Hardware-based microgrid testbed to facilitate development of Distributed Energy Resource (DER) systems for sustainable growth

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Abstract Distributed energy resource (DER) systems that can combine small-scale conventional energy sources with diverse renewable energy options and storage are ideal for addressing electrification needs of small communities, as well as proactively mitigating negative impacts of fossil energy sources on the environment. It is therefore imperative for academic institutions that wish to play a role in addressing energy challenges for sustainable rural development to be adequately equipped with a hardware testbed for the study and analysis of DER systems. This work features a 45kW hardware testbed installation at Penn State Harrisburg, highlighting its design, construction, and its uses in academic instruction and research. A case study on electric loading characteristics of the network is presented to illustrate its relevance and the potential for its use in preparing a skilled workforce for a new energy economy.

1. Introduction
Distributed energy resource (DER) systems that can combine small-scale conventional energy sources with diverse renewable energy options and storage are ideal for addressing electrification needs of small communities, as well as proactively mitigating negative impacts of fossil energy sources on the environment. DER systems concepts are in general, scalable and find relevance in larger distribution environments, even when a traditional electric power system is adequate.

In recent years academic institutions and research labs engaged in microgrid research have focused on software simulations, digital emulation, or hardware testbeds as the platform for validating conceptual ideas for potential uses in the field. Software simulations offer the desirable flexibility to quickly adapt system models to different needs with minimal cost implications. They can be scaled up to accommodate more devices, model larger service areas, and are amenable for introducing complexities as desired.
Hardware emulators, such as Real-Time Digital Simulator (RTDS) can reflect system characteristics more accurately through electromagnetic transient modeling and produce results that credibly represent conditions in a real network. Physical devices for automation, control, etc. may be connected to the RTDS to form Hardware in the Loop (HIL) to extend their capability. The system is in generally scalable but very expensive. Hardware-based microgrids incorporate physical systems and power generation devices on the testbed, they present realistic component characteristics in performance leading to higher levels of confidence in concept validation. In general, testbeds are expensive and not easily adaptable to new configurations but may be expanded through creative integration of hardware emulators such as RTDS. Hardware testbeds range from small desktop fixtures in university lab environments, to full-scale systems powering large communities.

The system featured by Liu et al. [1], is a small-scale hardware laboratory setup for instruction and research at the University of Texas at Arlington. The system described a microgrid architecture that could simplify renewable energy integration in remote communities with limited or non-existent public/commercial electric utility supply. The system would allow end-user participation is controlling energy costs through market-driven load management. Another academic institution-based microgrid testbed at the University of Genoa [2] was developed to validate algorithms for renewable energy production (wind, solar) forecasts, for optimal operation of energy storage systems and generation allocation, as well as for validation testing of smart converters for more effective incorporation of renewable sources into the smart grid.

Large research labs as well as commercial sectors are active in testbed development. The facility at Sandia National Laboratories [3] is designed to address new problems presented by substantial increases in stochastic renewable sources and the impact on reliable operation of power systems. A Megawatt-scale ship power system testbed presented by Pish et al. [4], was developed to investigate rapid power transfer between multiple loads, sources and storage systems. Such precision testbed models is critical for validation studies of operation and control schemes. The Duke Energy testbed highlighted in [5] was set up to interface with a real electric utility power grid. It integrates a photovoltaic (PV) installation and a battery energy storage system (BESS) with a standard substation, serving a node for interchange of power. Unlike testbeds developed for academic research and specialized environments, this testbed is fitted with features necessary in the field of operation. The microgrid adopted off-the-shelf components to achieve operation and control of power grid functions, using standard communications protocols for data and SCADA, physical I/O devices, Logic engine for managing resynchronization and other scenarios, as well as HMI for monitoring.

The pilot testbed facility presented by de Simon-Martin, et. al [6] considered the increases in the level of activities and the number of participants in the smart grid economy. There are interconnections of diverse renewable sources, storage, traditional utility grid, customer participants in electricity market, as well as voluntary peak-shaving activities, among others. These present a new category of challenges in network security with both hardware and software subject to cyberattacks. Other microgrid innovations [7][8][9] add on unique goals such as validation testing of commercial-grade microgrid controllers before deployment to the field and development of microgrid Energy Management System (EMS) to optimize energy delivery and integration to the utility grid.

The development of a microgrid lab at Penn State Harrisburg presented faculty and students the opportunity and challenge for innovation. The effort spans the entire process, from original conception, design, sourcing of support from industry and federal agencies, equipment acquisition, system fabrication, as well as development of operation and control software. Students were included in the design and implementation process through internships in the lab, paid employment for specific tasks, graduate
assistantships for the lab, and volunteer participation in a number of tasks. Since fabrication of large-scale projects is not a routine component of a traditional course, the process offered unique opportunities for training and engagement in technologies that support microgrid systems. The plug-and-play microgrid testbed incorporates features that reflects a true field environment. It is designed to adapt to changes in learning, its application in research and industry, and is scaled to operate and meet the electric energy needs of a small community. The design reflects physical challenges presented in integrating legacy equipment with evolving smart grid systems and technology, as well sufficient flexibility to investigate security needs in the rapidly evolving threat of attack on cyber systems. The next sections of this paper give an overview of the microgrid system at Penn State Harrisburg, covering the purpose of the facility, its design, fabrication, uses, and concludes with an application case study.

2. Electric energy grid model for sustainable rural environment
The traditional electric power grid illustrated in Figure 1 emerged over the early decades of growth in industrialization and the notable benefits of electric energy. The centralization of ownership and services was natural including generation, transmission, and distribution of power. Consumers or end-users had no active role in the commerce, and the business model made no provision for other participants in the generation, transmission, or distribution areas. The emerging Distributed Energy Resource (DER) model illustrated in Figure 2 made possible the smart grid (Figure 3). It opened the door to multiple new entities including suppliers of diverse renewable energy types, small and large electricity providers, decentralized services, and distributed systems control, energy markets, high speed communication across services, among others. The DER systems may combine small-scale conventional energy sources with diverse renewable energy options and storage, making it ideal for addressing electrification needs of small communities, as well as proactively mitigating negative impacts of fossil energy sources on the environment. The small grid system is attractive for its simplicity, scalability, flexibility with incorporation of new technologies, and adaptability of services to IoT.

![Figure 1. Centralized generation.](image1)

![Figure 2. Distributed generation.](image2)
3. Penn State Harrisburg’s Plug-and-Play Microgrid Testbed

3.1 A role for academia – Teaching, Research, and Industry support
Energy delivery models of the future will be flexible and non-static, highly evolving and will lend themselves to creativity as more sustainable options for electric power are explored. This naturally fits into the mission of academic institutions with talented and creative faculty and students to find solutions. The plug-and-play testbed at Penn State Harrisburg serves as a training and instruction tool for graduate and undergraduate students exploring a profession in the emerging modern power system and energy sector. While curricula at many electrical engineering programs rely on a classical set of coursework and laboratory work in preparing students for the energy and power industry, the microgrid facility brings about a major shift in student preparation. Students can perform experiments on a safe and flexible testbed, make observations and develop an awareness of critical issues involved in the operation of smart grids before joining the workforce. The flexibility proposed for integrating new technologies and hardware, e.g. advanced metering infrastructures (AMIs), storage, and distributed generators (DGs), will foster collaboration with industries for beta testing of equipment and evaluation of performance in the smart grid environment. As microgrids become widely deployed over the next decades, forming an integral part of electric power distribution, it is envisioned that this plug-and-play testbed will remain up to date to serve the needs of its diverse users.

3.2 Test-Bed Description
The 45kW plug-and-play microgrid testbed installation at Penn State Harrisburg is shown in Figure 4, and an electric schematic diagram for one of the buses (South bus) is shown in Figure 5. The facility combines four large motor-generator sets to emulate conventional sources and traditional electric grid coupling, emulators for photo-voltaic and fuel-cell sources, multiple inverters to interface DC battery storage to AC buses, transmission lines, and diverse end user electric loads. The range of smart devices, control and automation, protection relays, as well as wired and wireless communication networks facilitate distributed operation of the microgrid system. The diverse hardware systems and characteristics
necessitates network communication across multiple protocols. While this introduces undesirable complexities into the process of developing algorithms for operating the microgrid, it proves to be a strength of the system as it reflects real-life experience where legacy equipment must be combined with newer generation hardware devices on the field. The testbed is set up as a three-bus system (West, South and North), with each bus capable of autonomous operation as a separate microgrid controlled by local programmable logic controllers. A list of some major components of the testbed is shown in Table 1.

![Figure 4. 45kW plug-and-play microgrid testbed installation.](image)

![Figure 5. Microgrid testbed – schematic diagram (south bus).](image)
It is noteworthy that both graduate and undergraduate students played substantial roles in the conception, design, construction, and operation of the microgrid (Figure 6). Tremendous benefits accrued to these students on the experience gained and skills developed that would serve them well in their future careers. The idea of a smart grid came about within the context of a special course on smart grids with a dozen students enrolled in a semester course. The students subsequently selected different aspects of the subject for further investigation, including software simulation, multiagent-based operation and control, hardware testbeds, etc. A 22kW single bus microgrid prototype was constructed and successfully tested as proof of concept. The autonomous controller for the microgrid was developed in Java Agent Development Environment, using JADE-based intelligent agents.

| Equipment | Rating |
|-----------|--------|
| Power and Energy Sources | |
| Direct Coupled Motor-Generator sets | 10 KVA, 5kVA, 120/240V, 1800RPM |
| Generator Motor Drive VFD | 10HP |
| Generator Excitation System | DC general purpose drive, I/O |
| Smart Cell Battery Packs | 48V DC, 8–75AH, 8 – 90AH, 8 – 100AH |
| Wind emulator | 36” Drum Fan, Turbine, 400W, DC 12V |
| Fuel cell Emulator, Programmable DC Power Supply | 0-250 V, 2.6kW |
| PV Emulator, Programmable DC Power Supply | 0-250 V, 16 A, 4 kW |
| Solar Charge Controller, MPPT | 60 A |
| Power Inverters (DC-AC-DC) | 6.8kW 120/240V, 48V DC |
| Off-grid Power Inverter (DC-AC-DC) | 4kW, 120V AC, 48V DC |
| System Loads | |
| Induction Motors, VFD-driven | 3HP, 3-phase, 208-230/460 VAC, 1800rpm |
| Smart Programmable AC Load systems | 3.6KVA, 36A |
| Instruments, Networking, Automation and Control | |
| Three-phase SCADA Meters, Synchronizing Ethernet Transducers, Intelligent Electronic Devices, Bidirectional 2400 MHz transceivers, Command and Control Workstations - LED Monitors, PLCNext Engineer programmable logic controllers, SEL series real-time automation controller, Programmable relays, Orion Automation platform, Secure substation gateway, ETAP - analysis and operation software, MATLAB. |

Following development of the prototype system, the 45kW testbed was installed on campus, funded by US Department of Defense’s Defense University Research Instrumentation Program (DURIP) to address workforce needs of the future. As a plug-and-play testbed, the system is designed to allow system reconfiguration with minimal effort, including addition of devices, updating or replacement of legacy devices as needed, as well as upgrading or changing operation and control algorithms seamlessly. The testbed would lead to advances in smart grid research by providing a platform for testing innovative
hardware and software solutions, communication protocols, load management strategies, multi-agent systems, fault impacts and management, and processes and protocols for connecting and islanding microgrids.

**Figure 6.** Microgrid system fabrication: Hands-on training opportunity

**Figure 7.** Microgrid SCADA

The testbed is fitted with a highly flexible data communication structure by using AMIs, relays, PLCs and controllers capable of wireless and wired communication with diverse protocols. Also, equipment-to-human interfaces Figure 7 and Figure 8 are designed to provide safety for users and simplify the process
for inserting hardware or software for testing into the testbed. This will enable research students and faculty to use time efficiently by focusing on the intellectual aspects of the work, rather than the time-consuming mechanical process of customization and integration of new systems into the testbed.

Applications involving wind, solar and energy storage research could be studied on the microgrid testbed, with the potential for incorporating emulators for other renewable energy sources in the future.

Figure 8. Microgrid control HMI

4. Case study – Microgrid Islanding
A case study is presented to highlight some of the features of Penn State Harrisburg’s plug-and-play testbed. Figure 9 shows the testbed configured as a three-bus microgrid system with a local energy source, inverters connected to battery storage and other sources, various electrical power end-users, and interconnecting distribution lines. The electric energy provider for the area (electric utility) is connected to the North bus. A case study is designed to highlight some features of the microgrid testbed, loading characteristics, synchronization of electric utility to the microgrid, and microgrid islanding. Electrical loads representing diverse end users were turned on to generate a service area load pattern that would be useful for designing protective scheme for the microgrid. Electric utility supply was synchronized to the microgrid to reflect service restoration, and later interrupted to generate results for studying power sharing. Test results for the case study are presented in Figure 10 and Figure 11. These results would be helpful in designing operation and control algorithm to keep loads within microgrid source limit (load-leveling) during islanding. It would help in ranking loads, establishing prioritization for service, and including cost factors in services offered. Also, impact of short-term forecast of wind, solar, and other renewable sources, may be included in the energy management and planning algorithm.
| WMG00  | West Motor Generator |
|--------|----------------------|
| NMG00  | North Motor Generator|
| WS TL  | West-South Transmission Line |
| SN TL  | South-North Transmission Line |
| WInv   | West Inverter |
| WIM01  | West Induction Motor 01 |
| WIM02  | West Induction Motor 02 |
| NIM01  | North Induction Motor 01 |
| NIM02  | North Induction Motor 02 |
| SIM01  | South Induction Motor 01 |
| SIM02  | South Induction Motor 02 |
| NELD   | North Electronic Load |
| SELD   | South Electronic Load |
| Ext3Ph1| External Three Phase Motor on North Bus |
| Ext3Ph2| External Three Phase Motor on South Bus |

**Figure 9.** Testbed configured as a three-bus radial microgrid system.

**Figure 10.** Microgrid service area load curve (generated for case study).
5. Conclusions
The plug-and-play microgrid testbed at Penn State Harrisburg is developed to serve a broad range of users (graduate and undergraduate students, faculty, industry partners), and offers functionality that suits diverse interests. As a hardware-in-the-loop test facility that reflects true model and operating conditions of practical microgrids, it gives more credence to results and conclusions from research on operation, performance, and control of microgrid functions. The features increase flexibility making it possible to modify the system hardware and software configurations to reflect changing interests or expanding needs in microgrid research.

The testbed conception and its functions and applications directly support the goals of numerous private and governmental initiatives in advancing sustainability in the electric energy sector, and the enabling technologies through smart grid research.

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