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Converter-Based Reconfigurable Real-Time Electrical System Emulation Platform

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Abstract: A Hardware Testbed(HTB) is developed for accurate and flexible emulation and testing of electrical power system and their control, measurement, and protection systems. In the HTB, modular and programmable power electronics converters are used to mimic the static and dynamic characteristics of electrical power components. This paper overviews the development, integration, and application of the HTB, covering emulation principle, hardware and software configuration, and example results of power system research using the HTB. The advantages of the HTB, compared with real-time digital simulation and downscaled hardware-based testing platform are discussed.

Keywords: Emulation, modeling, real-time simulation.

1 Introduction

Offline digital simulation has been used widely to predict the behavior of an electrical system in time domain due to its low cost, easy accessibility, and flexible configuration. However, due to the limitations of the computational resources and run time, the simulation accuracy and fidelity suffer from different levels of model reductions. Often the results depend on the solver and time steps selected, and have numerical stability and convergence issues[1].

In recent years, the revolution of integrated circuits such as microprocessors or FPGAs has enabled real-time digital simulations, such as RTDS[2] or Opal-RT[3]. With deliberately designed network solutions and parallel computing technique, these tools can simulate a large system in real-time with fixed time-step. They can incorporate with digital and analog inputs and outputs(I/O) to connect with the physical world to form a Hardware in the Loop(HIL) simulation. It allows the real-time testing of the developed system controllers without having to develop a real hardware test platform[4]. Since they are still using mathematical models, the numerical stability of digital simulation can still sometimes be an issue.

These non-real-time or real-time digital simulation tools offer a large diversity of pre-defined models, and have the capability to integrate custom built models. Nevertheless, many critical conditions in the simulations tend to be simplified or ignored by the users, such as measurement error, control and communication time delay, device physical bounds and saturation, electromagnetic interference, etc.

Accounting for the uncertainties in the simulations is computationally challenging, but failing to address these issues could cause unrealistic or incorrect results[5].

On the other hand, hardware-based system testing can reveal the impact of the neglected aspects of digital simulation. It is an essential step before the deployment of any proposed controllers or developed devices. To assist with such a testing need, a real-time digital simulator can be paired with a power amplifier to form a Power HIL(PHIL) test platform. The PHIL platform can be connected to an Equipment under Test (EUT), and evaluate its behavior with the remainder of the system represented by the simulator[6]. While it has great fidelity to test the equipment, the overall system simulation accuracy is not better than digital simulation.

To study the system behavior, researchers have built a down-scaled electrical power system or transient network analyzer(TNA) to produce a hardware-based power testbed as early as the 1920s[7-8]. The capability of such a system has been enhanced to incorporate new technologies in recent years. Examples include National Renewable Energy Laboratory's(NREL) Energy Systems Integration Facility(ESIF)[9] and the Consortium for Electric Reliability Technology Solutions'(CERTS) microgrid testing platform[10].

While these down-scaled hardware-based testing platforms provide superior fidelity, they are generally bulky and costly. Their topology and configurations are difficult to change, usually requiring physical rewiring and component replacements for the testing in a different system configuration or parameters. Another challenging issue is rescaling. To precisely represent a power component with different power and voltage, the emulator should have the same per unit value of the original one. It is relatively easy for the passive components like resistor, inductors, and capacitors, but difficult for rotating machines with different impedances, inertia and saturation levels[11-12]. Transmission lines also pose challenges since many cascaded circuits made up with inductors and capacitors are required to represent the distributed parameters.

Taking advantage of the fast, accurate, and flexible closed-loop control of power electronics converters, it is feasible to program them to mimic the

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static and dynamic behaviors of electrical power components[13]. There have been industrial products developed that use power electronics based emulator for the testing of electrical vehicle, aircraft, motor drive, grid integration of energy storage, PV, etc[14-16]. These emulators are often dedicated and can only be re-purposed to emulate limited components. While these converter emulators are capable of being used to establish a large scale multi-emulator testing system, such a platform has not been reported in the literature.

With this concept in mind, a converter-based reconfigurable emulation testing platform called Hardware Testbed(HTB) has been established at CURENT Center at the University of Tennessee by connecting multiple modular converter emulators together[17]. This paper overviews this unique HTB testing platform.

2 Emulation principle and structure

2.1 Emulation principle and developed emulators

As mentioned in the introduction, each individual converter in the HTB serves as an emulating unit. It has the same steady-state and dynamic response as the emulated object with respect to its terminal voltage and current. The local voltage or current information is measured as the input of the object model, and the output current or voltage reference is calculated for the controller to track, ensuring the converter emulator behaves the same as the emulated object. The block diagram is shown in Fig.1.

The components in an electrical system could be considered as either voltage source or current source. Analogously, the converter emulators have two kinds of control schemes, one type regulates the terminal voltage, and the other controls the output current. For example, the load emulating converter often employs a current type of control, i.e., measures the emulated grid voltage, and generates the desired emulation current; and the generator emulating converter more naturally uses a voltage type of control.

Many types of emulators have been developed in the HTB. Available emulators include synchronous generator[18-19], static and dynamic loads[20-22], variable speed wind turbines[23], PV[24], flywheel[25] and batteries[26]. The fault conditions such as short circuit faults emulation have also been developed[27].

In addition to single converter emulators, a transmission line can be emulated by a set of back-to-back converters[28-29]. Short circuit faults within the emulated transmission line can also be modeled and represented by the converter emulator sets[30]. The emulators for HVDC transmission lines and multi-terminal HVDC(MT-HVDC) grid emulators with corresponding faults and protection have also been developed[31].

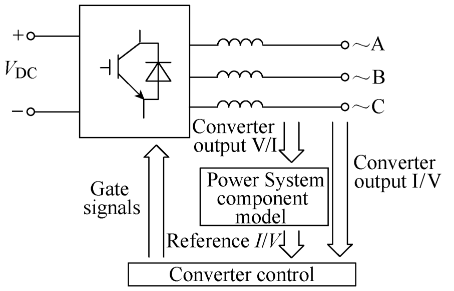


Fig.1 Emulator operating principles

2.2 Hardware configuration

The HTB has a paralleling converter structure as shown in Fig.2. Converter emulators share the same DC link, which is supported by an active rectifier, with its voltage regulated to a constant level. The AC terminals of the converters are connected together by filter inductors. Thus, the AC link of the converters can be considered as the emulated power system. Active power generated by generator emulators is absorbed by load emulators, reducing the total power consumption of the system. The undesired zero sequence and switching period circulating currents introduced by this paralleling topology is controlled and reduced[32], so that the emulating current flowing between the converters would represent the actual power flow. Between the converter emulators, inductors are used to emulate local connecting lines.

Because of the power circulating structure and large DC capacitance of the paralleled converters, the DC link voltage of the HTB remains relatively stable during system transients. The closed loop control of the individual emulators allows decoupling of the DC link voltage and emulated AC network behaviors.

Currently, three different power system topologies have been designed and tested using HTB platform, as shown in Fig.3. The first one is developed based on Kundur’s two-area system[33], which has 2 generators and 1 load at each area, and a long transmission line between the areas, as shown in Fig.3(a). Later, the capability of the system is enhanced by adding a third area representing the load center, a down-scaled MT-HVDC network, and two wind farm emulators. The topology of the three-area system is shown in Fig.3(b). The third system configuration is derived from a reduced model from Western Electricity Coordinating Council(WECC) interconnection, with the MT-HVDC network as an overlay. It is referred to as the four-area system. Fig.3(c) shows an example with 80% of renewable penetration by replacing some traditional synchronous generators with renewable energy sources.

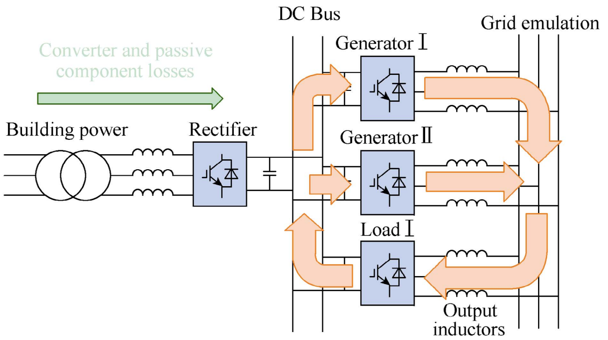
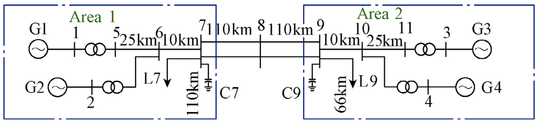
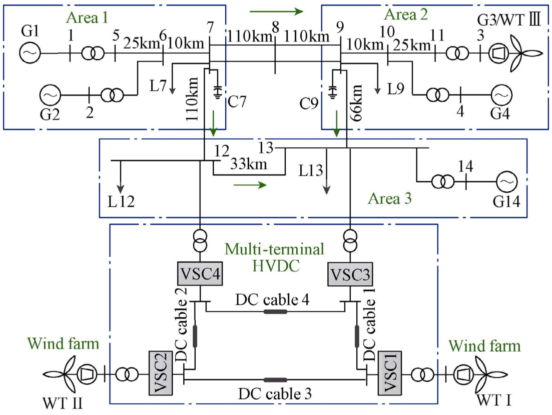


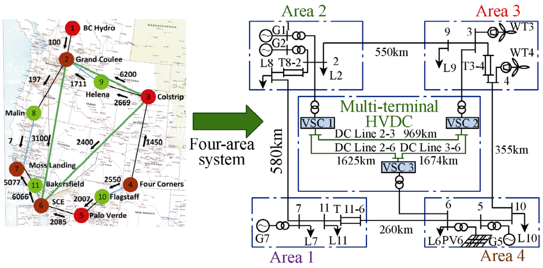
Fig.2 Structure of the HTB



(a) Two-area system



(b)Three-area system



(c) Four-area system

Fig.3 Power system emulation topology configurations in HTB

To preserve opportunities of testing in different system topologies, contactors are used to isolate the connections between the converter emulators and the system circuits. By controlling the circuit breakers and re-loading the programs of the converter emulators, the emulated system can be reconfigured to a different topology in less than one hour.

Fig.4 shows the photograph of the HTB. Each converter emulator is repurposed from a 600V, 75kW DC-fed motor drive manufactured by VACON, with DSP28335 as the controller. Each cabinet has four single unit emulators or 3 back-to-back transmission line emulators. Real measurements are integrated into the system, including potential transformers(PT), current transformers(CT), phasor measurement units (PMU) and frequency disturbance recorder(FDR).

Fig.4 Hardware configurations of the HTB

2.3 Communication and control architecture

The converter emulators can be controlled and monitored remotely through communication links estabilished by National Instruments' CompactRIOs (cRIO) using CAN bus. In addition, cRIOs can gather the data from PTs, CTs from analog input; and send data to computer for monitoring, closed-loop control, and visualization. PMUs and FDRs can directly communicate to the computer using OpenPDC software. The overall communication structure is shown in Fig.5.

Fig.6 shows the control architecture, which can

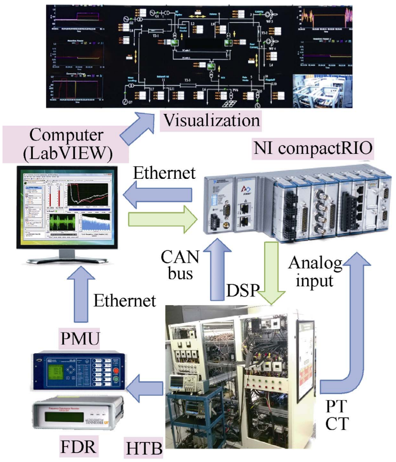


Fig.5 Communication structure

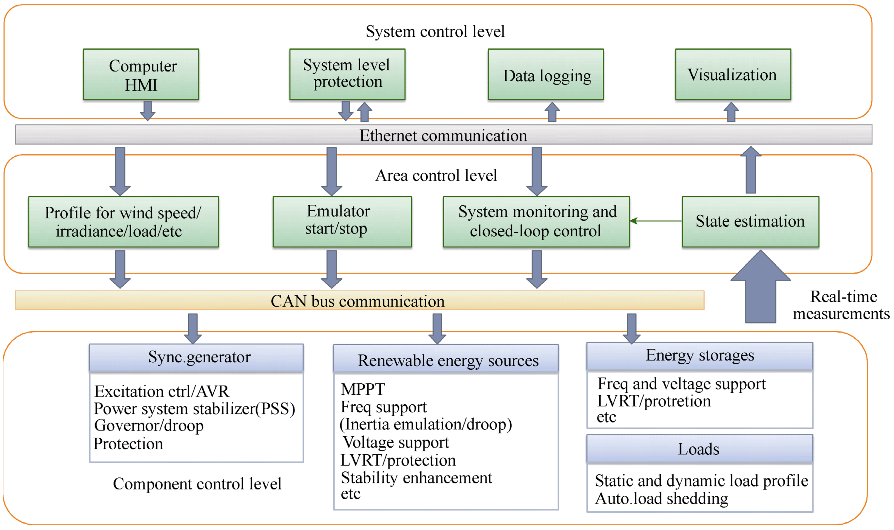


Fig.6 Control architecture

be divided into three layers. The system controls reside in the computer – they oversee the operations of different power system areas, provide functions like system level protection, data logging, visualization and human machine interface(HMI). Profile setpoints and start/stop commands can be determined by the operators and sent to the lower layers for the specific controls.

The area control level manages the components within the area, and do not have full information of the other areas. The control functions include state estimation and other monitoring and closed-loop controls such as automatic generation control(AGC), wide area damping control, voltage stability assessment, and renewable energy sources operating mode selection.

The bottom layer is the component controls, which are integrated in the DSP of the converter emulators in addition to the physical model. Each type of emulator has its own set of component controls. For example, the renewable energy source can be controlled to track the maximum power point, provide frequency and voltage support to the grid disturbance, ride through and protect itself during emulated grid faults, etc. The control functions implemented are shown in Fig.7.

3 System emulation demonstration

This reconfigurable converter-based testing platform offered a platform for development, testing and demonstration of various power system researches. This section presents several examples to illustrate the system emulation and testing capabilities of the HTB.

3.1 Critical clearing time investigation

The critical clearing time (CCT) of a short circuit fault can be used to assess 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 duration, the CCT can be easily identified by observing the system response.

Fig.8 shows an experimental recording of such test: a three-phase short circuit fault emulator is connected to bus 9 of the two-area system. It can be seen that the output frequency of the two generators will be oscillating out of step. This identified that 0.24s is the CCT, which is in accordance with the simulation results.

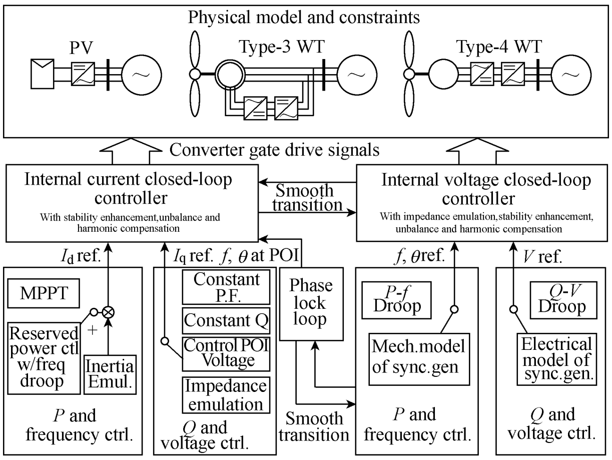


Fig.7 Control function implementations of renewable energy sources

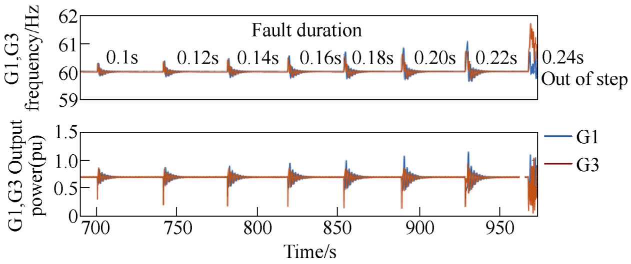


Fig.8 Test results of critical clearing time of two area system

3.2 Wide area damping control (WADC)

Inter-area oscillation often results from a poorly damped power system with weak transmission lines, and limits the power transfer capabilities. In the HTB two-area system, a measurement based wide area oscillation damping strategy has been tested and verified.

As shown in Fig.9, the frequency difference between G1 and G3 has a low damping ratio to a load step change event at L7. A proposed adaptive WADC control strategy can successfully suppress the oscillation, while the conventional one that does not consider the communication delay could trigger another oscillation mode in the testing system[34-35].

3.3 Renewable frequency support control

Frequency excursions would impact the power system reliability due to the loss of rotating inertia when renewable energy penetration increases. There are many control functions proposed to allow renewable energy sources to exhibit equivalent inertia in addition to the normal operation of maximum power point tracking(MPPT), such as frequency derivative based inertia emulation, virtual synchronous generator control (VSG), etc. These controls can be implemented into the component controls of the emulators.

Fig.10 shows the experimental results of a testing result in the three-area system, where G3 synchronous generator emulator is substituted with a wind farm emulator. Different frequency support control functions yield different results[36]. By adjusting the control parameters, the system impact of the controls can be investigated.

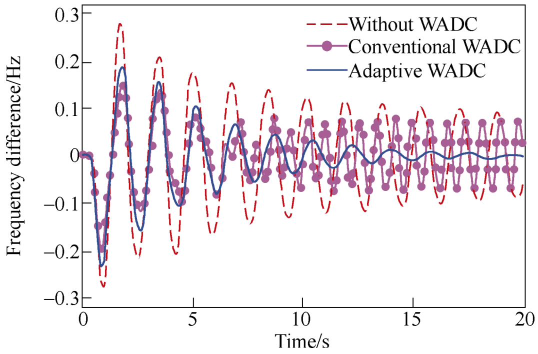


Fig.9 Test results of wide area damping control for two area system

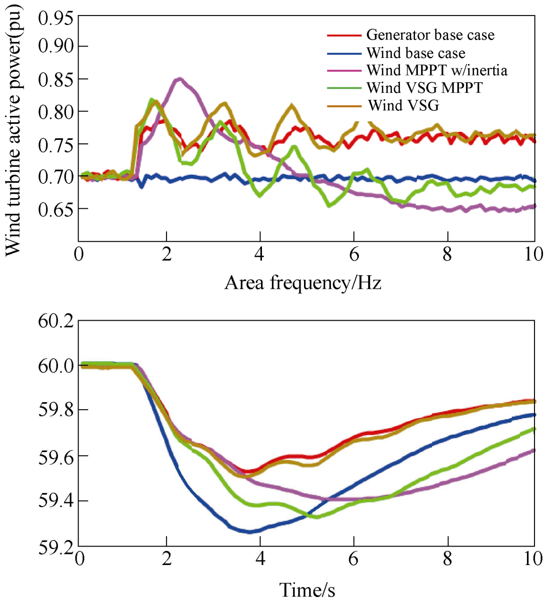


Fig.10 Test results of renewable frequency support control

3.4 Voltage stability assessment and control

Online voltage stability assessment helps the operators foresee potential voltage instability and take control action promptly to mitigate the situation. Power transfer limits of the transmission lines are calculated in real-time using the measured voltage and frequency data.

Fig.11 shows the algorithms in action in the three-area system, where the loads at bus 12 and bus 13 are ramping up. The transferred power on the tie-lines 7-12 and 9-13 increases and gradually reaches the calculated limits by the algorithm. When the margin is low enough, the reactive power support will be enabled from the HVDC station, and voltage collapse is avoided[37].

3.5 System controlled separation

Power system separation scheme divides a system into multiple islands to prevent system instability following a large disturbance. Remedial action scheme (RAS) is built into the HTB four-area system controller. When there is a three-phase short-circuit event, the transmission line 3-4 will be tripped due to overcurrent. RAS action saves the system by also tripping the line 2-8, so that the system is separated into two stable islands as shown in Fig.12.

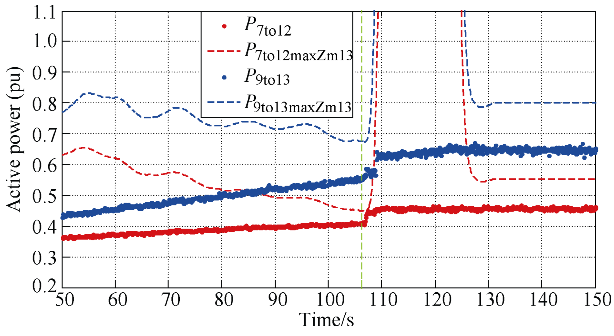


Fig.11 Test results of real-time voltage stability assessment and control in three area system

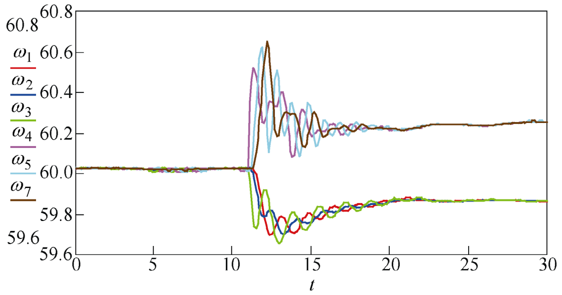


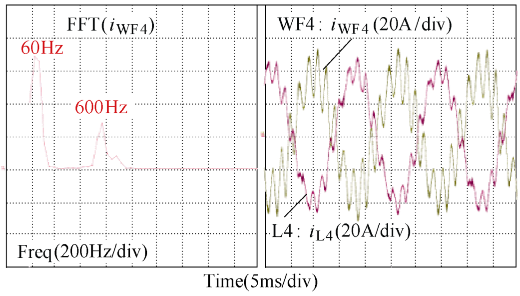
Fig.12 Test results of remedial action scheme of system controlled separation for four area system

3.6 Harmonic stability for high renewable penetrated system

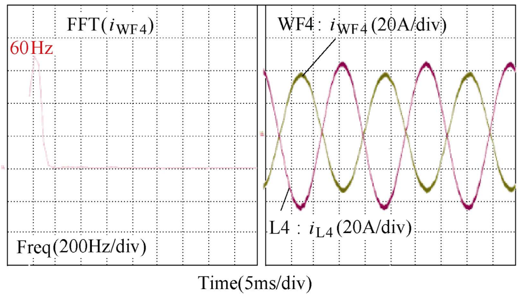
The fast closed-loop controls of the inverter may interact with one another and create small-signal stability problem, even if the inverters are all designed stable individually. This problem can introduce a higher order harmonic or subsynchronous resonance. Fig.13 shows an example of output current of a wind farm and a load at bus 4 the output currents exhibit a 600Hz 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[38-40].

4 Discussions

Compared with traditional hardware-based testing platform with actual down-scaled components, the HTB allows more precise and flexible scaling and modeling of many electrical components, such as rotating machines[19]. The emulators can be easily reprogrammed both in terms of model types and parameters to enable flexible reconfiguration and representation of different components. The power circulation scheme between sources and loads significantly reduces the need for laboratory power capacity and saves energy.



(a) Unstable case with parameters designed for ideal grid



(b) Stable case with properly designed parameters

Fig.13 Test results of harmonic stability problem

On the other hand, HTB is fundamentally different from real-time digital simulation. It is essentially an analog emulator with real power flows between real hardware emulating power system components. The HTB incorporates more realistic power hardware, especially in the case of power electronics based hardware such as converter interfaced renewable energy sources. It is also easy for the HTB to integrate real communication, measurement, control and protection equipment. Even though the emulators still largely rely on numerical models, similar to the case of real-time digital simulators, these models are truly distributed and computation is truly paralleled. As a result, HTB has shown to have much less numerical convergence problems. The limitation on the emulated number of buses is purely due to the space and resource issues. HTB also handles multi-physics models better covering shorter time-scale switching events to longer-term power system events.

Nevertheless, the HTB also has disadvantages compared with hardware based test platforms: the emulators are not perfect, the imperfections of the converter, measurements and closed loop control will introduce error; it is digital simulation inside of each converter emulator, and as such there could still be numerical issues; and emulator controls might have harmonics interactions that do not belong to the system behavior if not designed properly.

The HTB has also been combined with RTDS to further enhance the testing platform capability. Connected to RTDS through a power amplifier, the HTB can emulate one part of the electrical system, and RTDS is used to simulate the rest of the system[41]. Actual power equipment with HTB ratings can also be connected to the HTB as an EUT for PHIL testing.

This paper focuses on describing the use of HTB for power transmission system emulation. With its flexibility and reconfigurability, HTB can be applied to distribution system emulation as well as to emulation of other electrical power system systems, such as microgrid, shipboard and airplane electrical power systems. It has also been used to test interoperability of electrical system with other systems, such as power system communication cyber security.

The advanced integrated circuits 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 future.

5 Conclusion

This paper overviews the Hardware Testbed (HTB) developed to emulate electrical power systems in real-time using interconnected programmable and reconfigurable modular power electronics converters. Each converter represents a single or a congregated component of power sources or loads. Without using the actual power hardware, the HTB provides a good balance between the fidelity of the hardware-based testing platform, and the coverage of the digital simulation. Compared with the real-time digital simulators, the HTB provides better model fidelity, and incorporates real communication, measurement, control and protection equipment. Furthermore, the HTB can be used together with real-time digital simulators for even more flexible and accurate testing and emulation.

The HTB has already enabled emulation of many power transmission network scenarios, including wide area oscillation damping, voltage stability assessment and control, harmonic stability enhancement for high renewable penetrated systems, multi-terminal HVDC control and protection. The interoperability of power system and cyber systems have also been tested on the HTB. The HTB will also be employed for other systems such as microgrid, shipboard and airplane power systems in future.

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