Reconfigurable Real-Time Power Grid Emulator for Systems with High Penetration of Renewables

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***Abstract*-- Novel power system control and new utility devices need to be tested before their actual deployment to the power grid. To assist with such a testing need, real-time digital emulators such as RTDS and Opal-RT can be used to connect to the physical world and form a hardware in the loop (HIL) emulation. However, due to the limitations of today's computational resources, the accuracy and fidelity suffer from different levels of model reductions in purely digital simulations. CURENT has developed a reconfigurable electric grid hardware testbed (HTB) to overcome the limitations of digital emulators. The HTB has been used to develop measurement, control, modeling, and actuation techniques for a national grid with a high penetration of renewables. The power electronic-based system includes emulators for synchronous generators; photovoltaics with grid-interfacing inverter; wind turbines; induction motor loads, ZIP loads, power electronic loads; batteries; ac and dc transmission lines; short circuit faults and grid relay protection; and a multiterminal HVDC overlay including power electronics interfaces. The system contains real elements of power flow, measurement, communication, protection, and control that mimic what would be seen in an actual electric grid. This paper presents an overview of the HTB and several scenarios that have been run to determine control and actions needed for the future power grid.**

***Index Terms*—Hardware-in-the-loop, inverters, microgrids, emulation, distributed energy resources, multiterminal high voltage dc.**

I. Introduction

A. Background

A REAL-time grid emulator is a power electronics hardware-based system designed for studying future electric grids, especially those with high installed penetration levels of renewables. The NSF/DOE Engineering Research Center, CURENT, at The University of Tennessee has developed a one-of-a-kind control, modeling, visualization, and test platform for novel power system control and new utility devices before their actual deployment to the grid [1].

Early real-time grid emulators trace back to the 1920s [2], [3]. Analog-based grid emulators such as miniature systems and the transient network analyzer were used to investigate power flow, stability, and oscillation issues in power grids. With the advancement of microprocessors, real-time digital simulators, such as RTDS [4] and Opal-RT [5], have been developed to connect digital simulations and physical tests together to form a hardware-in-the-loop (HIL) emulation [6]–[8]. HIL systems have been applied to diverse scenarios, such as motor drive system test [9], wind turbine low-voltage ride through [10], [11], and microgrid synchronization schemes [12]. With deliberately designed network solutions and parallel computing techniques, these tools can emulate a large system with fixed time-step on a real-time basis. These allow real-time testing of the developed system controllers without having to develop a real hardware test platform [13].

HIL can be paired with a power amplifier to form a Power HIL (PHIL) test platform. The PHIL platform can be connected to equipment under test (EUT), and evaluate its behavior with the remainder of the system represented by the emulator [14].

B. Motivation

Analog-based grid emulators have several disadvantages compared with digital-based grid emulators. First, analog-based grid emulators are bulky, expensive, and less accessible, while digital-based grid emulators are comparatively inexpensive and can be installed on a personal computer. Second, analog-based grid emulators generally require more effort to reconfigure.

Digital-based grid emulators also have several disadvantages compared to analog based grid emulators. Accuracy and fidelity suffer from different levels of model reductions in purely digital simulations due to the limitations of today's computational resources. Often the accuracy depends on the solver and time steps selected. Also, digital-based grid emulators can have numerical stability and convergence issues similar to those experienced by offline simulation tools [15]. In addition, many critical conditions tend to be simplified or ignored in digital emulations, such as measurement error, control and communication time delay, device physical bounds and saturation, electromagnetic interference, etc. Failure to address these issues may cause unrealistic or incorrect results [16]. Digital based grid emulators typically involve only one emulation target or aim at systems with the complexity and power level no more than that of a microgrid [17]-[19]. This still leaves the need for transmission level emulation platforms.

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Hardware test results can be more convincing than digital simulation results. Digital simulation tools tend to oversimplify simulation scenarios and neglect critical conditions in practical applications such as time delay, communication bandwidth, electromagnetic interference, etc. Therefore, various experimental platforms still exist to test real equipment.

To overcome the drawbacks of digital real-time emulation tools, researchers have built down-scaled power system prototypes or hardware-based grid testbeds to test their proposed controllers or devices [20]–[23]. Examples include National Renewable Energy Laboratory's (NREL) Energy Systems Integration Facility (ESIF) [22] and the Consortium for Electric Reliability Technology Solutions' (CERTS) microgrid testing platform [23].

These scaled hardware-based grid testbeds provide superior fidelity when there are multiple interconnected sources and loads operating in parallel. However, because they are based on scaled physical devices, they too have limitations. First, each physical device can only be used to model its own particular type. For example, an electric machine can only model a motor or generator. Second, the scaled physical device often cannot provide a good representation of its real-sized counterpart. For example, a small kW-level generator has very different time constants from those of a large MW or GW level generator [24], [25]. Third, these hardware-based grid testbeds require rewiring and component replacements to test different system configurations or parameters.

C. Key Contributions

To design and operate future modern electrical systems, it is essential to emulate such systems from many aspects, physical as well as cyber, and include the ability to study phenomena and/or functions across wide time scales from sub-micro-seconds transients to minutes, hours, and days of system operation. Very often these different phenomena and/or functions can interact with one another and therefore need to be simulated simultaneously. It is very difficult for traditional digital real-time emulators to meet such multi-time-scale needs.

The HTB, a power electronics-based reconfigurable real-time grid emulator, was developed as a unique emulation platform to overcome various issues with digital simulators and conventional hardware-based platforms. Instead of using scaled physical devices as in a conventional hardware-based emulator, the HTB uses identical commercial-grade power electronics inverters to emulate the external properties of typical grid elements. Each inverter is programmed digitally with built-in digital signal processors (DSPs) to behave as various devices/equipment in an electrical system, including sources, loads, energy storage, and transmission/distribution equipment. The advantages of the proposed HTB can be summarized as follows:

1. The HTB releases some of the computation burden of digital simulators since the voltage and currents in the hardware follow Kirchhoff's laws and other physical elements in the system. The computation is truly distributed since individual power electronic converters have separate digital signal processors (DSPs) for their control and protection.
2. The proposed HTB system is more flexible than other down-scaled power system prototypes. The emulator inverters can be reprogrammed and reconfigured to represent different power systems and operating conditions.
3. The proposed HTB can integrate with other real-time simulator platforms with an amplifier since the HTB can output actual electrical/analog signals.

The HTB [26] has been used to study several different power system scenarios. This paper provides an overview of this unique HTB testing platform, its characteristics, including advantages and shortcomings, and provides a few examples of power system scenarios that have been studied with this platform.

This paper is organized as follows: Section II explains the emulation principle adopted in the proposed HTB system. Section III presents the hardware configuration and the measurement-control-communication architecture of the HTB system. Section IV gives several sample use cases of the HTB to demonstrate the possible applications of the HTB. Section V discusses the strengths and weaknesses of the HTB system.

II. GRID EMULATION PRINCIPLES

Grid elements are emulated by power electronics-based inverters in the HTB system. The inverters are programmed to have the same steady-state and dynamic response as the emulated grid elements.

The HTB models an electrical system using physical programmable power electronics inverters, and emulates in real time the complex behavior of the system. The principal application of the HTB is to test the design and operation of an electrical system. The test objectives can include system control, sensing and monitoring, protection, communication, and cybersecurity under various operating conditions and states, including normal, as well as abnormal and fault conditions.

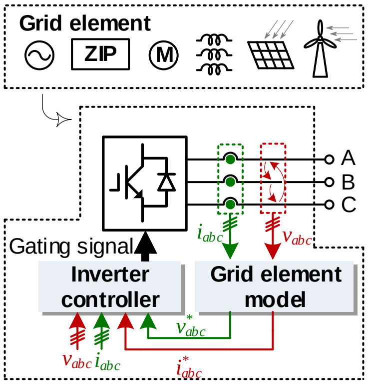


Fig. 1. Emulator operating principle.

The grid elements could be considered as either current-controlled voltage sources or voltage-controlled current sources. For example, an impedance-type load is normally emulated by a voltage-controlled current source inverter. The inverter measures the terminal voltage to derive the

TABLE I. AVAILABLE EMULATORS IN CURENT’S HTB SYSTEM

Emulator model	**Capability**	**Emulator output type**
Generator	- Synchronous generator	Voltage source
Load	- Single and three phase induction machine, motor drive load, FIDVR - Constant impedance, constant current, and constant power load (ZIP load) - Data center power supplies, EV charger, rectifier	Current source
Wind turbine	- Type IV wind turbine with permanent magnetic synchronous generator - Type III wind turbine with doubly-fed induction generator (DFIG)	Voltage/current source
Solar energy	- Solar panel with two-stage PV inverter	Voltage/current source
Transmission line	- Back-to-back converter to emulate ac transmission lines with compensation device (FACTS) and fault emulation	Voltage/current source
Short circuit fault	- Four types (line to ground, double line to ground, line to line, 3 phases)	Voltage/current source
Energy storage	- Batteries (Li-Ion, Pb-Acid, and flow), flywheels	Voltage/current source
HVDC	- Multi-terminal HVDC overlay including converters	Voltage/current source
RT simulator interface	- Integrate RTDS with HTB	Voltage/current source

corresponding terminal current as if the terminal voltage is fed to an impedance-type load. The general emulation principle is shown in Fig. 1.

The selection of voltage-control or current-control depends on the property of the emulated elements and the scenarios. In general, either the inverter terminal voltage or current is measured as the input of the emulated grid element model. Then, the resulting current or voltage reference is calculated from the grid element model and given to the inverter controller to track. This ensures that the inverter behaviors follow the emulated grid element model.

Many grid element emulators have been developed for CURENT’s HTB, which are listed in Table I. The available generator and energy source grid elements include synchronous generators [27], [28], wind turbine generators [29], PV generators [30], battery energy storage system (BESS) [31], and flywheel energy storage systems [32].

The available load type grid elements include induction motor [33], constant impedance/current/power loads (i.e. ZIP load) [34], nonlinear load [35], as well as power electronics interfaced loads (motor drives, EV chargers, data center power supplies). The available transmission or distribution level elements are ac lines [36] (including series-compensated lines), shunt compensators (static synchronous compensators or STATCOM), and HVDC converters [37]. Most types of bus and line faults can also be emulated [38].

III. HARDWARE CONFIGURATION AND MEASUREMENT, CONTROL, COMMUNICATION ARCHITECTURE

CURENT HTB allows flexibility as a software platform to evaluate novel power system infrastructure and validate wide-area measurement-based control methods. Fig. 2 shows the general structure of the HTB and its different control levels (central, interconnection, regional, and local) and interoperable functional capabilities that have been included in its design. The available control function blocks are shown in Fig. 3:

1. The local control includes controls for generator, renewable energy sources, controllable loads, and compensation equipment.
2. The regional control involves measurement and monitoring functions, modeling and estimation functions, control functions, and also involves system-level actuation functions. All functions are based on system operating states including normal, alert, emergency, extreme, and restorative states.
3. The interconnection control coordinates information exchange between regions and conducts cascaded failure control.

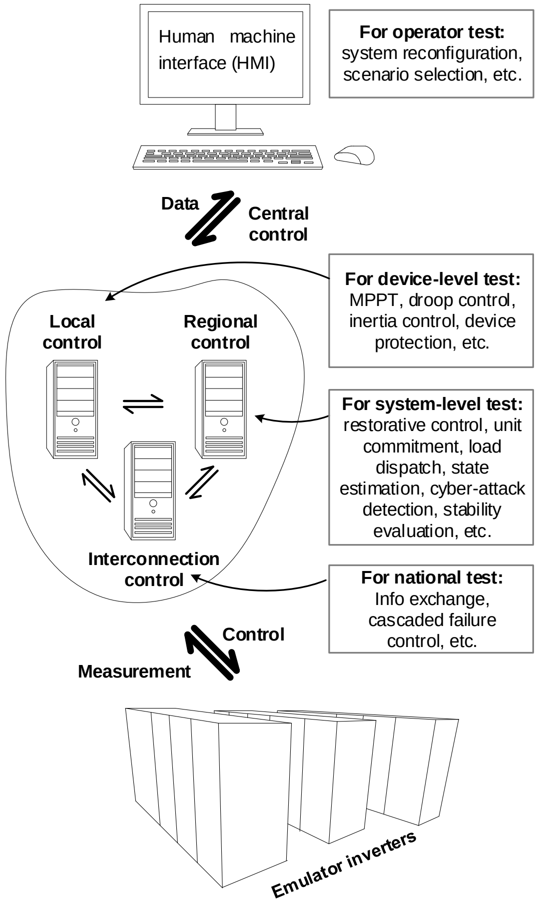


Fig. 2. HTB control levels and interoperable functional capabilities.

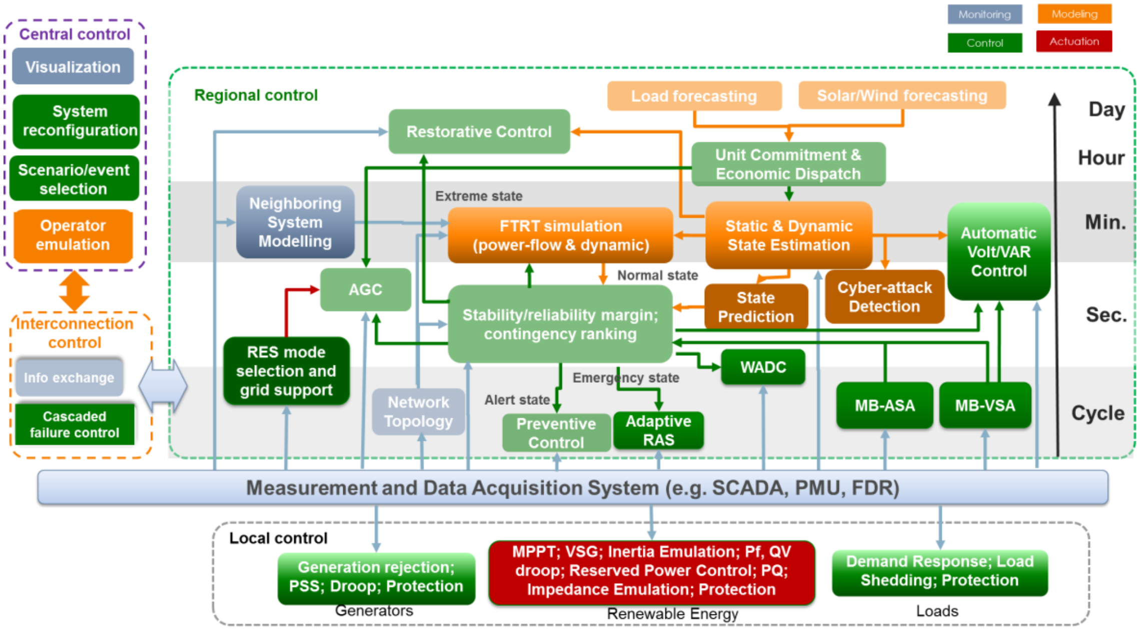


Fig. 3. Control diagram showing different control, monitoring, modeling, and actuation functions included in CURENT's grid emulator hardware testbed.

4. The central level control is responsible for aiding operators to set up and test different scenarios, system reconfiguration, and to interface with the visualization system.

To facilitate construction and reconfiguration, the emulator inverters are interconnected with a common dc link and ac link. The interconnection architecture is shown in Fig. 4. The illustrated structure includes interconnected conventional generator emulators, a load emulator, and an energy storage system emulator. The ac side emulates the power grid dynamics while the dc bus provides/absorbs the energy needed to emulate the grid element dynamics.

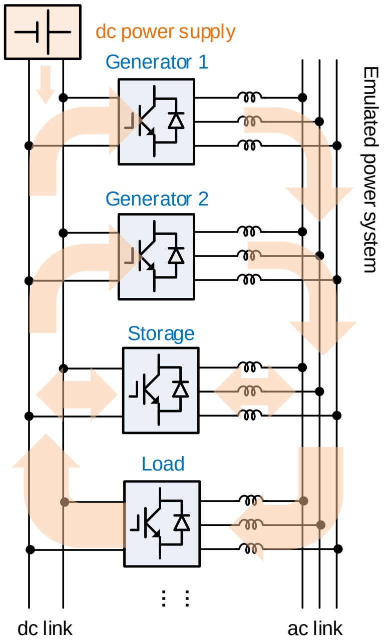


Fig. 4. Connection architecture of emulator inverters for one area showing generators, storage, and load cluster.

Each power converter switches at 10 kHz, which corresponds to a step size of 0.1 ms. With this step size, the control bandwidth of the emulators can be designed to around 1 kHz. However, due to the limitation of the time step, there are some power system transients that cannot be represented by the HTB. A transfer function perturbation (TFP) based error model [39, 40] was used to analyze its accuracy. The error is designed to be less than 5% within the frequency range of interest [41].

Table II shows a rough classification of power system transients. The green shaded transients can be accurately studied by the HTB, while the red shaded transients cannot. With emerging wide band gap (WBG) power electronic devices, the switching frequency of the converters in the HTB could reach even higher (>100 kHz), and the emulator would have the potential to represent system dynamics at a higher frequency.

TABLE II. TIME SCALES FOR DIFFERENT POWER SYSTEM EVENTS.

Type of system event	Time scale / frequency	System event
Electromechanical behavior	100 s / 0.01 Hz	Secondary frequency control
	10 s / 0.1 Hz	Governor / primary frequency control
	1 s / 1Hz	Inertial response, system transient stability
	0.1 s / 10 Hz	Sub-synchronous oscillation
	0.01 s / 100 Hz	Short circuit fault, stator transients
Electromagnetic behavior	0.001 s / 1000 Hz	
	0.0001 s / 10000 Hz	Switching surge
	0.00001 s / 100000 Hz	Traveling wave, lightning propagation

To emulate the grid involving multiple grid elements, several emulator inverters need to be connected together. Note that each emulator inverter can provide/absorb a significant amount of power depending on the grid element it emulates. However, since the HTB system is emulating a power grid, the grid power is always balanced at steady state. Therefore, the HTB power is physically self-circulating through the common dc bus as shown in Fig. 4. The dc voltage is provided by an external dc power supply. The dc power supply only needs to provide the power loss from the operation of the HTB system, which is less than 5% of the actual power flow emulated in the system.

CURENT's HTB is composed of three basic types of cabinets as illustrated in Fig. 5. Type I cabinets, or emulator cabinets, consist of four inverters that have DSPs that can be programmed to act as various generation, load, or storage emulators. Type II cabinets consist of switchable inductors to emulate the impedance of transformers or short transmission lines. Type III cabinets include both ac transmission line emulator cabinets and dc transmission system line emulator cabinets.

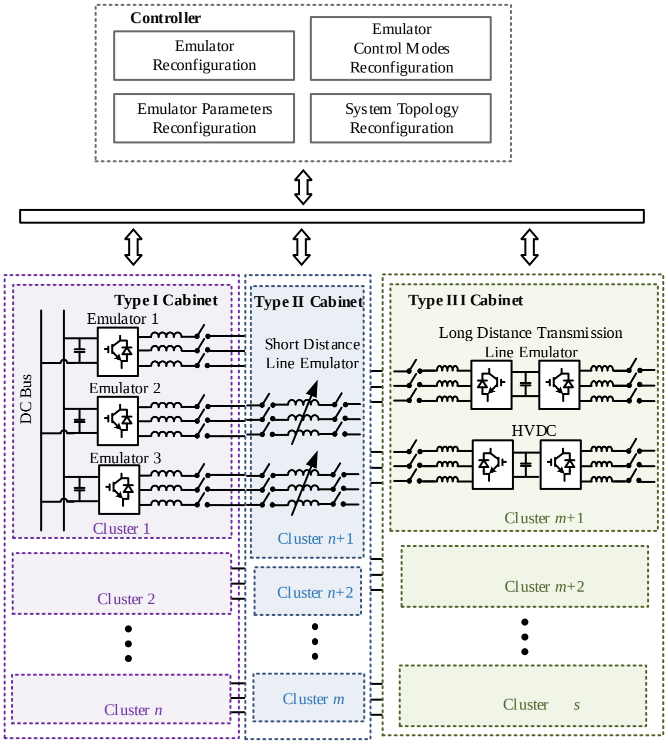


Fig. 5. Three types of emulator cabinet configurations.

The CURENT HTB system can emulate several future electric systems including (1) an aggregated portion of the Eastern Interconnection (EI), (2) Electric Reliability Council of Texas (ERCOT), (3) Western Coordinating Council (WECC), and (4) an overall North America grid with HVDC overlay through nodes representing clusters of generation, storage, and loads connected through transmission lines. Each node represents a dynamic cluster of generation and loads. Other systems such as Kundur's two-area system and a reduced three-area Northeast Power Coordinating Council (NPCC) system with off-shore wind have also been developed.

Fig. 6 depicts a 4-area clustered system representing the future WECC electric grid containing a high penetration of renewables (80% of capacity is from wind and PV) and a multiterminal (3 terminal) HVDC ring overlay as well as utility-scale energy storage. Since the HTB is an inverter-based testing platform, it provides a more realistic environment for emulating a grid with a large number of inverter-interfaced generation and storage sources like PV, wind, and batteries.

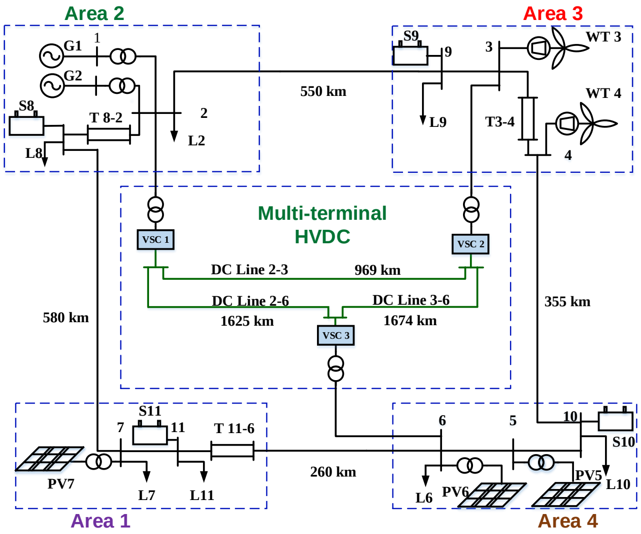


Fig. 6. Emulated 4-area system considered to be a future aggregated WECC system with high penetration of renewables and multiterminal HVDC overlay.

The HTB has been extended to represent a national grid model that emulates the WECC and ERCOT in hardware and also connects with the EI, which is emulated with RTDS (Fig. 7) with a high penetration of renewables (>80%) in all three interconnections (WECC, ERCOT, and EI). A 500 kV HVDC overlay (represented by light blue lines) connects the three interconnections with the overlay lines having capacities of 2400 to 3300 MVA. Coordinated control for the whole continental grid during normal and various contingencies have been developed and demonstrated.

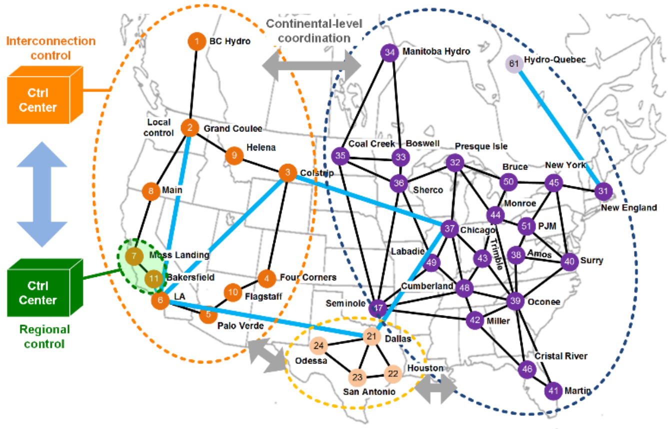


Fig. 7. CURENT's HTB North America grid with HVDC overlay (represented by light blue lines).

The HTB has real-time measurement, control, and communication systems. A private network is used as a backbone to connect with the CompactRIOs (cabinet controllers) and PCs (system-level and sub-system controllers) of the HTB. Depending on the actual system and control to be emulated, cabinet controllers (CompactRIOs) and system-level or sub-system controllers (PCs) can be configured to access certain data on the network. Equipment-level controllers (DSPs) are responsible for local control of the inverters.

System-level or sub-system controllers (PCs) are responsible for the corresponding system or sub-system level control, programmed in LabVIEW and Matlab. In addition to communicating between equipment and system-level and sub-system controllers, the cabinet controllers also collect data from measurement devices such as current transformers (CTs), potential transformers (PTs), and phasor measurement units (PMUs) that are in the HTB. Cyber events such as vulnerability assessment of phasor networks or PV inverter hardware and controls can be emulated in the communication system. The control and communication system are shown in Fig. 8.

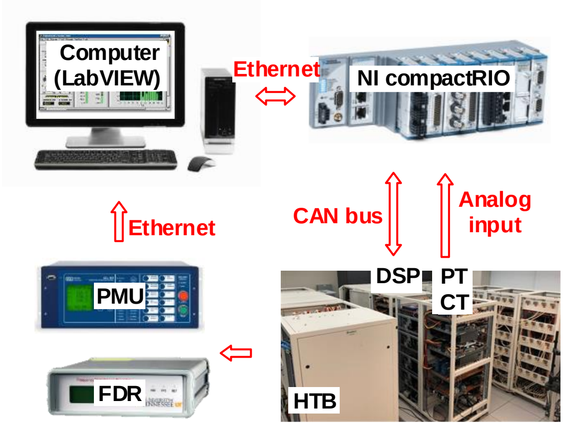


Fig. 8. HTB measurement, control and communication system.

CURENT’s HTB does not presently have the capability of communication emulation to make the system operate like regions are physically separated by long distances, but this capability has been planned to be incorporated into the HTB in the future.

IV. SAMPLE USE CASES OF HTB EMULATED SCENARIOS

The CURENT HTB has the capability of performing a variety of system scenarios to evaluate proposed new systems and controls. Several of these are described in the following subsections.

A. *Oscillation Damping*

The HTB has demonstrated scenarios involving oscillation damping including using PV inverters across a wide area to provide this service. Also, a wide-area damping controller (WADC) was developed and added to the exciter voltage reference for synchronous generators. The input to the controller was the frequency difference between two areas in a system with 50% renewable penetration, which had a poorly-damped inter-area oscillation following a system disturbance.

The HTB proved valuable in demonstrating the effectiveness of the damping controller and the need to consider time delay involved in measurement, communication, and actuation in its implementation. A sample result is shown in Fig. 9 [42], which illustrates the effectiveness of the adaptive WADC to more effectively damp the system.

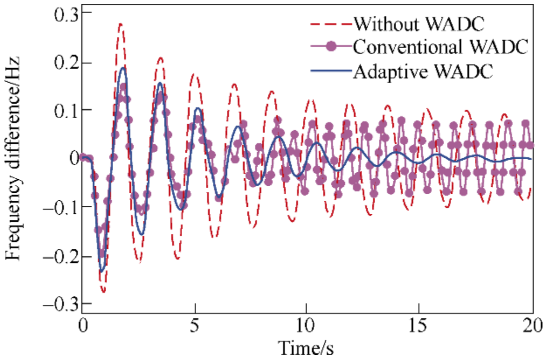


Fig. 9. Test results of wide area damping control demonstrated on the CURENT HTB.

B. *Multiterminal HVDC Scenarios*

A multiterminal HVDC hardware system was built and demonstrated for several HTB emulated systems including for the NPCC, WECC, and North American grid (see Fig. 7) models with high penetration (>50%) of renewable generation. Controls were developed such that the system can detect and act on faults on the interconnected ac or dc lines and dc converters and quickly reconfigure and change power flows to maintain system stability [37]. The HTB was also used to represent the interconnection of an off-shore wind farm to an on-shore ac transmission system through a MTDC system [43].

C. *Measurement Based Voltage Stability Assessment (MBVSA) and Control*

Algorithms have been developed to detect imminent voltage collapse and to provide necessary reactive power support in order to maintain sufficient stability margin to avoid collapse. These algorithms were tested on the hardware testbed to show how load increasing across a long line would result in eventual collapse; however, with the MBVSA algorithm, the stability margin was able to be continuously monitored and reactive power support provided when needed to maintain a sufficient margin. Fig. 10 gives a sample result of using MBVSA for power transferred between two areas across a transmission line. If the index estimated by MBVSA reaches a predefined threshold, reactive power support is enabled to enhance the system voltage stability [44].

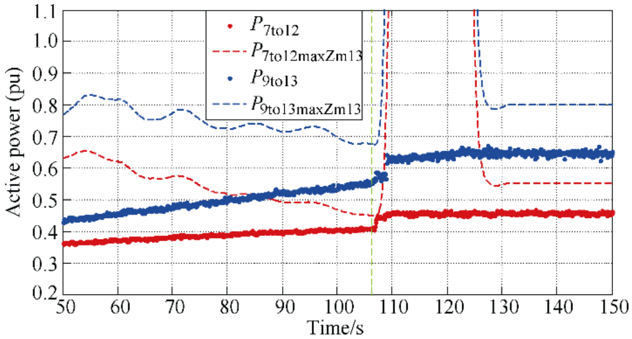


Fig. 10. HTB test results of real-time voltage stability assessment and control.

D. *Wind and PV Providing Frequency Regulation (Inertia Emulation)*

Dynamic scenarios using high penetration levels of wind and PV have been run on the hardware testbed where there was a loss of an HVDC line and the renewable sources then had to provide frequency regulation to the system. One study was for the NPCC system to examine how different wind turbine control modes would affect the system frequency following a system disturbance (loss of HVDC station) [43].

Fig. 11 shows HTB test results with Type IV (full converter) wind turbines with their active power injection and system frequencies for different controls: base case with synchronous generation, MPPT, MPPT with inertia emulation, virtual synchronous generator (VSG) control mode, and VSG control mode with storage. It shows that the VSG control mode with storage comes the closest to providing quick frequency support and more closely mimicking the behavior of a synchronous generator.

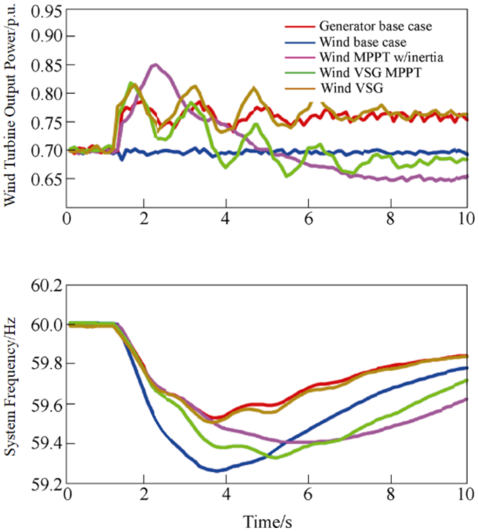


Fig. 11. Test results of wind turbine frequency response with different controls.

E. *Event Detection Using Sparse Coding*

A sparse coding-based multiple-event detection algorithm was studied on the HTB platform for detecting and recognizing multiple events, (i.e., generator trip (GT), load shedding (LS), and line trip (LT)). Most state-of-the-art techniques can only handle single event analysis; the challenging problem of multiple-event detection and recognition with the method of event unmixing was conducted in [45]-[46]. The detection accuracy for the single event can be 100% with 1 second window size while multiple event detection needs 8 seconds. Details of the experimental results are shown in Table III and Table IV.

TABLE III. DETECTION ACCURACY FOR SINGLE EVENT

Window Size / Event Type	1 s	2 s	3 s	4 s	5 s
GT	100%	100%	100%	100%	100%
LS	100%	100%	100%	100%	100%

TABLE IV. DETECTION ACCURACY (%) FOR MULTIPLE EVENTS

Window / Event Types	0~3s	4 s	5 s	6 s	7 s	8 s	9 s	10 s
GT+GT	×	100%	100%	100%	100%	100%	100%	100%
LS+LS	×	100%	100%	100%	100%	100%	100%	100%
GT+LS	×	×	100%	×	×	100%	100%	100%

F. *Microgrid Controller Development*

Fig. 12 shows a demonstration case where the HTB is used to test a microgrid control system [47] that represents an actual microgrid in the Electric Power Board (EPB) system in Chattanooga, Tennessee, which has flexible and dynamic boundaries. In this case, the microgrid is implemented in the HTB, including its connecting distribution feeder, local PV sources, battery energy storage systems, and smart switches and lines.

The microgrid controller under test is implemented in the HTB platform, and communicates with the HTB hardware functions via CompactRIO-based cabinet controllers. The platform offers a realistic environment to test the microgrid controller functions and protection system under different system conditions prior to implementation in the actual utility system. Several microgrid operation sequences, including black start, islanded operation, re-synchronization to grid-connected operation, islanding transition, and system protection, have been demonstrated in the hardware testbed.

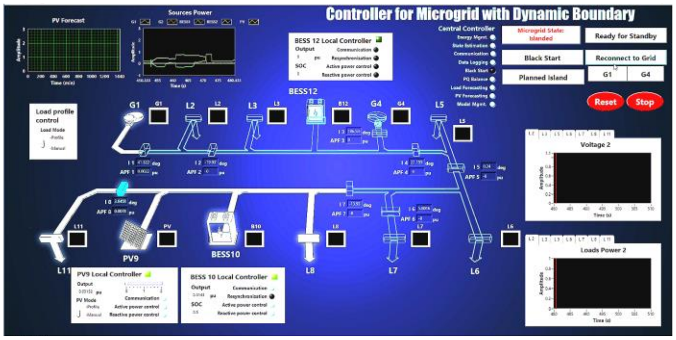


Fig. 12. Visualization and control interface for the reconfigured HTB to test a microgrid control system.

G. *System Transient Stability Analysis*

The critical clearing time (CCT) of a short circuit fault can be used to assess the severity of the contingency and the transient stability of a power system. By applying an emulated short circuit fault at the same location with different durations, the CCT can be easily identified by observing the system response.

Fig. 13 shows an experimental recording of such test on the HTB: a three-phase short circuit fault emulator is connected to the system under test at Load 7 (L7). The output frequency of the two generators oscillate out of step when the fault is cleared after 0.32 s. This identified that 0.30 s is the CCT, which is in agreement with simulation results.

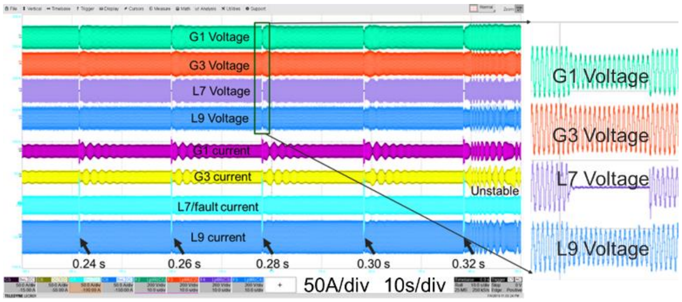
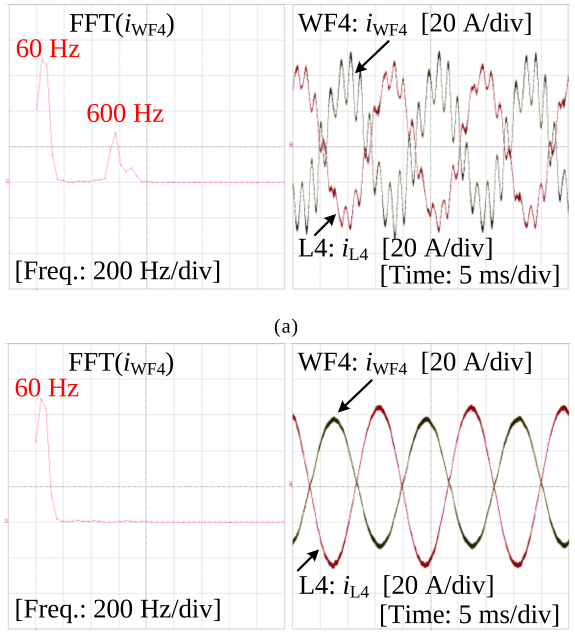


Fig. 13. Test results of critical clearing time determination for a fault.

H. Harmonic Stability for High Renewable Penetrated System

The fast closed-loop controls of an inverter may interact with other inverters if there are several in close proximity on the grid such as would be the case in a system with a high penetration of renewables. This can create small-signal stability issues, even if the inverters are all individually stable. This problem can introduce higher order harmonic or subsynchronous resonance.

Fig. 14 shows an example of the output current of a wind farm and a load. The output currents exhibit a 600 Hz harmonic resonance when connected to the rest of the system. After tuning the control parameters using the impedance based stability criterion, the voltages and currents can return to stable operation [48].



(a)

(b)

Fig. 14. Test results of harmonic stability issue with high renewable penetration. (a) Unstable case with parameters designed for ideal grid. (b) Stable case with properly designed parameters.

V. DISCUSSION

CURENT HTB has several strengths compared to conventional hardware-based grid emulators and digital emulators [31]. Compared with conventional hardware-based grid emulators, the CURENT HTB is more reconfigurable. The grid elements can be changed by reprograming controllers instead of replacing the physical down-scaled prototype. Because of the ability to represent physical generation and loads in a per unit basis through the models programmed into the DSP-controlled inverters, the CURENT HTB is more representative of larger equipment than using scaled physical equipment.

CURENT HTB is essentially an analog emulator with real power flows between real hardware emulating power system components. Compared with digital emulators or HIL-systems, CURENT HTB has real power flow and voltage and current measurements. The testbed also has an independent CPU for each grid element emulation. This guarantees each grid element with enough computation resources to calculate the detailed model and also allows the system and control to run in a true distributed fashion much like the real grid.

Even though the emulators largely rely on numerical models, similar to the case of real-time digital simulators, these models are truly distributed and computation is truly paralleled. Because of the real power flow in the HTB, the system operating point follows Kirchhoff's laws. As a result, the HTB has been shown to have much less numerical convergence problems. One limitation on the emulated number of buses is the space and resource issues of adding cabinets. HTB also handles multi-physics models and has no issues combining multiple shorter time-scale switching events with longer-term power system events.

In the case of power electronics interfaced renewable energy systems, the CURENT HTB has an actual grid-representative emulating performance since commercial inverters are in the system as well as their inherent switching and filtering. Future advanced integrated circuits will allow faster model calculation, and wide band gap (WBG) device technology enables faster switching speed for the converter emulator. HTB will benefit greatly from these emerging technologies, and provide even more accurate testing capabilities in the future.

The behaviors of the CURENT HTB emulators are closer to real world in terms of measurement error and communication delay. The HTB uses commercialized voltage/current sensors and standard sensing systems for measurements. The errors in the HTB are not purposely injected but result from the actual sensor errors. Similarly, the communication delay in the HTB is not purposely designed but obtained from industrial communication protocols. The HTB uses CAN bus and LAN for communication. The properties of these standard communication methods, such as communication delay, exist in the HTB system.

The HTB has also been used to test interoperability of an electrical system with other systems, such as power system communication cybersecurity. The HTB has been used for penetration testing of PMUs and inverters as well as for man-in-the-middle scenarios where some system measurements are detected and/or changed in the communication systems. A method to detect missing or falsely injected measurements has also been tested on the HTB and is ongoing work.

CURENT HTB has also been integrated with RTDS to further extend the testing platform capability. Connected to RTDS through two power amplifiers, the HTB can emulate one part of the electrical system, and RTDS is used to provide a real-time simulation for the rest of the system [41]. Another possible use for the CURENT HTB is that actual commercial prototype power equipment can be tested such as motor drives on the system if their rating is less than the 100 kVA inverter ratings that compose the HTB.

On the other hand, HTB also has some disadvantages. Compared with hardware-based test platforms, the CURENT HTB emulates grid elements by using a mathematical model instead of an actual physical prototype. Therefore, there could still be numerical issues similar to digital emulations. Compared with digital emulators, CURENT HTB may have control and measurement error because of the imperfections of the emulator inverters. CURENT HTB can only represent limited system complexity in numbers of nodes and lines because of the limited number of inverters. It presently can emulate a system up to 50 buses. Also, emulator controls might have harmonics interactions that do not belong to the system behavior if not designed properly.

VI. CONCLUSIONS

This paper describes the use of CURENT HTB for power transmission system emulation. This HTB can also be applied to distribution system emulation such as feeders with high penetration of DER as well as for emulation of other electrical power system systems, such as microgrids, electric vehicles, or shipboard and airplane electrical power systems.

This hardware testbed is useful as a planning tool for the future U.S. electric grid because of its salient features:

- Provides insight into how high penetration levels of different energy sources impact the future grid and how modern measurements, modeling, and controls can impact the grid.
- Ability to examine the future electric grid infrastructure to see what impact technologies such as multiterminal HVDC overlay or energy storage would have on the grid.
- Test cyber-physical measurement and communication schemes to identify potential security threats and ways to detect and mitigate them.

The testbeds at the system and component levels compare well with already established models and available system measurements. The HTB has been used to run several transmission system scenarios on a national grid model with high penetration of renewables as well as to develop a microgrid controller that has been implemented in a utility system.

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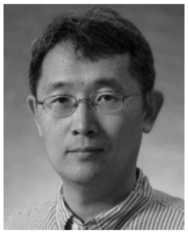

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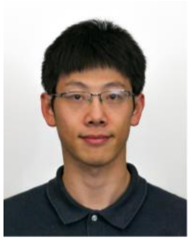

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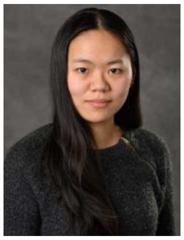

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