Title
Hardware-In-the-Loop Benchmarking Setup for Phasor Based Control Validation

Permalink
https://escholarship.org/uc/item/8086c2t7

Authors
Baudette, Maxime
Swartz, Jaimie
Moffat, Keith
et al.

Publication Date
2021-10-25

DOI
10.20357/B7XP4R

Building Technologies & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

Hardware-In-the-Loop Benchmarking Setup for Phasor Based Control Validation

Maxime Baudette[1], Jaimie Swartz[2], Keith Moffat[2], Jasper Pakshong[2], Leo Chu[2],
Christoph Gehbauer[1], Alexandra von Meier[1,2]

[1]Lawrence Berkeley National Laboratory, Berkeley, CA
[2]University of California, Berkeley, Berkeley, CA

Energy Technologies Area
October 2021

doi:10.20357/B7XP4R

FLEXLAB at Lawrence Berkeley National Lab's component of this work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Hardware-In-the-Loop Benchmarking Setup for Phasor Based Control Validation [★]

Maxime Baudette [*] **Jaimie Swartz** [**] **Keith Moffat** [**]
Jasper Pakshong [**] **Leo Chu** [**] **Christoph Gehbauer** [*]
Alexandra von Meier [*,**]

[*] *Lawrence Berkeley National Lab, Berkeley, CA*
[**] *Department of Electrical Engineering and Computer Science, University of California, Berkeley, Berkeley, CA*
Emails: baudette@lbl.gov, jaimie.swartz@berkeley.edu, vonmeier@berkeley.edu

---

Abstract: Phasor Based Control is a novel approach to controlling Distributed Energy Resources that aims at relieving various constraints that arise in the distribution grid. It is a two-layer control system with a supervisory control that coordinates distributed controllers to reach voltage phasor targets. The distributed controllers use local synchrophasor measurements and operate as feedback controllers. This control method is currently under development with several algorithms being under consideration for both the central and ditributed components. In this paper, we present the experimental setup that was prepared to prototype a hardware implementation and validate the control method in Hardware-In-the-Loop.

Keywords: DER, μPMU, phasor based control, renewable energies

---

1. INTRODUCTION

The electric grid is seeing a significant influx of Distributed Energy Resources (DERs), such as solar photovoltaic (PV), wind power, and battery energy storage systems (BESS). These additional generation units are spread out in the distribution grid and create a new paradigm, where power not only flows from the transmission grid down to the distribution grid, but also flows back up to the transmission grid. These reverse power flows introduce new challenges that distribution grids were not designed to accommodate, resulting in new constraints, in particular voltage violations may occur during certain periods of the day Kroposki et al. (2017). As these challenges appear, there is a growing interest to leverage DERs to improve the grid operation, by deploying new control algorithms that actively coordinate distributed resources to relieve constraints. This development is aided by the democratization of high accuracy sensors throughout the distribution grid von Meier et al. (2017).

Phasor Based Control (PBC) is a novel control framework that aims at relieving such constraints by controlling the voltage phasor (voltage magnitude and angle) at strategically chosen nodes of the grid. It provides a flexible framework to recruit one or more DER to participate in a common objective to remedy various voltage or power constraints occurring in the distribution grid. The abstraction of the DER's output through the control of a voltage phasor allows more advanced and granular control features, compared to other direct control methods, such as Volt/VAr controls. PBC is currently being developed, and several formulations and approaches are still being considered for the control algorithms to be used von Meier et al. (2020); Swartz et al. (2020).

After initial rounds of software simulations (i.e. in-silico tests) Swartz et al. (2020), the research team prepared the validation of the PBC concept with a hardware prototype. The controller was implemented using a platform developed in house Fierro et al. (2020), and deployed on generic hardware Moffat et al. (2021). We validated the controller in Hardware-In-the-Loop (HIL) experiments that were carried out at FLEXLAB with the Flexgrid micro-grid test-bed at Lawrence Berkeley National Laboratory (LBNL) Baudette et al. (2020). This last step in the development of a new and unproven technology for the grid is essential to evaluate the practicality and feasibility of such a novel control approach Chakraborty et al. (2015). In particular, the setup was developed to allow both Controller-In-the-Loop (CIL) and HIL experiments in a seamless configuration that featured several grid models, a set of remotely configurable sensors and up to six separate DERs to act as actuators in common control scheme; this allowed to test the controller in a wide array of scenarios. The CIL setup was used to finalize the development of the controller remotely during the *Shelter In Place (SIP)* order that was enacted in the Bay Area of California during the *COVID-19* outbreak.

In this paper, we describe the experimental setup that was prepared to integrate the hardware implementation of PBC that was developed. The paper also presents results from different experimental scenarios that validate PBC in various grid conditions. The remainder of the paper is organized as follows: Section 2 briefly introduces the PBC concept and its hardware implementation. The

---

[★] This work was supported by U.S. Dept. of Energy, Award DE-EE0008008.

Flexgrid test bed is presented in Section 3. In Section 4, we detail the experimental setup. The models chosen for the validation experiments and associated results are presented in 5, and conclusion are drawn.

2. PHASOR BASED CONTROL

The development of control methods dedicated to managing a pool of several DERs that abstracts the complexity of the physical installation will allow to leverage DER to improve the operation of the grid.

2.1 Control Architecture and Algorithms

The Phasor Based Control (PBC) concept was developed to propose a flexible framework for incorporating several DERs into a single control scheme. It is organized into two layer: a supervisory layer for coordination (SPBC), and distributed local controllers (LPBC) that manage a set of DER. The supervisory layer defines an objective to optimize by computing target phasors for each of the distributed controllers. It is also responsible for re-dispatching the target phasors in the case where one or more resources reach capacity limitations. The distributed controllers leverage local Phasor Measurements Units (PMU) measurements in a feedback loop to reach their designated target phasor by changing the active and / or reactive power outputs of their associated DER.

The PBC concept primarily defines the framework as aforementioned, while the exact formulation is still in development; several algorithms are under consideration. In particular, in this round of experiments, we considered two formulations for the LPBC: a Proportional - Integral (PI) and a Linear Quadratic Regulator (LQR) formulation. In this paper, we focus on the results from the PI controller.

2.2 Communication Implementation

A prototype implementation of PBC was prepared for HIL validation at Berkeley Lab. The full controller stack was implemented using the Distributed, Extensible Grid Control (DEGC) platform that was deployed on a conventional computer for the SPBC, and an embedded computer for all the LPBCs. The controller received synchrophasor measurements using a standard C37.118.2 stream IEEE (2011), and controlled the actuators remotely via a network connection to the Local Area Network (LAN) using the inverter's remote control capabilities.

The development was carried out over two test phases that allowed us to focus on building a working prototype in the first phase, and improve its performances in the second phase. The second testing phase was carried out as a two step process: a Controller-In-the-Loop (CIL) version of the controller that communicated directly with the real-time simulation allowed to refine the experiment parameters and scenarios and a final round of HIL experiments was carried out once the local SIP order was lifted.

The implementation of the communication platform is presented in Fierro et al. (2020); Moffat et al. (2021)

3. FLEXGRID TEST BED

Flexgrid is the LBNL facility for testing micro-grid technologies that is hosted at FLEXLAB. It features a small-scale micro-grid with a single three-phase bus to which a Photovoltaic (PV) / battery system is connected. The system comprises three 8.3 kVA SolarEdge smart inverters that each interface a 3.3 kW / 6.4 kWh battery and 3.75 kW PV strings. The full PV installation amounts to 15 kW, hence, one of the inverters is connected to two PV strings (the two most prone to shading from the building). The smart inverters allow for remote control of the PV / battery system over MODBUS, and a web API was developed to interface the inverters with any kind of controller through simple web requests.

The three-phase PV / battery system is connected in a Delta configuration to a step up 208/240 transformer that allows it to run at a 240 V voltage level using the local three-phase 120 V distribution grid (208 V in line-to-line voltage). The micro-grid is equipped with a micro Phasor Measurement Unit (μPMU) [1] that measures the three-phase voltages and currents at its point of connection. The local grid connection can be switched to a three-phase 30 kVA grid emulator that is interfaced with an Opal-RT real-time digital grid simulator box. This configuration enables Power Hardware-in-the-Loop (P-HIL) experiments, where the grid emulator is mapped to a chosen bus in the simulation. A set of voltage and current sensors feed back the instantaneous measurements of the micro-grid at the point of connection, while the physical power flows back to the local grid through the regenerative mode of the grid emulator.

The real-time grid simulator box is also wired to a set of three HIL μPMUs through their low level interface that can be mapped to any node / equipment in the simulation to measure their voltage and current phasors.

The other FLEXLAB facilities focus on experiments for various building technologies (climate / energy control, lighting, etc.). The test cells feature an extensive set of sensors that monitor all the equipment installed. The measurements can be accessed through a common data acquisition system that was used to integrate the custom fan racks' data in the real-time simulation.

3.1 Wiring Reconfiguration

In its original construction, the PV / battery inverters were connected in a delta configuration. The grid emulator is interfaced through a *wye* mapping in the grid simulation. Hence, it was difficult to use the setup in another configuration than a single three-phase load. In the context of this experiment, it reduced the three inverters to a single actuator, thus limiting the range of test scenarios.

In preparation of the second testing phase, an extension of the Flexgrid micro-grid was built to circumvent this limitation. A set of three-way switches was added to the setup to allow the connection of the micro-grid in a *wye* configuration. This was achieved using the Ametek grid emulator's extended range mode to output voltages in the 240 V range, and its internal construction that allows

---

[1] μPMU commonly refer to a PMU for the distribution grid

to drive each phase independently to faithfully reproduce imbalanced conditions. This extended the possible scenarios by providing three separate actuators that could be mapped to different nodes in the grid simulation.

4. EXPERIMENTAL SETUP

The experimental setup was designed to allow the comparison and validation of PBC schemes that used different algorithms. This flexible setup could be remotely configured to be used in all the desired configurations of both sensor locations, and actuator locations.

4.1 Data Acquisition

PBC uses phasor measurements of the system; more specifically, it needs measurements at: a ***reference node*** measurement, ***performance nodes***, and ***actuation nodes***. The performance nodes are the nodes where we wish to drive the voltage phasor to a target voltage phasor. The actuation nodes are located at the point of connection of the recruited DERs that are governed by the LPBC. The reference node is primarily used as common reference to compute the angles of all the other phasor measurements.

In this setup we used three HIL μPMUs to provide the measurements that were reported at a rate of 120 Samples/second. Each μPMU had their voltage and current transformer inputs of each of the three phases connected to analog outputs of the grid simulator. Internal grid simulator switching mechanisms allowed us to map each μPMU to different nodes of the grid models. Note that each phase of each μPMU was independently located, allowing a single μPMU to be mapped to the same phase on three different nodes. The μPMUs were connected to a Phasor Data Concentrator (PDC) server that was used to forward the stream of measurements to the PBC controller. The PDC server could have been used to time align all the incoming measurements for the controller, but the PMU stream parser of the controller was not developed to support aggregated streams, so instead each μPMU had their own independent stream, and the time alignment was carried out on the controller.

4.2 Actuators

The actuators in the PBC scheme are primarily envisioned to be DER that can vary their active power and / or reactive power injections in the network. Ideally, for best results the actuators should operate in all four quadrants of the apparent power plane. In this experimental setup we considered two types of physical actuators, and a CIL setup that are introduced below.

Controller-In-the-Loop (CIL) Setup As mentioned in the Introduction, the controller prototype was developed and tested in two separate phases, with the second phase focused on improving the performances of the prototype, and refining the testing scenarios. This second phase also started shortly before the SIP order that shut down all lab onsite research and work. A Controller-In-the-Loop (CIL) setup was developed to allow the integration of the controller prototype with the real-time grid simulator over a digital link using MODBUS over IP, bypassing the physical actuators of the setup. The solution adopted consists of a direct mapping of the future HIL actuators (load racks and inverters) as modbus registers in the simulation. The controller was updated to generate digital outputs to the corresponding registers, allowing a fully digital integration in the simulation setup. A toggle in the model allows to choose between the CIL or corresponding HIL actuator input, and a similar setting must be set on the controller. The remainder of the experimental setup is identical to that of the HIL setup.

Load Racks in Hardware-In-the-Loop (HIL) A set of custom load racks built with a set of fans and their respective variable-frequency drive (VFD) totalling 1000 W were used as actuators. The racks were assembled in three groups of two racks, corresponding to a maximal load of 2 kW. A dedicated web API was developed to control the racks remotely by giving an active power command (W) through a HTTP request. The reactive power consumption of the load racks was an uncontrolled variable.

The load racks were connected to outlets at FLEXLAB, from which the real time consumption was measured and used to integrate in the real-time simulation. A script fetched the measurement data from the FLEXLAB database and transmitted them to the simulator at regular intervals through a MODBUS IP connection. It was decided to add a static negative offset of 1 kW to the active power measurements, to emulate resources that could both consume and inject up to 1 kW of active power. Also the reactive power measurements were zeroed out in the incoming measurements to emulate a unity power factor.

Inverters in Power-Hardware-In-the-Loop (P-HIL) The three Flexgrid inverters were used as actuators using both batteries and PV panels as power sources to ensure a full availability of each resource. The inverters were connected in wye configuration to the grid emulator and integrated into the grid simulation through physical sensors measuring the voltages and currents of each phase. This allowed us to map each inverter to different nodes in various phase configurations.

Initial tests pointed to a need for a good precision in the actuator commands to be able to control the phasors as expected. Hence, the regular mode, where an *integer* percentage value of the active power limit and a *real* power factor value are provided as commands, was not providing sufficient granularity, limiting the actuators to steps of 83 W in the physical system, scaled up to several kW in the simulated system. The advanced control mode allowed to specify an active and reactive power commands as a *real* percentage value, albeit no sign information could be provided. Thus, we created a separate communication channel from the controller, directly to the simulator (i.e. similar to that of the CIL setup) to provide a quadrant "flag" to emulate four-quadrant operation of the inverters in this advanced control mode.

After preliminary tests, it was deemed that the scaling factor used to simulate a larger resource when including the inverters in the real-time simulation, was too high, causing measurement and system noises to perturb the ongoing experiments. We decided to have the controller send 90 % of the control action in a similar way to the CIL

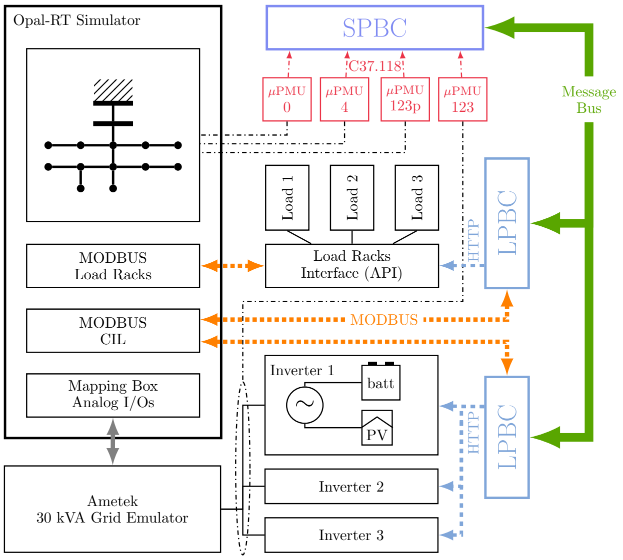

Fig. 1. HIL Setup at Flexlab

setup, and 10 % of the control action to the P-HIL inverter. This effectively allowed to reduce the scaling factor used for the inverters incoming measurements.

The final experimental setup is summarized in Fig. 1.

4.3 Remote Configuration

In the early design phase, it appeared that several configurations would be considered for the full experiment sets. Hence, we implemented each model with a remote configuration capability that let us map both the CIL / HIL sensors and actuators to various pre-selected locations in the feeder models. This was achieved via a set of digital switches connected to MODBUS registers. Additional registers were reserved to configure various scaling factors, and to control the playback of the load profiles that allowed to conduct multiple cases seamlessly.

The remote configuration facility, combined with the CIL setup allowed to finalize all the development of the controller remotely, until work was re-authorized onsite for P-HIL experiments. The remote facilities also allowed to conduct the experiments with minimal staff on premises for the P-HIL experiments (1 person), which helped to comply with safety protocols put in place.

5. EXPERIMENTS AND RESULTS

In this section we compare voltage phasor tracking and actuator effort between software, CIL, and HIL tests in order to validate the hardware implementation of PBC. We include one test from each of the IEEE 13-node unbalanced (13NFunbal), 13-node balanced (13NFbal), 33-node balanced (33NFbal), and a 344-node unbalanced PG&E distribution feeder (341NFunbal).

For all tests, we included time-varying load data profiles that were constructed as follows. Reported spot loads on IEEE feeders or otherwise were replaced with aggregate second-wise time-varying net load data. The data is generated based on public commercial and residential loads and solar PV generation profiles from Southern California Edison during a typical summer day. We considered a PV penetration level at 100 % of the non-coincident feeder peak. Figure 2 shows the net active and reactive power of uncontrolled PV and loads on each node of the 13NFunbal across a typical day. Observe that the 100 % PV penetration causes some slightly negative net loads during our simulation window of 11am-11:50pm. Actuator limits were set at 500 kW and 500 kVAr for all tests in software, CIL, and HIL.

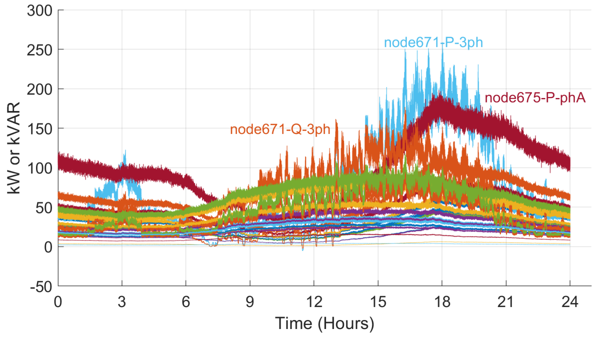

Fig. 2. Daily active and reactive power net load profiles of the 13NFunbal, with 100% PV penetration

For all software tests, controllers turned on when the simulation began, at 11:00am. We used a simulation timestep of fifteen seconds, to match the HIL setup's expected delay of fifteen seconds between consecutive control actions. The Proportional-Integral (PI) controller parameters were designed using an offline genetic algorithm method from Swartz et al. (2020) for the software tests. For CIL and HIL tests the controller gains were modified to improve the hardware controller's response.

5.1 33 Node Model

On the 33NFbal we placed inverters on three-phases of node 18 and load racks on three-phases of node 26, both to track the 3-phase phasor target at node 6. The phasor target was constant at $0.97Vp.u$ and $-0.5°$ on three phases. In addition to the voltage disturbances caused by the time-varying load and PV data, we applied two sets of square wave disturbances at nodes 6, 13, 21, 25, and 26 from 1080 to 1440 and 2160 to 2520 seconds, equal to 300 % of the nodal active and reactive power.

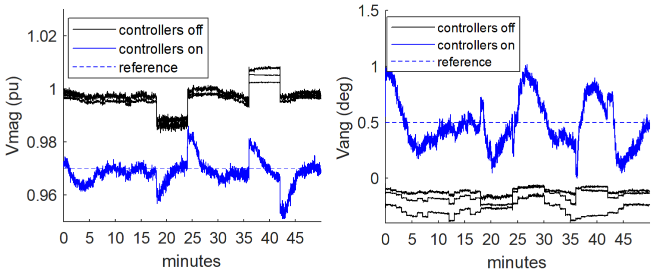

Fig. 3. Voltage magnitude and phase angle from HIL tests when controllers are off (black) and on (blue).

In Fig. 3 we compare voltage magnitude and phase angle at the performance node when the controllers are turned off and when they are on. We observe that the curves for each phase are close to overlapping, due to the feeder being balanced. When the controllers are on they successfully drive the target on each phase to its target both when the simulation begins and when rejecting each step of the large load disturbances.

Typically, the communication setup for inverter control is local, where inverters use measurements at their own node to modify their power output with the goal of regulating voltage and/or frequency. Hence it is notable that in this setup we demonstrate three-phase devices actuating at two different nodes to collaboratively track the three-phase voltage magnitude and phase angle target at a third node.

5.2 13 Node Unbalanced Model

On the 13NFunbal we place inverters on three-phases of node 675 and load racks on three-phases of node 671, both to track the phasor target at node 632. The phasor target is constant at 0.99 p.u. and $-1°$ on three phases. In addition to the voltage disturbances caused by the time-varying load and PV data, we apply two sets of square wave disturbances at nodes 623, 671, 675, 632, and 645 from 1080 to 1440 and 2160 to 2520 seconds, equal to 90 % of the nodal real and reactive power.

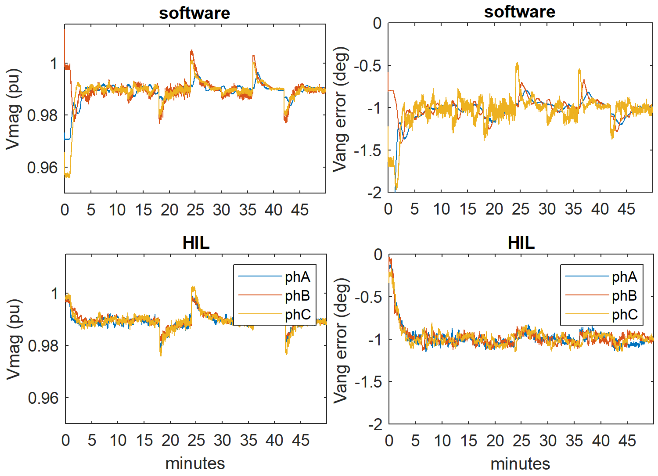

Fig. 4. Comparison of voltage magnitude and phase angle between software and HIL tests on the 13NFunbal

In Fig. 4 We compare the performance of the PI controllers between software and HIL tests by plotting the voltage magnitude and phase angle at the performance node. We observe convergence to the phasor target both when the simulation begins and when rejecting each step of the large load disturbances. This test demonstrates that our setup and control algorithm is successful on an unbalanced distribution grid.

5.3 13 Node Balanced Model

On the 13NFbal we place inverters on phase A of node 671, 652, and 692 to track the phase A targets at the same locations (co-located tracking setup). There are no square wave disturbances, but the phasor target is changed twice in real-time to illustrate a scenario in which the L-PBC handles problematic phasor targets.

The test is conducted in software, CIL, and HIL. We plot the voltage magnitude and phase angles in Fig. 5, and in Fig. 6 we plot real and reactive power inverter actuation.

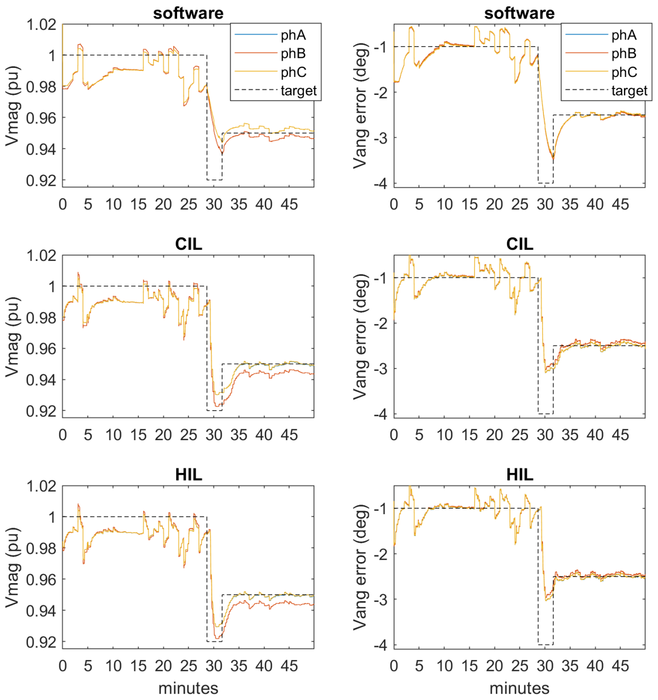

Fig. 5. Comparison of voltage magnitude and phase angle between software, CIL, and HIL tests on the 13NFbal

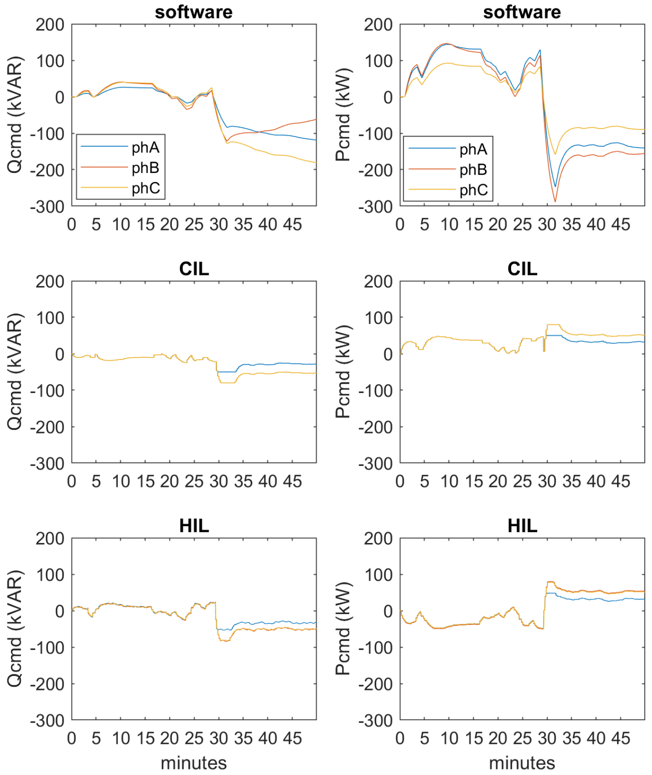

Fig. 6. Comparison of inverter real and reactive power between software, CIL, and HIL tests on the 13NFbal

The S-PBC initially sent the L-PBC an achievable magnitude and angle target of 0.99 p.u. and $-1°$ on three phases. After 30 minutes (1750 seconds), the targets were updated to 0.92 p.u. and and $-4°$, which were not achievable with the available actuation of 500kW/500kVAR. After reaching saturation, the L-PBC alerts its saturated status to the S-PBC, causing the S-PBC to send back an updated phasor target of 0.95 p.u. and $-2.5°$ at 1800 seconds. Finally, the feedback controller at 671 tracked this target with a successful, non-saturated status. This test demonstrates effective communication between the L-PBC and S-PBC during HIL.

5.4 PG&E Distribution Feeder

Finally, to assess the scalability of PBC we conduct tests on the 344NF. We place inverters on three-phases of node 300063911 that track the phasor target at the same node. The phasor target is constant at 0.98 p.u and $-3°$ on three phases. Time-varying load and PV data causes second-wise disturbances that the controllers must reject to maintain the phasor target.

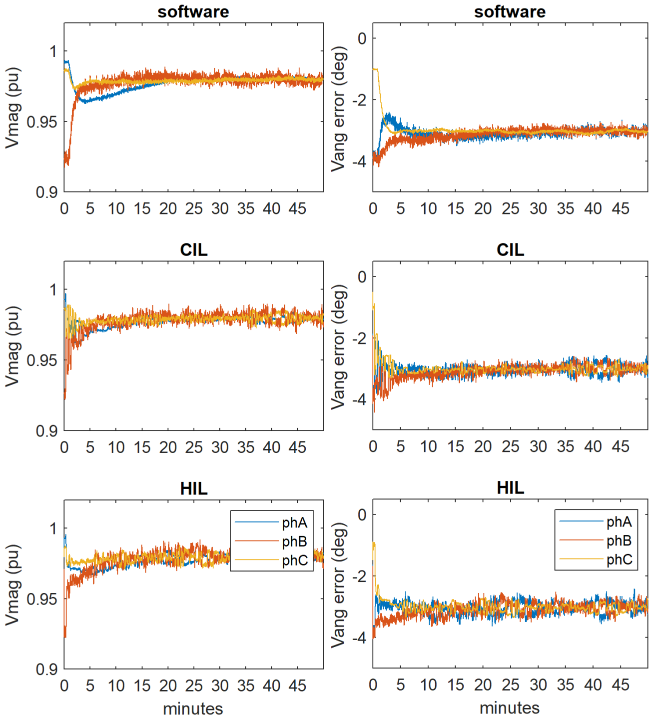

Fig. 7. Comparison of voltage magnitude and phase angle between software, CIL, and HIL tests on the 344NFunbal

In Fig. 7 We compare the performance of the PI controllers between software, CIL, and HIL tests by plotting the voltage magnitude and phase angle at the performance node. All three tests successfully track the phasor target on this large feeder. Our previous work Swartz et al. (2020) exhibited challenges with coupling between real and reactive power actuation and A/B/C phase coupling when simulating on large feeders. Hence it is notable that our designed controllers overcome the coupling affects in all three testing modes, resulting in good tracking of the phasor target with minimal steady-state error.

6. CONCLUSION

In this work we implement the novel control framework of Phasor-Based Control on real hardware at LBNL. The test setup is successful in coordinating multiple DERs to execute real and reactive power commands for tracking μPMU measurements. In particular, the testbed includes smart inverters, a PV and battery system, controllable loads, and a μPMU. In creating the hardware implementation we overcame several practical challenges, including the rewiring of the original 3-phase connections from Delta to WYE configurations, and the creation of an advanced control mode to enable 4-quadrant inverter control. The test results exhibit effective phasor tracking, where PI-controlled actuators and load racks overcome second-wise solar PV variations and large load disturbances. By comparing the software simulations to CIL and HIL tests, we observe similarly effective performance, with reasonable differences in settling time and amount of noise.

REFERENCES

Baudette, M., Arnold, D., Breaden, C., Sankur, M.D., Callaway, D.S., and MacDonald, J. (2020). Hil-validation of an extremum seeking-based controller for advanced der management. In *2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 1–5. IEEE.

Chakraborty, S., Hoke, A., and Lundstrom, B. (2015). Evaluation of multiple inverter volt-var control interactions with realistic grid impedances. In *2015 IEEE Power Energy Society General Meeting*, 1–5. doi: 10.1109/PESGM.2015.7285795.

Fierro, G., Moffat, K., Pakshong, J., and von Meier, A. (2020). An extensible software and communication platform for distributed energy resource management. In *2020 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*. IEEE.

IEEE (2011). C37.118.2 - standard for synchrophasor data transfer for power systems. `https://standards.ieee.org/project/C37_118_2.html`. Accessed: 2020-07-06.

Kroposki, B., Johnson, B., Zhang, Y., Gevorgian, V., Denholm, P., Hodge, B., and Hannegan, B. (2017). Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy. *IEEE Power Energy Mag.*, 15(2), 61–73.

Moffat, K., Pakshong, J., Chu, L., Fierro, G., Swartz, J., Baudette, M., Gehbauer, C., and von Meier, A. (2021). Phasor based control with the distributed extensible grid control platform. In *IEEE Innovative Smart Grid Technologies (ISGT)*.

Swartz, J., Ratnam, E., Roberts, T., and von Meier, A. (2020). Local phasor-based control of DER inverters for voltage regulation on distribution feeders. In *press, IEEE Green Technologies Conference*.

von Meier, A., Stewart, E., McEachern, A., Andersen, M., and Mehrmanesh, L. (2017). Precision micro-synchrophasors for distribution systems: A summary of applications. *IEEE Transactions on Smart Grid*, 8(6), 2926–2936. doi:10.1109/TSG.2017.2720543.

von Meier, A., Ratnam, E.L., Brady, K., Moffat, K., and Swartz, J. (2020). Phasor-based control for scalable integration of variable energy resources. *Energies*, 13(1). URL `https://www.mdpi.com/1996-1073/13/1/190`.