utilization of 100% indicates marginally stable operation with no remaining computational margin. The results

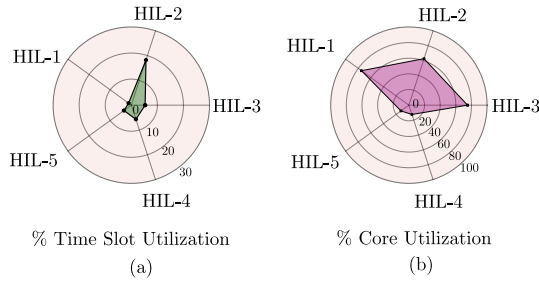


Fig. 7. % Computational load on each Typhoon HIL device

TABLE II

COMPARISON OF SMALL-SCALE HIL AND MULTI-HIL SIMULATION

Parameter	Small-Scale HIL Setup	Multi-HIL Simulation Architecture
System Scale	Limited to a single real-time simulator or a small number of I/O channels	Scalable architecture using multiple interconnected HIL units
Latency	Low for local models but increases rapidly with external expansion	Deterministic and ultra-low latency across distributed HIL units
Synchronization Accuracy	High within a single HIL unit	Maintained across units using hardware-level synchronization and time alignment
Scalability	Limited; requires hardware replacement to scale	Linear scalability by adding additional HIL units
Cost Efficiency	Lower initial cost	Higher upfront cost but improved cost-per-scale
Use Case Suitability	Component-level or subsystem testing	System-level, grid-scale, and multi-converter HIL simulations
Failure Modes	FPGA overload, I/O saturation, timing overruns	Communication link failure, clock desynchronization, node failure
Validation Coverage	Limited interaction scenarios	Enables cross-domain and large-system validation

show that both time-slot and core utilization remain well below 100% for all HIL units, indicating sufficient computational headroom to support additional models or devices. This confirms that the system operates well within the hardware's maximum capacity. In addition, Table II compares the proposed multi-HIL platform with small-scale or single-HIL systems in terms of scalability, cost efficiency, failure modes, and limitations. The comparison demonstrates that the proposed architecture offers superior scalability and flexibility for large-scale and complex simulation scenarios.

V. CONCLUSION

This paper demonstrated the world's largest CHIL integration of industry-grade controllers and relays in a real time testbed. The testbed included 7 Woodward Easygen-3500 generator controllers, 4 EPC Power inverter controllers, and 6 SEL-751 protection relays, enabling real-time simulation and validation of 17 controllers. The results confirm effective active-reactive power control in GCM and stable voltage-frequency droop operation in ISM. The proposed multi-CHIL setup provides a reliable and low-risk environment for testing and verifying DER functionalities before field deployment. Furthermore, the developed platform supports

scalable modeling of single and multiple interconnected microgrids, demonstrating stable and synchronized operation of five parallel Typhoon HIL racks without instability or oscillation.

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