A Remote Development Process and Platform for Power Electronic Systems

Michael Starke, Bailu Xiao, Mitch Smith, Pankaj Bhowmik, Steven Campbell, Radha K Moorthy, Benjamin Dean, Madhu Chinthavali
Power Electronics Systems Integration Group
Oak Ridge National Laboratory
Oak Ridge, Tennessee
{starkemr, xiaob, thapaa, bhowmikp, campbellsl, krishnamoorr, deanbr, chinthavalim} @ornl.gov

***Abstract*— Like many areas in research and development, power electronic and distributed energy resource research and development slowed during the COVID pandemic. While the presence of the virus has reduced and workers are returning to shared offices, uncertainty of potential future challenges are still present. This work proposes a development and testing network that provides researchers the ability to operate remotely and coordinate control and debug activities for power electronic systems. This development and testing network has been demonstrated in both controller hardware-in-the-loop (C-HIL) and hardware testing.**

Keywords—component, formatting, style, styling, insert *(key words)*

I. Introduction

The novel Coronavirus Disease of 2019 (COVID) has resulted in the illness and death of millions world-wide [1]. Despite the development and distribution of vaccines, there is still significant uncertainty on the long-term impacts on world health and economy. Isolation and social distancing have been used as mechanisms to reduce the spread of this virus but have also resulted in reduced human-to-human interactions. As a consequence, online platforms have been quickly adopted and accelerated to support collaboration between remote coworkers. Many academic conferences have even shifted to online formats [2].

While these online platforms have supported dialog and discussion of academic concepts and applications, development of physical hardware systems has observed shortfalls. Human presence, currently limited or restricted to ensure uncompromised safety of researchers, is often needed to push new concepts in technologies; particularly in controller hardware-in the loop (CHIL) and full hardware system platforms. This is especially true for power electronic systems (PES).

The development of PES technologies is often a long, multi-stage process with hardware, software, and communications. Even before the actual development of any physical product, identification of product features and capabilities through use cases is undertaken to establish the needed controls, communications, and hardware specifications. A depiction of a proposed process flow for a prototype is provided in Fig. 1. Simulation provides identification of basic functionality and upon completion can be passed to hardware and software engineers and scientists to find the best means for implementation. For early-stage testing, hardware in the loop (HIL) systems have been an important instrument to speed up this development process [3]. These platforms can be used to validate the real-time operations of controls and communication networks to ensure stable operation without risking damage to power electronics hardware. The final stage (development of the physical prototype) requires a collection of hardware components often from several different manufacturers that must be carefully configured both electrically and spatially. Full testing of the system often requires other hardware systems and electrical systems.

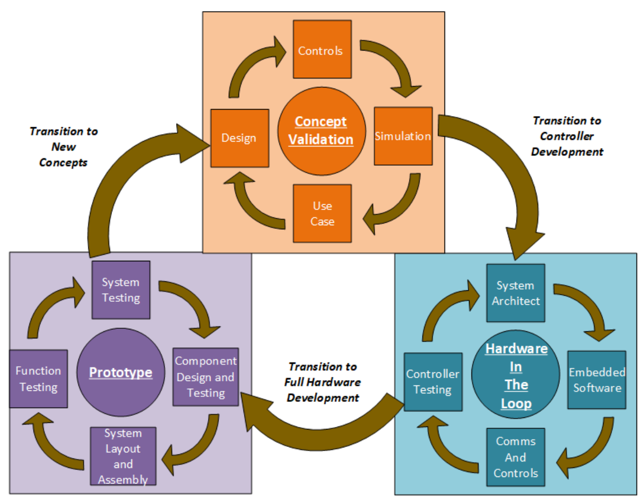


Fig. 1: Process flow for delivering prototype hardware systems

This work proposes a novel methodology and set of platforms for HIL and hardware testing for the development and testing of PES considering remote operating staff members to maintain isolation safeguards for COVID and other potential future viruses. In the next section, a review of CHIL and hardware testbeds for evaluating power electronic systems is conducted followed by a discussion on the proposed remote platform.

II. Background

Real-time operational testbeds for verification of control concepts, communication and control networks, and hardware systems have many value propositions as presented in [3]. Today, different combinations of platforms have been developed based on research focus. In general three basic types exist as part of real-time prototyping and validation and include: 1) fully digital real-time simulation, 2) hardware-in-the-loop (HIL) with either controllers (CHIL) or power equipment (PHIL), and 3) full hardware platforms.

As computational horsepower and techniques to support real-time simulation capabilities have taken hold, prototyping approaches have adopted the utilization of HIL systems for rapid verification. This includes the evaluation of grid-connected converters, voltage stability of electrical networks, and supporting system level controls and system controllers [4]. An example of this type of evaluation has been adopted in power electronic system, microgrid, and distribution management research and design [5]- [21].

Power electronic research systems have been investigated in [5]- [8] considering various HIL platforms. In [5], a CHIL system has been constructed for testing a control strategy and design of a convertible static transmission controller (CSTC). A CSTC is a fractionally rated power electronic system integrated to conventional transformer to perform power flow control in transmission systems. In this work, a Typhoon HIL platform has been applied. For [6], CHIL and PHIL platforms have been constructed using a combination of RTDS (simulation) and dSPACE (controller) systems. The goal is the validation of a hybrid transformer and power electronic system control strategy. In [7], a hardware testbed has been constructed for evaluation of DC nanogrid technologies. Converters have been used with a set of load banks and emulators to simulate resource behavior. In [8], power electronic models are presented and deployed on National Instruments floating point gate arrays (FPGAs) for analytical calculation of electric circuit response. DC protection considering a floating ground is evaluated as a novel challenge.

Microgrid controls, protection, and DER resource management are applied to a CHIL platform in [9]-[10]. In these works, National Instruments (NI) hardware system (controllers) and Schweizer Engineering Laboratories (SEL) relays are integrated with a RTDS (simulation) to examine resource and protection coordination. A Mathworks MATLAB platform is used to perform the energy management optimization. This system has been transferred to a hardware testbed in [11] with resources emulated using power supplies and load banks. Similar work is presented in [12] utilizing a Opal-RT platform for simulation and DSPs for converter controls in a CHIL configuration. In [13], Opal-RT and NI are used. In [14], a set of researchers adapted GridLab-D (simulation platform) with two solar inverters interconnected for distribution system impact evaluation in a PHIL configuration. In this case, the linkage demonstration focused on interconnecting platforms from a long distance (simulation and hardware platforms were remote from one another).

Agent systems have also been deployed on controllers in a CHIL configuration utilizing a RTDS for simulation [15]. In this work, naval shipboard systems are the primary focus due to the needed resiliency and complexity of the multiple integrated systems. A hardware testbed for testing controls for a shipboard propulsion are discussed and developed in [16].

In [17], a remote system has been developed to test controls for 120kVA power electronic system. This platform has been interconnected to multiple motors and loads for validation. Another remote platform for electric drive experiments is discussed in [18]. In this case, Mathworks MATLAB platform has been integrated to a tabletop motor and motor drive for testing. *In all of these works, the primary focus has been the development of the testbed and the final research product with little to no focus on creating a flexible platform consisting of multi-layer architectures and the ability to operate remotely in a collaborative fashion.*

As discussed from previous literature, HIL systems are available from many different manufacturers [19] and have been utilized in many different configurations for evaluation of power electronic controls and systems. In summary:

- *CHIL systems have been demonstrated with programmed controllers linked to analog and digital connections on simulation platforms.*
- *Hardware platforms have adopted power supplies and load banks to perform resource emulation.*

Standardized frameworks for performing CHIL and PHIL evaluations are in discussion [20] and include methods for calibration of modeling details [21]. This work looks to expand on previous CHIL and hardware concepts while adopting new strategies to increase flexibility and configurability. The novelty in this work includes:

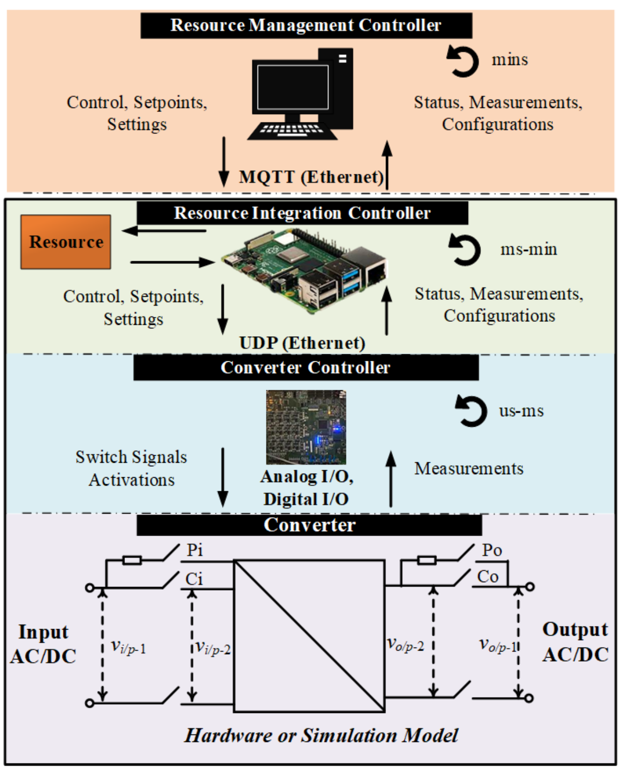
- *Integrated systems have been designed to consider hierarchal systems and support development from a single power electronic converter to an electrical network with distributed energy resources (DERs) without changes in controller hardware.*
- *Power electronic converters and electrical network topologies can be adapted to support many different use cases and scenarios.*
- *Control and implementation layers of code are exposed at all levels to provide complete flexibility.*
- *Computing interfaces have been included to allow internet connected users access to each level individually or in a shared frame.*

The developed approach has already been applied to deliver power electronic system designs and prototypes for energy storage, extreme fast charging, and other hybrid AC-DC systems in times of isolation. The approach continues to be useful for collaboration with industry partners in demonstrating new ideas remotely and in real-time. The methodology discussed in this paper is presented in the context of delivering a final hardware prototype for a secondary-use energy storage system. The proposed system distributed energy resource (DER) implementation architecture is discussed in the next section.

III. Generalized Supporting DER Architecture

A generalized hierarchal system of controllers has been developed to support power electronic system research as presented in [22]. This hierarchal system utilizes converter controllers (CC) or digital signal processors (DSPs), resource integration controllers (RIC), and a resource management controller (RMC) in coordination with an energy management system (EMS) to optimize and coordinate power electronic integrated resources (PEIR). Each controller layer of this architecture supports decision making, state machines, and timing. This hierarchal system is compatible with both simulation and full hardware platforms. A depiction of the linkages between the different controllers is shown in Fig 2.

As shown, two layers of communication couplings are utilized for interconnecting the controllers: a network socket user datagram protocol (UDP) and a message queuing telemetry transport (MQTT). Communication schemas have been designed to provide automatic configurability and real-time measurements from the CC stage up to the RMC as described in [22]. These communication layers can be replaced by other communication approaches-based use case and need. In the next subsections, the different controllers are described in detail.



Power Electrics Integrated Resource

A. Converter Controller (CC)

In this work, the converter controller (CC) has the primary purpose of directly controlling a power electronic converter (PEC) either in a virtual environment or in physical hardware. This allows a rapid transition from initial control testing to full prototype development. This controller can either take the form of a commercially off the shelf (COTS) digital signal processor (DSP) or that of an in-house developed prototype. For direct swappable compatibility between research focuses, the analog and digital inputs and outputs must be consistently defined for each CC and calibrated appropriately. This includes model calibration in the simulator environment.

The CC hosts three core processes: 1) a state machine for process control (~5ms), 2) background loop for communications with the RIC (~10ms), and 3) closed loop control for enacting modes of operation and fault detection and management (~100us). The CC state machine determines allowed operational control modes and states of the converter.

B. Resource Integration Controller (RIC)

The resource integrated controller (RIC) performs the task of integrating the PEC with an available resource. This could be a energy storage technology with battery management system (BMS), a photovoltaic array with DC isolation and forecasting capability, or a load such as an extreme fast charger for an electric vehicle. The RIC utilizes an agent framework to support the resource and power electronics integration as presented in [23]. A Raspberry Pi is the currently employed platform for the RIC due to the low bulk cost versus computational horsepower and flexibility offered.

C. Resource Management Controller (RMC)

The resource management controller (RMC) supports several services including: automatic interconnection with RICs and optimization considering system wide stability, data collection and record keeping, and communication with an outside entity such as a utility. The RMC can optimize hybrid networks of AC and DC systems and uses open-source linear programming tools such as Pulp [24] and COIN-OR [25]. A Linux desktop computer is the main platform applied for the RMC.

The strategy for commissioning a system of PEIRs is to evaluate the available control modes for each converter systems (confirm which assets can support bus stability) and ensure that the assumed generation resource (such as energy storage or a grid connection) are larger than the load resource. For continuous operation, an optimization routine is called periodically (every 5 minutes).

IV. Remote CHIL Simulation Approach

With the implementation of social distancing, only a single user can be present at the CHIL platform. Hence, even as the proposed architecture provides flexibility with multiple interfacing devices set in hierarchy of systems, the number of system interfaces can be difficult to debug without experienced staff.

This challenge has been mitigated through the development of an expertise versus engagement layer matrix as shown in Fig 3. The expertise is composed of software, power electronics controls, simulation, and hardware with human actors at each stage while the engagement layers represent the interconnectivity of the actors to the CHIL platform. The lowest engagement layer (hardware layer) represents the traditional CHIL platform where controllers are interconnected to an isolated or off-network simulation environment. In the proposed CHIL framework, the power electronic converter, energy resource, and the electrical network are all virtualized within the real-time simulation environment. Analog and digital input/output interfaces link the converter controllers to the virtual environment. Ethernet connections allow for communication protocols to be adopted with a simulated resource. This framework has been applied for both Opal-RT and Typhoon HIL systems but could easily be applied to others (such as RTDS).

A hardware actor (within the hardware layer) performs the physical integration of the systems and can reboot and troubleshoot interconnections. Oscilloscope data probed from real-time system analog channels locally is displayed to remote actors using a video capture card which imports the measured signal from the external display connection on the oscilloscope.

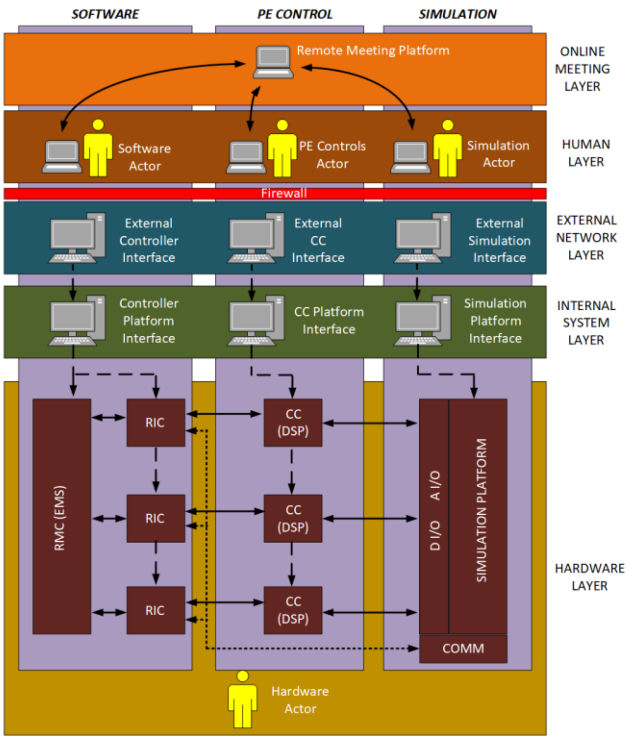


Fig. 3. Simplified schematic of the Remote - Controller Hardware-in-the-Loop (CHIL) system.

The hardware layer is interconnected to an Internal System Layer (ISL) which hosts the various software and code needed for deployment and testing within the CHIL platform. A generalized architecture for each computer in the ISL is presented in Fig. 4 where code and system programs are available for launching the application on the respective platforms. For example, in the simulation platform interface, system models exist as the deployable code and the real-time simulator software as the deployment program to the real-time simulation platform. The converter controller platform interface hosts the different power electronic control code implementations, and the Code Composer Studio Debug Server is available for deployment to the CCS. Finally, the controller platform interface hosts the different agent and energy management system software packages to be deployed through a remote access platform.

To ensure that these systems do not have any compatibility issues with the dynamic security of the institution, a separate layer of computers (External Network Layer or ENL) has been added to provide a bridge for the ISL and Human Layer (HL). The ENL is only accessible via the correct institution credentials and institution provided computers.

Access to the various systems from the ENL is performed through remote access platforms such as Microsoft Windows Remote Desktop and Virtual Network Computing (VNC) or more specifically RealVNC and Team Viewer. These remote platforms utilize a remote frame buffer to display the graphics of the target computer host while sending keyboard and mouse commands for interactions [26].

The three computers used for the ENL are combined into a single display for sharing over other platforms. Each platform host is given a separate display for local troubleshooting as well as future in-person development when restrictions have eased as shown in Fig. 5. Today, five Opal-RT and three Typhoon-HIL platforms have been configured in this way.

Using online meeting platforms (such as Microsoft Teams), information by each user or actor can be shared in real-time and the system debugging can be conducted to support full CHIL testing and validation. The equivalent full hardware implementation is discussed in the next section.

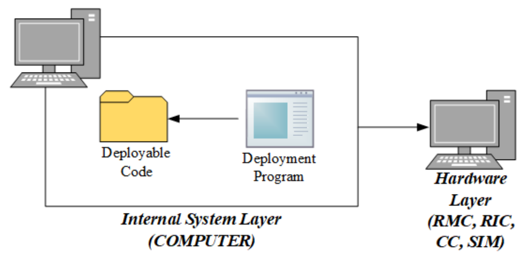


Fig. 4. Generalized Architecture for each ISL Inteface

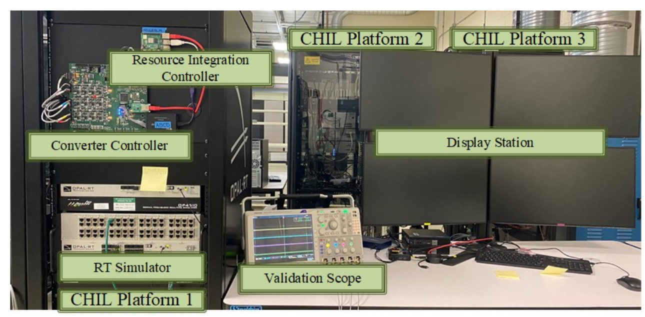


Fig. 5. Physical setup in laboratory of CHIL Opal-RT example.

V. Remote Hardware Approach

A full hardware remote testbed has also been constructed to support the building and testing of hardware prototypes. The platform maintains similar actors to those presented in the CHIL platform with software and power electronic controls assessable to the remote users as shown in Fig. 6. However, hardware systems are setup and managed by the local hardware actor and separate communication and resource simulation agents have been developed and deployed to emulate interconnected resources. The resource emulation capability is derived from different types of industry developed test equipment including: battery testing emulators (bi-directional DC supplies with programmable battery characteristic behavior), DC supplies (single directional DC supply with programmable PV characteristic behavior), real and reactive load banks consisting of switchable resistive and reactive elements, and four quadrant regenerative grid emulators (back-to-back converters configured to be bi-directional and flexible for AC or DC testing.) Many of the emulators support the capability to be programmed to follow setpoint profiles. These provide the base for testing of PEIRs under different resource integrations scenarios.

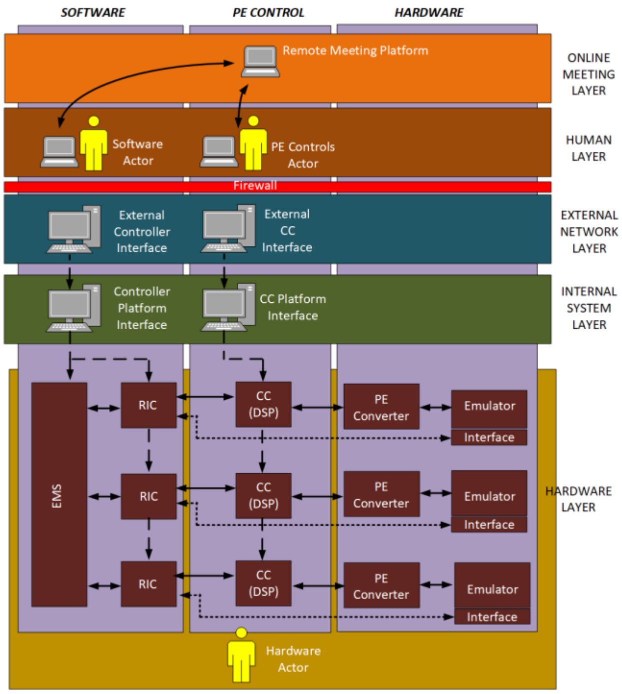


Fig. 6. Simplified schematic of the Remote - Hardware Testbed.

The converters for testing are either on a benchtop (enclosed in a protective see-through enclosure) or fully enclosed in a National Electrical Manufacturers Association (NEMA) enclosure for safety. These converters utilize the same communication and control architecture presented for the CHIL platform. The hardware actor is responsible for physically performing the electrical interconnections to the emulators, activating the emulators upon system commissioning, and enabling the emulator modes for testing. The hardware actor also watches the system for any abnormal response and is able to immediately stop experiments through the use of a emergency stop system.

Today various hardware remote platforms have been developed. A residential platform with single-phase 240V/120VAC interconnections has been developed for testing single phase inverters for residential use cases [22]. This platform consists of three single phase inverters interconnected to emulated PV, ES, and residential building load. A commercial platform with three-phase 480VAC interconnections has also been constructed. This platform will be discussed in further detail in the next section with specific focus on a energy storage use case. These platforms are hosted in a new facility focused on grid level systems validation and testing, the Grid Research Integration and Deployment Center (Grid-C).

For hardware testing, an additional hardware actor must be present for testing. When the available energy of a system exceeds 100 Vdc or 100 A, the "buddy system" is often required to ensure any significant safety event is not life threatening. This additional actor can be in another room separated by glass provided the main actor is visible. In the next section, details on the implementation of the CHIL and hardware development and testbeds are provided in terms a secondary use multi-chemistry system.

VI. Secondary Use Energy Storage System

To demonstrate that the proposed testbeds support full functionality as described, a multi-chemistry secondary use system composed of three power electronic converters is presented. This system has been first introduced in [27]-[28] with a plug and play architecture with agents and three converters: a 100kW three phase 480V connected DC/AC converter for grid connection and two 50kW DC/DC converters for management of two separate DC integrated battery systems as shown in Fig. 7. These systems are all coupled on a common 1000VDC bus. The original work in [27] leveraged the remote platform discussed in this paper.

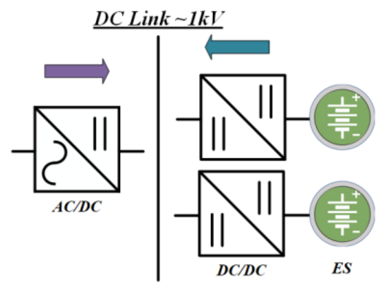


Fig. 7. General schematic of 100kW ES composed of two separate ES systems. [27]

A. CHIL Implementation

Detailed schematics of the converters as modeled within the simulation platform and interconnected to the converter controller are presented in Fig. 8 and Fig. 9 (which portray the elements of the physical hardware). The modelled systems within the real-time environment include filtering components, precharge and contactor circuitry, and system measurements.

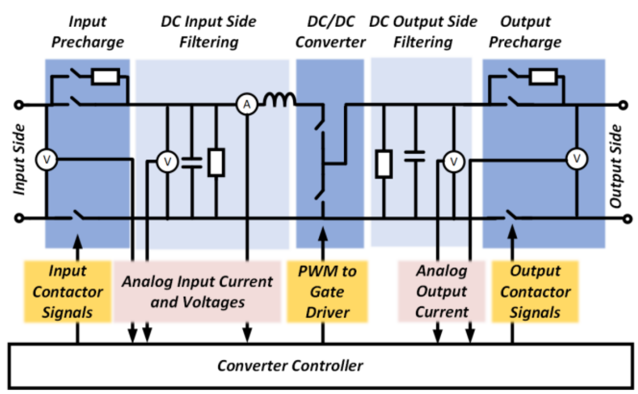


Fig. 8. Simplified circuit schematic of 50 kW Energy Storage DC-DC Converter [27]

To provide closed loop control capabilities, the analog measurements from the circuit model are scaled to the voltage range limited by the external analog I/O ports on the HIL system. These ports are interconnected to analog I/O ports on the converter controller and scaled to represent the measurements of the system for closed loop control. Digital I/O ports on the HIL platform are used to distribute power electronic module pulse width modulation (PWM) and contactor control signals to the modeled components. These signals are generated by the converter controller digital I/O ports for control. Fig. 10 shows the implementation of the different hardware layers to the simulation platform. A Modbus communication layer has been added to interconnect the RIC to the resource model within the HIL platform. This communication layer utilizes the same communication network already supporting the MQTT communications for RIC to RIC and RIC to RMC communications.

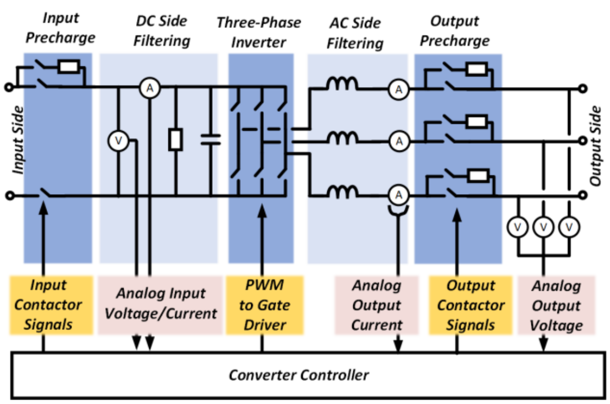


Fig. 9. Simplified circuit schematic of 100 kW Grid Interfacing DC-AC Converter [27]

B. *Hardware Implementation*

The implementation of the system for hardware testing the 100kW system is presented in Fig 11. For this work, NHR 9300 battery test systems are used to interact with the DC/DC conversion stages. These bidirectional DC supplies have been programmed to emulate a 400VDC energy storage system. A four quadrant Ametek RS90 grid emulator is used to represent the grid connection and is interconnected to the AC side of the AC/DC converter. This has been programmed as a three phase 480V grid source. A Yokogawa WT5000 power analyzer has been interconnected to both capture and document performance of the power electronic network. In the next section, results of experimentation per discussion of the different actors are discussed.

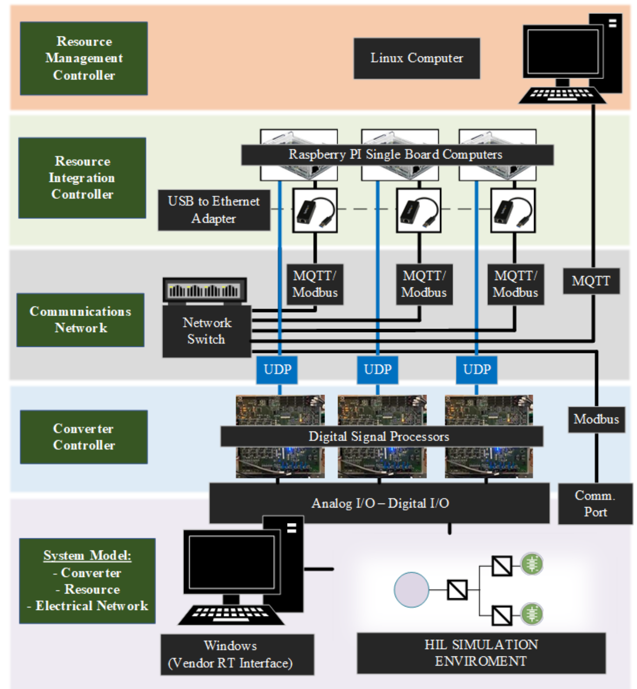


Fig. 11. CHIL physical implementation of systems.

VII. Discussion on Experimental Results from CHIL and Hardware

For demonstrating the approach in the remote platforms, a secondary use system considering CHIL and hardware platforms is discussed and measurement results from the two platforms are presented. As previously mentioned, CHIL represents the primary development and testing stage before implementation on hardware.

A. *Validation in CHIL platform*

With the CHIL platform, a single user can play the roles of the software, PE controls, and simulator actors by simultaneously logging into each of the computers within the ENL (and corresponding ISL). With full knowledge of the platform, this user can operate and run the full model from

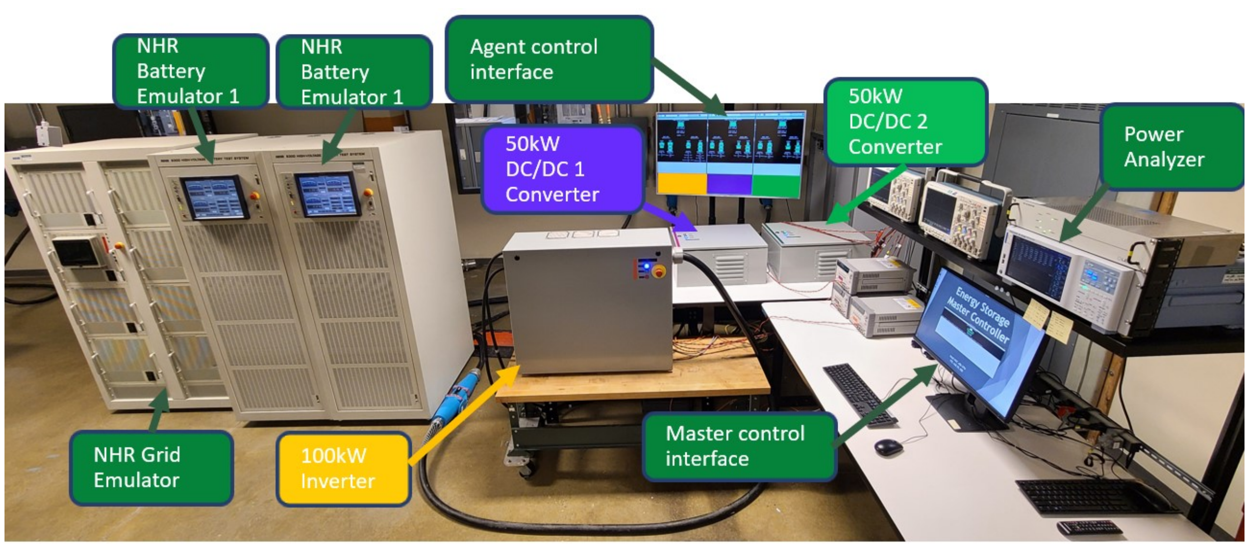


Fig. 10. Hardware testbed of 100kW multi-chemistry energy storage system.

energy management to converter within an electrical network. The results collected in this case, have been collected by a single user operating the system remotely as shown in Fig 12. In this case, no hardware actor was necessary as none of the computers needed to be cycled.

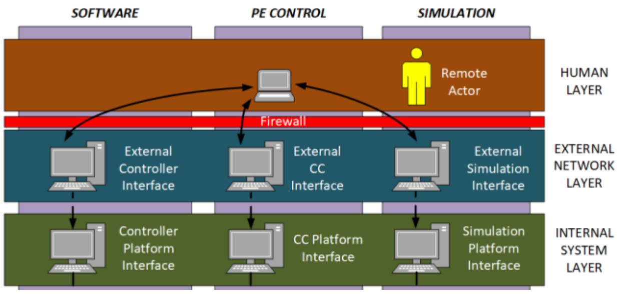


Fig. 12. Actor representation for CHIL implementation

For demonstration, a single user activated the simulation, deployed the converter controller code, and finally the RIC and EMS code. A simulation of approximately 35 mins was performed to test the controls for a system composed of two 50kW ES systems and a 100kW inverter. The results are shown in Fig. 13 and Fig. 14. The DC/DC converters were dispatched to 50kW charge and discharge cycles. The inverter control was activated for DC bus regulation mode. As shown, the DC bus remained stable during the cycling of the unit system.

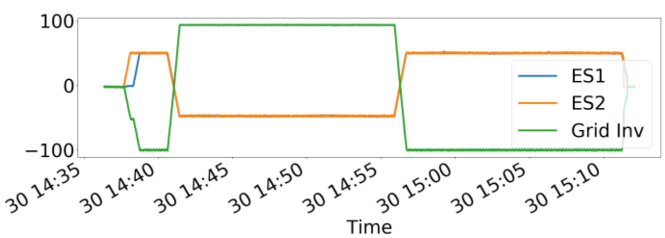


Fig. 13. Measured power (kW) through the converters as captured from converter controller measurements from the CHIL enviornment.

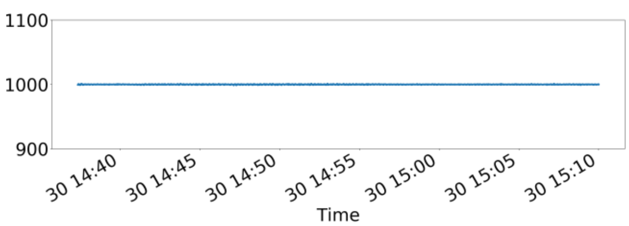


Fig. 14. DC bus voltage (V) for the ES system as captured from converter controller measurements from the CHIL environment.

B. Validation in hardware platform

With the hardware platform, a single user can perform the role of both the software and PE controls actors. However, two additional actors are needed for activating and setting the emulators (two ES emulations and a grid connection) to the correct configuration and monitoring the experiment as presented in Fig. 15.

A early hardware prototype of the simulated system developed and discussed in [27] is used for the hardware demonstration. In this case, the system is operated at low power to verify control behavior and ensure operations are stable before transitioning of the system to higher power levels.

The test examines the dispatch of the DC/D converter and the regulation capability of the inverter of the DC link. Fig 16 shows measured results from the experiment as captured by the power analyzer. In this short test, the DC/DC converters are operated at 2.45kW and 7.8kW respectively, and the inverter regulating the DC bus, pushes 9.7kW to the grid emulator.

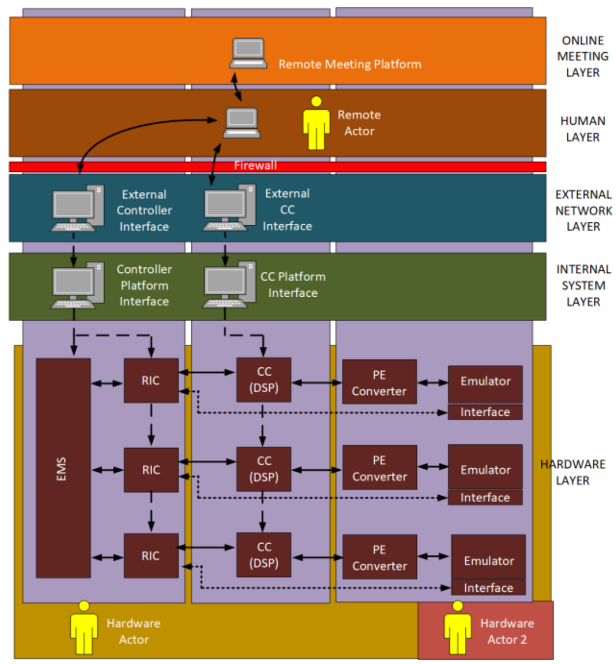
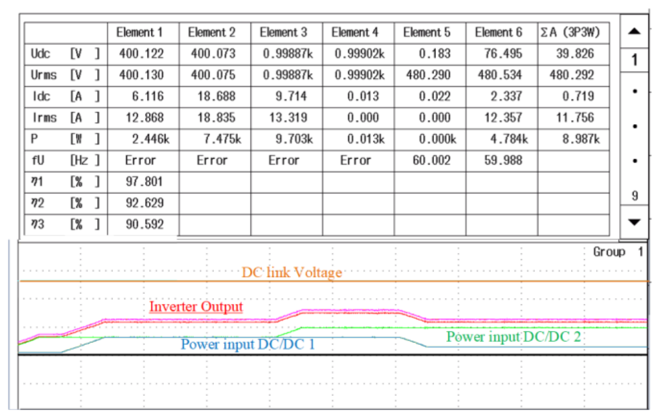


Fig. 15. Actor representation for hardware implementation



	Element 1	Element 2	Element 3	Element 4	Element 5	Element 6	ΣA (3P3W)
Udc [V]	400.122	400.073	0.99887k	0.99902k	0.183	76.495	39.826
Urms [V]	400.130	400.075	0.99887k	0.99902k	480.290	480.534	480.292
Idc [A]	6.116	18.688	9.714	0.013	0.022	2.337	0.719
Irms [A]	12.868	18.835	13.319	0.000	0.000	12.357	11.756
P [W]	2.446k	7.475k	9.703k	0.013k	0.000k	4.784k	8.987k
fU [Hz]	Error	Error	Error	Error	60.002	59.988	
η1 [%]	97.801						
η2 [%]	92.629						
η3 [%]	90.592						

Fig. 16. Meaured results from a Yokogawa WT5000 power analyzer connected to DC-DC 1, DC-DC 2, and the inverter.

VIII. Conlclusion and Future Work

This paper presents an approach for developing and testing novel CHIL and hardware power electronic systems while considering the need for isolationism practices. This system supports multiple layers in the development process including the DSP controls, communication networks, and central optimization and control strategies. Laboratory layouts with integrated physical hardware systems are shown with testing results of a converter system shown both for CHIL and hardware.

While this platform was initially designed as means to support the need to work while isolated, the concept has continued to be applied to offer researchers the ability to develop and test while at home or on travel. Future expansion of this platform will focus on linking the three systems (software, controls, and simulation/hardware) under a single umbrella for auto-deployment of different system models. This will expand the prototyping of and control development beyond single converter prototypes, but into systems of systems to examine new power electronic converter coordinated control techniques from a large power system perspective.

IX. Acknowledgment

This work was funded by the U.S. Department of Energy Office of Electricity, Energy Storage Program under contract number DE-AC05-00OR22725.

X. References

[1] COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU), available at: https://gisanddata.maps.arcgis.com/apps/opsdashboard/index.html#/bda7594740fd40299423467b48e9ecf6

[2] Michael R. Fulcher, Marian L. Bolton, Michael D. Millican, Matthew J. Michalska-Smith, José Pablo Dundore-Arias, Jo Handelsman, Jonathan L. Klassen, Kathryn C. Milligan-Myhre, Ashley Shade, Benjamin E. Wolfe, Linda L. Kinkel, Broadening Participation in Scientific Conferences during the Era of Social Distancing, Trends in Microbiology, Volume 28, Issue 12, 2020, Pages 949-952.

[3] X. Guillaud et al., "Applications of Real-Time Simulation Technologies in Power and Energy Systems," in IEEE Power and Energy Technology Systems Journal, vol. 2, no. 3, pp. 103-115, Sept. 2015.

[4] G. Lauss, F. P. Andren, F. Leimgruber and T. I. Strasser, "Analyzing standardization needs for CHIL-based testing of power systems and components," 2018 IEEE International Conference on Industrial Electronics for Sustainable Energy Systems (IESES), 2018.

[5] N. Yousefpoor, B. Parkhideh, A. Azidehak and S. Bhattacharya, "Convertible static transmission controller (CSTC) system model validation by controller hardware-in-the-loop-simulation," 2014 IEEE Energy Conversion Congress and Exposition (ECCE), 2014, pp. 2960-2966.

[6] C. Kumar, Z. Zou and M. Liserre, "Smart transformer-based hybrid grid loads support in partial disconnection of MV/HV power system," 2016 IEEE Energy Conversion Congress and Exposition (ECCE), 2016, pp. 1-8.

[7] M. C. di Piazza, M. Luna, M. Pucci, G. L. Tona and A. Accetta, "Electrical Storage Integration into a DC Nanogrid Testbed for Smart Home Applications," 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2018, pp. 1-5.

[8] M. Vygoder, M. Milton, J. Gudex, R. Cuzner and A. Benigni, "A Hardware-in-the-Loop Platform for DC Protection," in IEEE Journal of Emerging and Selected Topics in Power Electronics.

[9] Xiao, Bailu; Starke, Michael; King, Dan; Irminger, Philip; Herron, Andrew; Ollis, Ben; Xue,Yaosuo, Implementation of System Level Control and Communications in a Hardware-in-the-Loop Microgrid Testbed, IEEE Innovative Smart Grid Technologies, 2016.

[10] Xiao, Bailu; Prabakar, Kumaraguru; Starke, Michael R; Liu, Guodong; Dowling, Kevin; Ollis, T Ben; Irminger, Philip; Xu, Yan; Dimitrovski, Aleksandar D; Development of Hardware-in-the-loop Microgrid Testbed, IEEE Energy Conversion Congress and Exposition, September 2015.

[11] Starke, Michael; Xiao, Bailu; Liu, Guodong; Ollis, Ben; Irminger, Philip; King, Dan; Herron, Andrew; Xue,Yaosuo; Architecture and Implementation of Microgrid Controller, IEEE Innovative Smart Grid Technologies, 2016.

[12] Y. Du, H. Tu, S. Lukic, D. Lubkeman, A. Dubey and G. Karsai, "Development of a Controller Hardware-in-the-Loop Platform for Microgrid Distributed Control Applications," 2018 IEEE Electronic Power Grid (eGrid), 2018, pp. 1-6.

[13] C. Sun, J. N. Paquin, F. Al Jajeh, G. Joos and F. Bouffard, "Implementation and CHIL Testing of a Microgrid Control System," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), 2018, pp. 2073-2080

[14] B. Palmintier, B. Lundstrom, S. Chakraborty, T. Williams, K. Schneider and D. Chassin, "A Power Hardware-in-the-Loop Platform With Remote Distribution Circuit Cosimulation," in IEEE Transactions on Industrial Electronics, vol. 62, no. 4, pp. 2236-2245, April 2015.

[15] M. J. Stanovich, S. K. Srivastava, D. A. Cartes and T. L. Bevis, "Multi-agent testbed for emerging power systems," 2013 IEEE Power & Energy Society General Meeting, 2013, pp. 1-5.

[16] S. D. Sudhoff, S. Pekarek, B. Kuhn, S. Glover, J. Sauer and D. Delisle, "Naval combat survivability testbeds for investigation of issues in shipboard power electronics based power and propulsion systems," IEEE Power Engineering Society Summer Meeting,, 2002, pp. 347-350 vol.1.

[17] E. Matheson, A. von Jouanne and A. Wallace, "A remotely operated power quality test platform based on a 120 kVA fully programmable three-phase source," Conference Record of the 2001 IEEE Industry Applications Conference, 2001, pp. 1188-1195 vol.2.

[18] S. Bogosyan, M. Gokasan, A. Turan and R. W. Wies, "Development of Remotely Accessible Matlab/Simulink Based Electrical Drive Experiments," 2007 IEEE International Symposium on Industrial Electronics, 2007, pp. 2984-2989.

[19] M. D. Omar Faruque et al., "Real-Time Simulation Technologies for Power Systems Design, Testing, and Analysis," in IEEE Power and Energy Technology Systems Journal, vol. 2, no. 2, pp. 63-73, June 2015.

[20] P. Kotsampopoulos et al., "A Benchmark System for Hardware-in-the-Loop Testing of Distributed Energy Resources," in IEEE Power and Energy Technology Systems Journal, vol. 5, no. 3, pp. 94-103, Sept. 2018.

[21] F. Li et al., "Review of Real-time Simulation of Power Electronics," in Journal of Modern Power Systems and Clean Energy, vol. 8, no. 4, pp. 796-808, July 2020.

[22] Michael Starke, Bailu Xiao, Pankaj Bhowmik, Radha Sree Krishna Moorthy, Steven Campbell, Benjamin Dean, Madhu Chinthavali, Jongchan Choi, "A plug and play design suite for converters for the electric grid", Energy Conversion Congress and Expo, 2020.

[23] Starke, M. Chinthavali, S. Zheng, S. Campbell, R. Zeng, M. Smith, T. Kuruganti, Agent-Based Framework for Supporting Behind the Meter Transactive Power Electronic Systems, IEEE Innovative Smart Grid Technologies, 2020.

[24] Pulp, https://www.coin-or.org/PuLP/

[25] COIN-OR, https://projects.coin-or.org/Clp

[26] T. Richardson, Q. Stafford-Fraser, K. R. Wood and A. Hopper, "Virtual network computing," in IEEE Internet Computing, vol. 2, no. 1, pp. 33-38, Jan.-Feb. 1998.

[27] Michael Starke, Pankaj Bhowmik, Bailu Xiao, Radha Sree Krishna Moorthy, Steven Campbell, Ben Dean, Anup Thapa, Madhu Chinthavali, A Secondary Use – Plug-and-Play Energy Storage System Composed of Multiple Energy Storage Technologies, IEEE Innovative Smart Grid Technologies 2020.

[28] Mitchell Smith, Michael Starke, Leon Tolbert and Madhu Chinthavali, "Architecture for Utility-Scale Multi-Chemistry Battery Energy Storage," Energy Conversion Congress and Expo, 2019.