Extended heterogeneous controller hardware-in-the-loop testbed for evaluating distributed controls

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Synopsis

A framework and testbed for evaluating system-level controls through quantifiable metrics has been developed following a hardware-in-the-loop approach. The testbed builds on a combination of real-time modelling and simulation, network communication and surrogate control platforms, and allows testing control algorithms early in the design and development cycle. The framework facilitates derisking and benchmarking of a wide variety of applications, but power, energy and reconfiguration management schemes for the notional zonal MVDC shipboard power system architecture are of primary interest. As part of the testbed developments, real-time dynamic simulation models of future naval shipboard power system have been implemented using several simulation platforms and various levels of fidelity. The second core testbed component is based on a heterogeneous set of controller platforms that allows realization of distributed controllers with a node count on the order of 100, each interfaced to a digital real-time simulator. Third, a dedicated network simulator provides a means to emulate computer networks linking simulation and controls. Extending previous efforts, this testbed significantly increases the hosting and evaluation capabilities of physically separate control units. To improve flexibility and affordability, surrogate control platforms were chosen that enable real-time execution but may not have all characteristics of the deployed hardware. As surrogate platforms and power system simulation are linked by digital communication means, the need for individual channel rewiring is avoided and replaced by automation for experiment reconfiguration, enabling the integrated testbed to support dynamic selection and execution of a large number of experiments.

Keywords: Controller hardware-in-the-loop simulation; distributed embedded controls; testbed; all electric ships

1. Introduction

As new power electronics technologies emerge, interest in higher voltage architectures is increasing. The possibilities offered by medium voltage direct current (MVDC) includes superior power density, power quality, and affordability when compared to the current alternating current (AC) centric electric power distributions system architectures (Doerry and Amy, 2008 and 2015a). To enable finding solutions to the many associated control challenges, a framework and testbed for evaluating system-level controls through quantifiable metrics has been developed following a controller hardware-in-the-loop (CHIL) approach, referred to here as the controls evaluation framework (CEF) and depicted in Figure 1 (Schoder et al., 2017). This paper summarizes the efforts made and initial experience gained with the platform in the context of a notional 12 kV/100 MW-class multi-zone MVDC shipboard power system (SPS) model for evaluation of power, energy, and reconfiguration control solutions. The zonal distribution system encompasses major components such as switchboards, propulsion motor modules, gas turbine-power generation modules, emergency generation, power conversion modules, energy storage modules, and large and pulsating loads. While the SPS model includes fundamental controls to run simulations, the primary objective is to use it in a CHIL context. To this end, control interfaces have been implemented to allow linking external controls for their evaluation including aspects of survivability (Doerry, 2009).

To support testing of control algorithms including distributed control approaches, a heterogeneous set of computation and control platforms have been added to extend an existing testbed (Schoder et al, 2016)) to a large-scale cyber-physical simulation testbed. The current realization is based on approximately 100 distributed control platform nodes, and all are interfaced to a digital real-time simulator (DRTS) with data exchange capabilities in the microseconds-range. The target control applications are currently geared toward system-level controls, i.e., not at the switching level of the many simulated power electronic converters, and address power, energy, and automated configuration challenges. The computation and control nodes are linked via dedicated computer networks with the option to integrate with a network emulator, which supports simulating communication network characteristics including failures and software-based reconfiguration of network layouts and protocols.

The computational and control platforms were chosen to reflect a surrogate controls approach that supports capabilities of implementing, executing, and monitoring controls in real-time. These surrogate platforms are not

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intended to be deployed, but rather, provide a subset of the characteristics meaningful to what is being tested. Another critical difference is the link between the surrogates and the real-time simulated power systems, which is purely digital over a computer network rather than device-specific analogue and digital signals. This interface approach alleviates much of the burden and errors due to manual rewiring and allows automation for more efficiently running larger experiment sets.

The difficulty in transitioning from theoretical concepts, especially with respect to distributed controls, to a physical testbed implementation are not to be underestimated as the verification and validated occurs in a larger, multi-faceted environment. The choice of digital control systems for realizing system-level controls can result in significantly different performance for the same power hardware. For instance, the ability to quickly re-route power to vital loads can improve the probability of mission success. To provide the means to evaluate control solutions, the CEF functional components consist of control options, control partitioning and implementation, SPS model of interest, operation scenarios, metrics, CHIL experiment, and evaluation. These functional aspects are implemented and linked as depicted in Figure 1.

The following sections provide an overview of the zonal MVDC system, surrogates and network infrastructure, a review of the system-level control challenges and performance metrics, and an application example to realize a distributed power management concept.

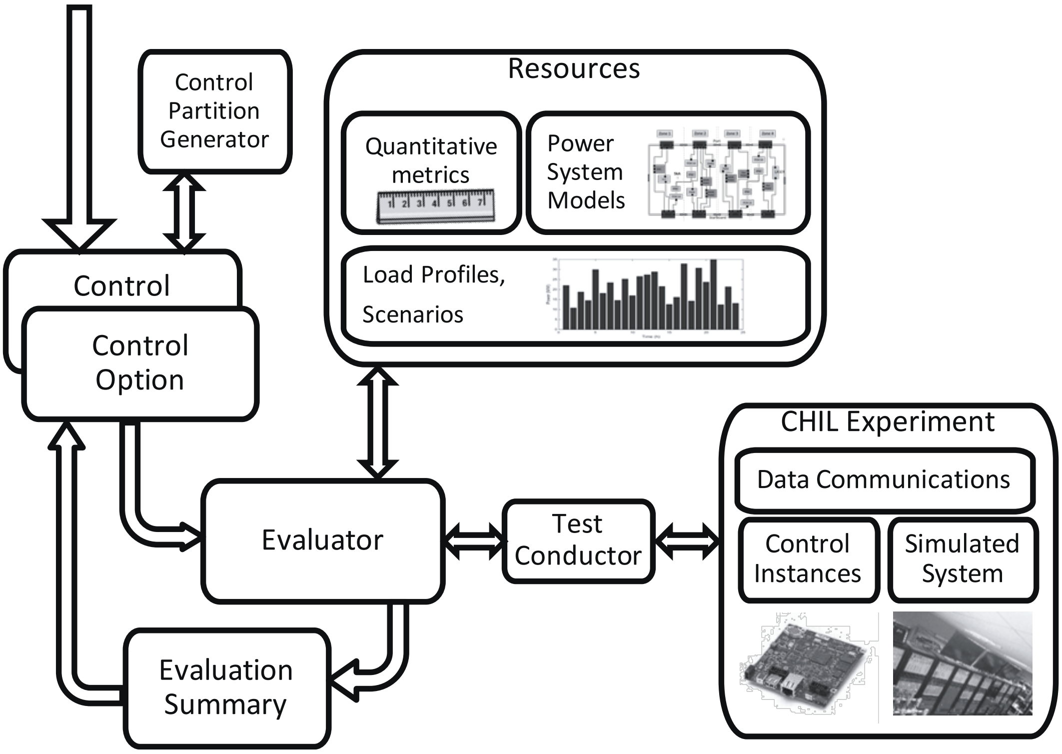

Figure 1: Functional overview of the controls evaluation framework

2. Notional zonal MVDC shipboard power system

Key to the evaluation of control algorithms and their performance are power system models that provide sufficient dynamics for specific investigations while also being able to satisfy real-time simulation constraints. Extending the steady-state data for the notional MVDC zonal shipboard power system as available through S3D (ESRDC, 2017a), an environment geared toward early stage design and analysis, dynamic component models have been implemented on electromagnetic transient program type digital real-time simulator (DRTS) platforms (ESRDC, 2017b and 2018) as follows.

The notional shipboard distribution system is based on zones to increase flexibility in routing power and provide means for reconfiguration in case of subsystem faults. The main distribution bus, after rectification directly at the turbine-generator units, is operated at 12kV DC. Figure 2 provides an overview of the structure and salient components. For increased operational efficiency and redundancy, five dual-winding power generation modules (PGM), three main and two auxiliary units, provide nominally up to 100 MW. Switchboards (SWBD) include disconnects to electrically isolate the zonal subsystem as appropriate for conditions at hand, including isolation of faulty sections. Power conversion modules (PCM-1A) and integrated power node centres (IPNC) are the main means of linking generation and loads, providing appropriate voltage levels and power quality. Load modules reflect the salient power demands and include propulsion motor modules (PMM) and special mission loads such as electromagnetic railgun module (EMRG), LASER, and RADAR. Motivation for component placement and additional component information can be found in (Doerry and Amy, 2015a and 2015b). The converter model implementation is based on an averaged value representation, and the DC and AC load centres operate at 1 kV and 450 V, respectively. Loads are aggregated for these voltage levels and grouped according to vitality status. All zones are fed from a single PCM-1A with a cross-zone connection providing redundant power supplies in emergency conditions.

In the last decade, interest in complementing generation resources with dedicated energy storage has increased as pulse loading becomes larger and more frequent. To this end, energy storage modules (ESM) are integrated into PCMs; energy storage solutions are a main driver for simulation guided selections with respect to sizing and placement.

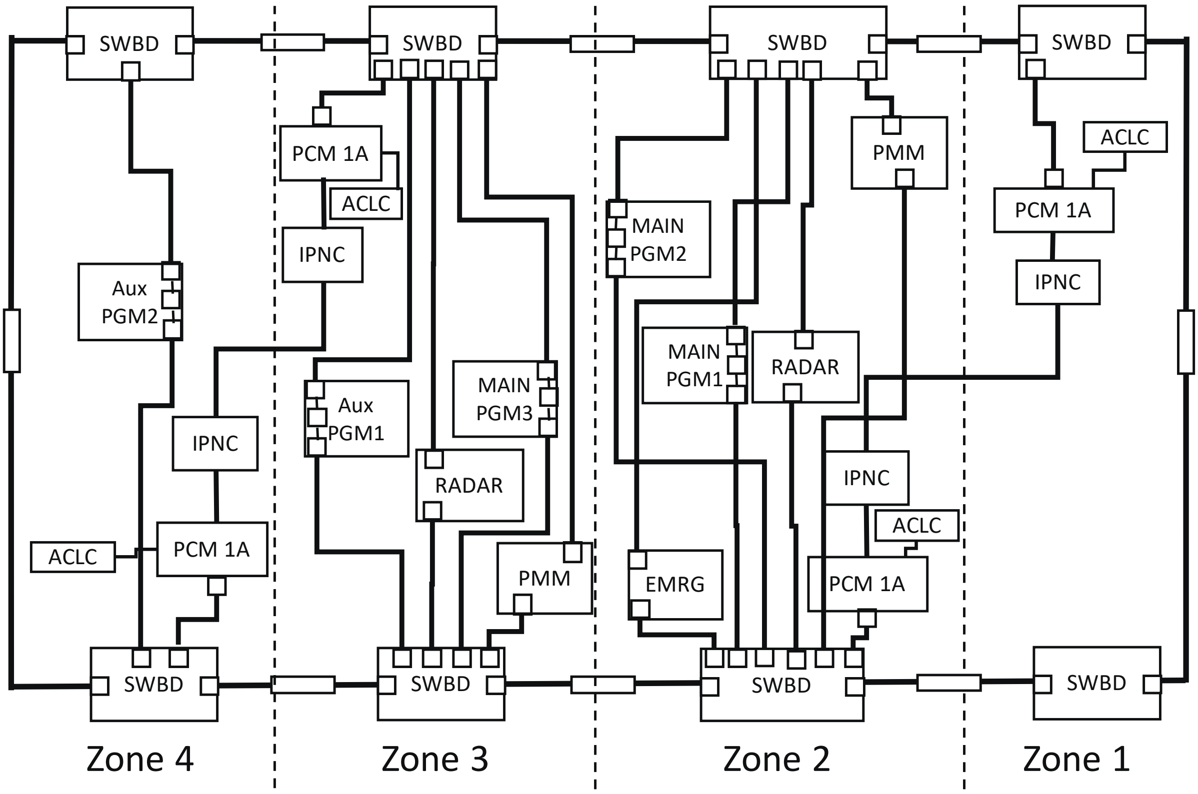

Figure 2: Overview of the zonal MVDC system

In addition to this more detailed implementation, a second version of the zonal power system was developed on another DRTS platform with simplified device modules and controls (Ravindra, 2018). This implementation is meant for rapidly prototyping controls within the CEF testbed to realize power and energy management options and demonstration. The reduced amount of resources to run the simplified models means that, from a practical point of view, execution times are reduced and ability to quickly alter the system is increased, resulting in a shorter turnaround time for running experiments.

3. Computer networks and computational platforms

Designing and developing real-time system-level controls is best accomplished by means beyond the DRTS platforms. By building on additional, dedicated resources many challenges can be avoided and the narrow constraints of such environments bypassed. Concerns of specific interest here include the possibility to realize multiple data communication channels with distinct properties in the evaluation process of distributed controls. The network for linking the control hosting platforms is based on off-the-shelf Ethernet equipment for the primary reasons of 1) readily available on the majority of computational platforms; 2) provides representative characteristics of data communications among system-level controls; and 3) real-time simulation of data communications can further be leveraged to provide additional data communication characteristics. More specifically, our testbed has incorporated OPNET for data communication simulation (Riverbed, 2018). The CEF testbed connects computational platforms preferably through dedicated interfaces to allow data exchange between

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virtual power hardware and computational platforms without interfering in control-to-control node communication.

The selected computational platforms have significant impact on the capabilities to implement and evaluate the CEF relevant CHIL experiments. The objective herein is to establish a CEF testbed that realizes characteristics comparable to final, deployed systems, with a focus on computational and data communication features. The testbed as described in this paper enables realizing power systems and controls early in the design and development cycle, complementing other development stages including power hardware-in-the-loop and dedicated test sites (Langston et al., 2013). While conventional CHIL considers testing embedded controllers in later design and development stages with knowledge of both the deployed hardware and control logic, an example of such a CHIL setup is discussed in (Steurer et al., 2016), the CHIL of interest here is to support earlier stages of the design cycle with the assumption that the specific hardware to be deployed is not yet known or secondary to the development efforts.

We refer to the chosen computational platforms to host controls as surrogates, and these platforms are envisioned to provide salient characteristics similar to final platforms (e.g., computational performance) but do not necessarily match other characteristics such as temperature range and ruggedness. The expectation is that these platforms will commonly run Linux to provide basic services for controls, but others are possible. A combination of a server and industrial developer platforms was selected. While the servers provide up-to-date processor capabilities, the latter contain processing units geared towards lower power, embedded designs and include field-programable gate array (FPGA) fabrics for improved input-output interfacing. Additional systems were selected to provide FPGA fabrics with high-speed transceivers supporting optical fiber connections, which are capable of low-latency communication with the DRTS processors. Today a large variety of options exist to select components for a testbed as of interest here and in the following the three main factors considered in making choices are elaborated in more detail, reflecting costs, development software and process, and flexible communication interfaces.

First, a large range of capabilities and costs is available today. The costs involved in providing on the order of 100 physically separate platforms can be substantial, and, as a rough estimate, a purchase of 100 of the lower cost platforms may be equal to the price of the higher cost platforms. Efforts were made to reduce costs by focusing on functionality specific to our purposes and accepting application limitations such as physical robustness to temperature and vibrations. Second, difficulties in developing and executing on control platforms can be challenging, and the possibility to support in-house control software becomes an important consideration. While platforms may technically be able to host different types of controls, development without dedicated toolchains can be prohibitive. Third, communication among the testbed components ideally requires minimal physical interconnections and manual efforts. Furthermore, the communication abilities should reflect the expected network characteristics and support transparent interconnections between surrogates and DRTS. One option pursued is based on dual-Ethernet ports that allow separation of simulation related communication from control node interactions. On a technical level, lower level protocols for improved throughput and reduced latency such as the user datagram protocol (UDP) and transmission control protocol/internet protocol (TCP/IP), and higher-level means such as the data distributions service (DDS) are available (OMG, 2015). DDS, for example, allows for a publisher-subscribe architecture that scales well with an increased control node count.

However, the UDP-TCP/IP based communication mechanisms tend to introduce artificially large and variable latencies. These artefacts of the simulation are often exacerbated due to improper operating system configuration and limitations of processing resources. A memory mapped interface to a PCIe peripheral has been one of the better solutions. Using the PCIe bus provides a much easier to use interface and significantly alleviates much of the significant processor contention between control logic, networking stack and device driver execution. Between the DRTS and external controls, measurements and control signals can be exchanged every simulation timestep, which is typically at about every 50 μs. Smaller timestep subsystems are included for power electronics converters, which are executed with a timestep in the 2–4 μs range. The interfaces to the simulated power system are not limited to the controls context but, for additional flexibility, are used to, for example, realize mission scenarios by sending load demand information from external resources into the SPS simulation.

4. Developing controls: power and energy management

Naval power system platforms need to accomplish multiple missions within their intended ship class (U.S. Naval History and Heritage Command, 2016). To be successful, control and management algorithms are essential and, in general, serve to address long-term efficiency and cost effectiveness requirements and short-term dynamic needs to support, for example, pulsed power loads (Vu, Gonsoulin et al., 2017) (ERSDC, 2017a). The coordination of generation, storage, and load resources is still an outstanding research and development challenge. For example, optimized central control and management systems (Papari et al, 2017), distributed approaches to operational fuel efficiency options (Vijlee, 2007) of directly-coupled gas turbines have been addressed recently. Nevertheless, improved energy and power management means are still required, and the CEF is envisioned to facilitate research and evaluation on a broader scale. The following provides details on a distributed power management scheme.

The main objective of the power management algorithm is to take reference set points from the energy management and interact with the physical system (Edrington et al, 2018). While implementing the respective reference commands, the power management subsystem has to ensure that generation is shared among available resources as desired. The power management layer as developed augments conventional droop control schemes for applications in converter dominated distribution systems. While the conventional droop control methodology is an open-loop approach, a secondary layer was added to incorporate feedback and compensate for inherent inaccuracies and capability limitations. The secondary layer with its distributed control nodes (Figure 3) placed at PGMs, takes voltage and current information from both the local component and its immediate electrical neighbours, and outputs a voltage-based signal to the local controls for implementation. In turn, the local voltage and current information is forwarded to the respective neighbouring controllers.

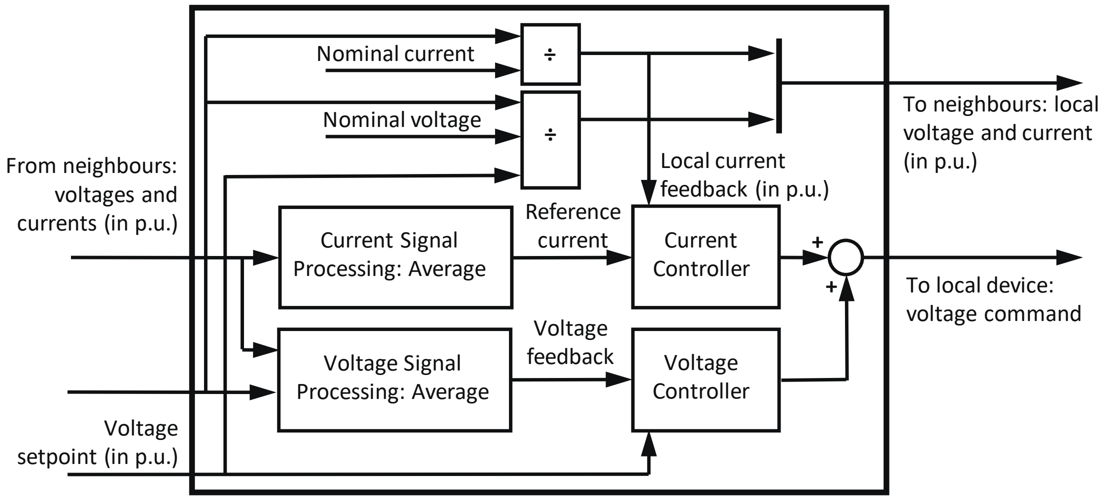


Figure 3: Distributed power management controller

The local controller processes local and remote current and voltage data to derive average values. The droop-based scheme derives local control command references to ensure proportional load demand sharing using proportional-integral controllers for determining the final control signal. In addition to the relative sharing of generation, the second objective is to operate close to a desired voltage level throughout the distribution system. This control scheme was tested in the context of the MVDC zonal system with a distributed control node count of 10, one for each of the windings-rectifiers of the power generation modules, and an example is discussed below.

5. Measuring control performance: metrics

A major cornerstone of the evaluation framework is the ability to provide high-fidelity data of realistic SPS plant alignments and loading scenarios. To a large extent, the data can be streamed in real-time to allow online analysis but is primarily designed for offline, post-processing that computes quantities that help benchmark control solutions. Several metrics are of interest in the evaluation of control quality aspects, and the following applies with respect to energy and power management challenges.

Energy storage is incorporated for two main reasons, uninterrupted supply and minimizing the impact of fast ramp rates. Storage for the SPS is envisioned to allow handle challenging power demand profiles while avoiding deployment of dedicated storage units for single-purpose applications. Optimizing overall system performance needs to trade-off wear-and-tear on electro-mechanical subsystems, power distribution requirements and coordination, and expected charge-discharge cycles over the lifetimes of storage solutions. In addition, a combination of storage technologies may be required to find a compromise between response capabilities and size-weight concerns. Metrics of interest are the average number of charge and discharge events over a specified time horizon, power levels, ramp rates, storage placement, power routing, timing constraints in coordinating load demands and storage controls, and storage ratings. In the case of longer-term generation scheduling for improved energy cost efficiency, fuel consumption as used in conventional dispatch problems is typically used as a measure.

From a power management perspective, metrics of interest concern the performance of the controls under transient conditions. Many of the measures as used in designing controls apply directly and include the integral square error of, for example, output voltages and output power of generators and power converter modules. Its evaluation can be automated over a time horizon as based on response and settling times, which themselves provide useful performance information.

In the context of overall system evaluation, system deficiencies with respect to voltage and power quality are evaluated using performance indices based on deviations from setpoints (e.g., nominal) and profiles, current loading factors, and subsystems not supplied with energy (Edrington et al, 2018). The individual indices may consider weighting factors to differentiate subsystem and load priorities, and importance of individual aspects when combining metrics into overall performance indices.

6. Application example: power management

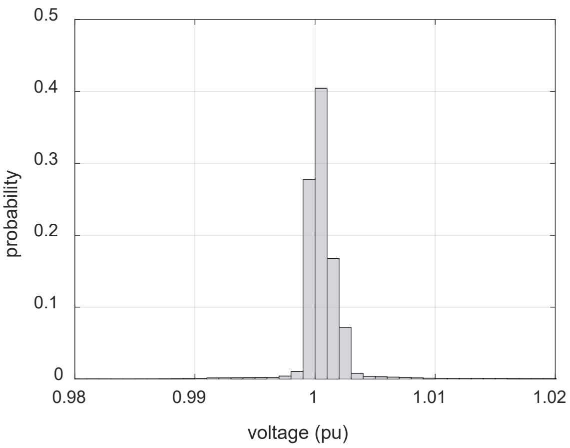
The CEF testbed was used to evaluate several control and energy management options, but the following focuses on a power management example. As outlined above, the power management is responsible for sharing generation on a relative basis and keeping voltages close to nominal. To test scenarios, information on loading profiles was used based on data from (Stevens et al., 2017) and simulated using the simplified zonal system model. The distributed controls keep the operating voltages at the five dual-winding PGMs within 2–3% of the desired setpoint. Figure 4(a)–(c) depict the statistical information derived from operating in three scenarios (two cruising and one battle mode) as simulated over one hour. The power management improves the bus voltage regulation as compared to the conventional, fixed droop scheme, which shows deviations of up to 8%.

Additionally, the output currents of the five main and auxiliary port and starboard PGMs are well controlled to share load demand as shown in Figure 4(d). When the power management controllers are enabled, the load is shared in accordance with the individual power ratings. Power sharing is also maintained during large and rapid load demand changes as simulated for part of the test profile. This outcome is in part due to responding to transient conditions locally and overruling the energy management’s efficiency objectives in favour of better dynamic performance. However, before and after such dynamic engagements, the active power management receives setpoints from the energy management that optimize resource allocations, operating the generation modules at their most efficient conditions.

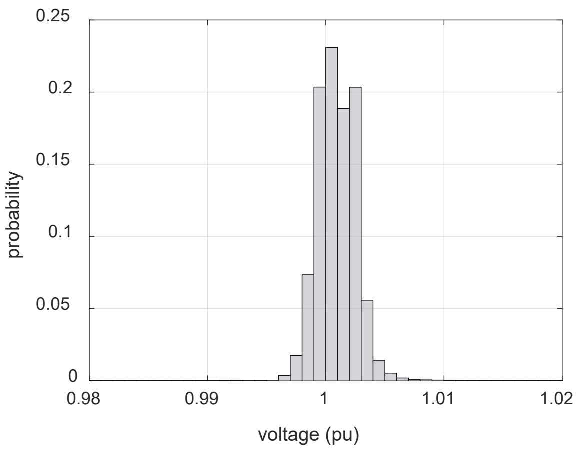
7. Conclusions

The controls evaluation framework integrates power system models and systems, communications and networking, and controller hardware-in-the-loop hosting capabilities for evaluating controls. The shipboard power system models are based on dynamic modules that represent the notional zonal MVDC shipboard power system with its characteristics as envisioned for future U.S. naval platforms. The selected computational platforms provide alternate and complementing means of developing and implementing control solutions. Combined with the communication networks and real-time simulation, evaluation of control algorithms within the larger shipboard power system context becomes feasible. While the current SPS model has primarily supported power and energy management analysis, future applications will address fault management and automated system reconfiguration.

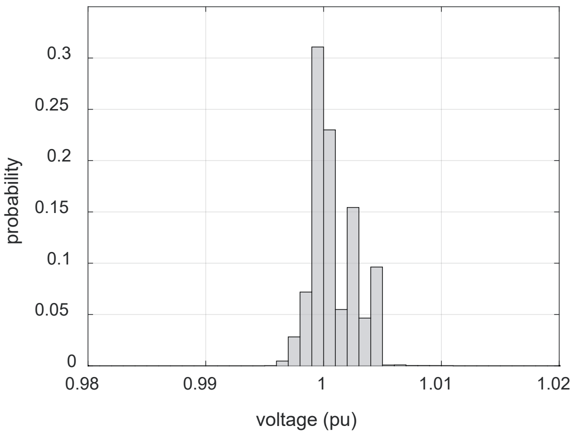
Establishing a CEF testbed for evaluating early-stage control designs was challenging as the computational hardware, controls, and communication means are constantly changing. Enabling replication of real-time environments is only one aspect of a useful CEF and considerations such as flexibility in automation, cost, ease of instantiating and running controls are a concern. Nevertheless, the choices available in building a CHIL and distributed computational platform provide the means necessary to study controls related aspects. Our expectation is that the increase in number of computational platforms for control nodes provides the capabilities to execute meaningful evaluation studies for larger-scale distributed controls and, more specifically, for the zonal SPS. Next steps in using the CEF will be to extend the controls to a higher node count and to implement multiple control schemes concurrently to evaluate interaction and coordination across multiple tasks and time ranges.



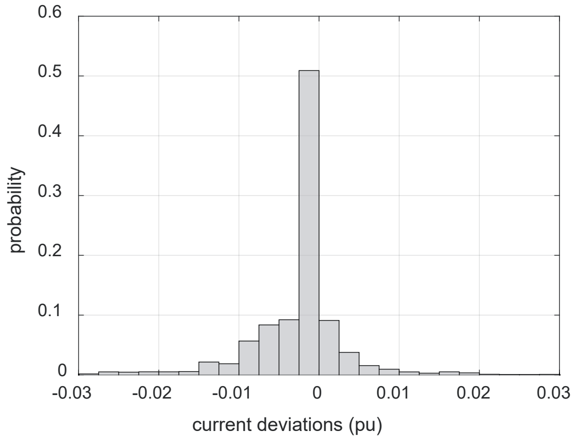
(a) Voltage histogram (Cruise mode 1)



(b) Voltage histogram (Battle mode)



(c) Voltage histogram (Cruise mode 2)



(d) Current deviations from mean histogram

Figure 4: Controlling voltages and sharing current demand at power generation modules: histograms show the resulting voltages (setpoint of 1 p.u.) and current deviations from the reference (mean) current

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