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Testbed for Transactive Energy and its Effects on the Distribution System and Protective Devices Settings

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Introduction

The introduction of renewable resources is leading to significant variability in supply. This, in turn, leads to necessity of balancing supply and demand. Penetration of renewables to distribution level, including microgrids, requires new approaches to maintain distribution systems balanced and reliable. This is a complicated and challenging process that necessitates an increased level of sensors, measurements, monitoring, and protection coordination among other aspects. Integration of renewable resources with the grid is also associated with a new economic model. Move to Transactive Energy requires novel approaches in power systems design and operation, especially on a distribution level.

Another important aspect of penetration of renewables is the effect on protective relays settings, especially at the distribution level. Investigation of effects of renewable distributed generation and possible solutions require pilot projects and testbeds.

The purpose of the project was to design and implement a testbed to study the Transactive Energy concept, to investigate the impact of Distributed Generation (DG) on the microgrid and integrate protective devices. Physical modeling of the microgrid with DG resources was performed using Smart Grid Laboratory at SUNY Buffalo State. The testbed was developed using various state-of the art laboratory modules, such as microgrid controller, Double-Fed Induction Generator (DFIG), photovoltaic systems (PV) with grid inverter, underground line module, and a number of smart meters and sensors. Monitoring and control utilized Supervisory Control and Data Acquisition System (SCADA).

The project resulted in a testbed to demonstrate the effects of distributed renewable resources on the balanced operation of the distribution system/microgrid as well as transactive energy in terms of automatic switching operations as applied to residential microgrid. The project was part of a senior design course with associated assessment of student outcomes and was supported by a grant from Electric Power Research Institute (EPRI) and its Center for Grid Engineering Education (GridEd) in 2016 – 2017 and the second time in 2017 – 2018 academic years.

Foundational knowledge for the project came from the courses in Electric Machines, Power Electronics, Power Systems I and II, Distributed Renewable Generation and Storage, as well as courses in Control Systems I and II, Digital Systems, and Microcontrollers.

Transactive energy in the context of the project

According to the Gridwise Architecture Council (GWAC), transactive energy is a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using the value as a key operational parameter [1]. The transactive energy approach offers a way for producers and consumers to more closely balance energy supply and demand based on technical and economic factors. One of the transactive energy principles as to maintain system reliability and control while enabling optimal integration of renewable and distributed energy resources. Transactive energy systems should be scalable, adaptable and extensible across a number of devices, participants and geographic extent [2]. One of examples of a scalable system is residential microgrid. Energy sharing across a neighborhood promotes sustainability through the efficient utilization of local energy resources and reducing reliance on the utility grid [3]. In traditional grid, houses are connected to the main grid, which supplies their total load demand. In microgrid, and specifically, residential microgrid, all or partial demand is satisfied from local sources, typically PV. There are two major types of houses in residential microgrid: the ones with PV system installed and those without it. When own energy demand of the house with PV system installed is met, it is possible to share (sell) energy with their neighbors or with the grid. If not enough power from PV system is produced, the sharing discontinues and the house without PV system automatically switches back to the grid. Likewise, the house with PV system will switch to the grid if its demand is no longer satisfied from the solar PV source.

Besides the economics of sharing, other challenges, such as automatic switching and monitoring of energy flow have to be met.

Project activities in residential microgrid transactive energy

The first step was familiarization with various Lucas-Nuelle (LN)® laboratory modules and experiments related to photovoltaics. These experiments include operation of the solar panel emulator, manual and automatic voltage regulation of local network transformer, manual and automatic derating of invertor, power quality meters, and provisions for reactive power control. With familiarization of the standard lab experiments supplied by LN completed, a physical model was constructed to emulate a residential microgrid with two houses: one with PV system and another one without it.   To explore the concept of transactive energy, students developed a physical model consisting of the components mentioned above. One load module was connected directly to the inverter to emulate a house with solar panels, whereas the other load module emulated a house without solar panels. Circuit breakers were installed to perform switching operations. When the house with solar panels is capable of producing enough power to supply the house without solar panels, a circuit breaker will open and disconnect grid power, and therefore consume only power generated by the house with solar panels. If the house with solar panels is not capable of generating enough power, the circuit breaker would close and reconnect the house without solar panels to the grid. This is accomplished by the LN SCADA, which interprets the data from the Siemens® power quality meters and controls the circuit breaker via digital outputs. Opening or closing the circuit breaker is based on the code consisting of a series of if /then, elsif decision statements. If the meter saw a negative power flow, the circuit breaker would open. If the meter saw a positive flow, the circuit breaker would close.

Siemens® power quality meters are TCP/IP enabled and serve as sensors for the system. They were installed at the following points:

- Connection point to utility power source after transformer
- Two meters per house, one each at connection point to monitor grid-fed power, and the other to monitor power fed from the inverter.

This allows for accurate power flow monitoring at all points of the circuit. Circuit breakers were installed at the points necessary to provide flexibility and control of switching operations.

The next step was development of SCADA program and human-machine interface (HMI), which combined all the concepts from the training labs as well as switching experiments into a single

system. The code was written for SCADA to provide monitoring, metering, visualization of power flow direction, and automatic switching operations.
Figures 1 and 2 illustrate transactive energy part of the project.

Fig. 1. Layout of residential microgrid for transactive energy experiments

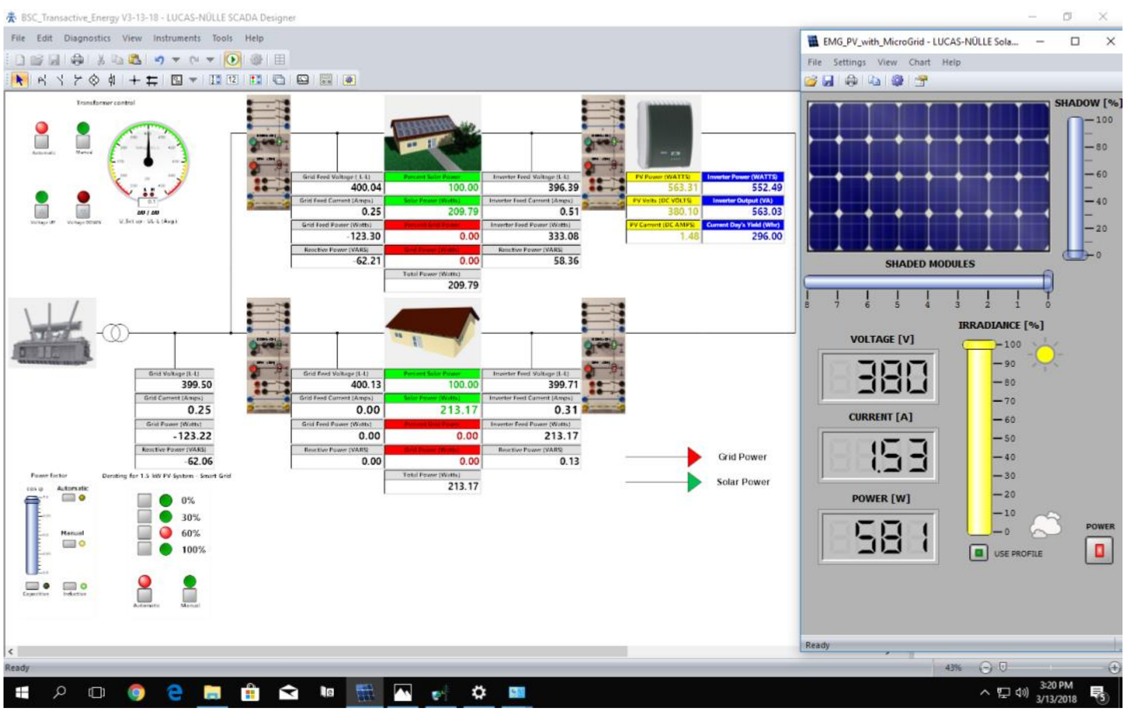

Fig. 2. SCADA screen to control and monitor residential microgrid

Project activities in a microgrid with distributed generation

Besides residential microgrid, the project involved investigation of a larger microgrid with DG sources, such as combined heat and power (CHP) and wind generation.

The design of the microgrid testbed in the lab is based around the presence of renewable energy sources. For the testbed, a 1kW double-fed induction generator (DFIG) was chosen to represent a wind turbine. An active servobrake is connected to the input shaft of the generator and emulates the prime mover of a wind turbine rotor. This servobrake is controlled through WindSim software that varies its output based on either a user defined wind speed or a wind profile.
To accomplish the outlined project, ETAP® power systems simulation software was used extensively to simulate the project before and during the construction and testing phases. The hardware used to build the microgrid consisted primarily of LN modules that represent various components of the power system. The modules include a utility source, DFIG, PV system with grid inverters, wind turbines, overhead and underground transmission lines, switchgear, and smart meters. An induction motor with varying load emulate a variable load on the microgrid and its load profile is programmed to represent actual load profile of a distribution feeder. SCADA software was utilized in conjunction with the previously mentioned equipment. Schweitzer Engineering Laboratories® SEL-751and SEL-411L protective relays were incorporated into the project and programmed using the AcSELerator QuickSet Software. Preliminary experiments with separate subsystems were conducted to gain a working knowledge of the individual components.
Figure 3 represents microgrid testbed configuration and points of connection of protective relays.

Construction of the testbed began with designing a microgrid utilizing the previously outlined equipment. The first iteration simply consisted of a synchronous generator (emulating CHP) and a utility source supplying a static load. The utility supplied the power through a transmission line, while the generator was connected in close proximity to the load. SEL relays were applied at both ends of the transmission line to provide overcurrent protection.

The synchronous generator is a 1kW smooth core synchronous machine with its input connected to an activeservo drive motor. In this case, the activeservo drive represents a stable and predictable mechanical input such as diesel backup generator or a CHP generator, which is typical of powering large facilities. This generator serves two main purposes. The first purpose is providing a stable voltage for the line side of the IGBT converter, which is required for the operation of the DFIG. The second purpose is compensating for real and reactive power levels which the DFIG is incapable of producing, dependent on the simulated wind speed. In some cases, the synchronous machine runs as motor to dissipate excess power when used in island mode.

Synchronizing the generators with the rest of the system is achieved with a Schweitzer Engineering Laboratories® (SEL) model SEL-547 interconnection relay. SEL relays are commonly found in low, medium, and high voltage power systems and are used throughout the testbed. SEL-547 relay achieves synchronization by performing a frequency and voltage check before a breaker is closed. With this setup, the relay acts as a pass through for a breaker close signal. When the command to close the breaker is received, the relay verifies that the microgrid is in phase with the utility before allowing the breaker to close. If the system does not pass the synchronism check, the relay will send a signal back to the system to adjust its frequency until the system is in synchronization mode.

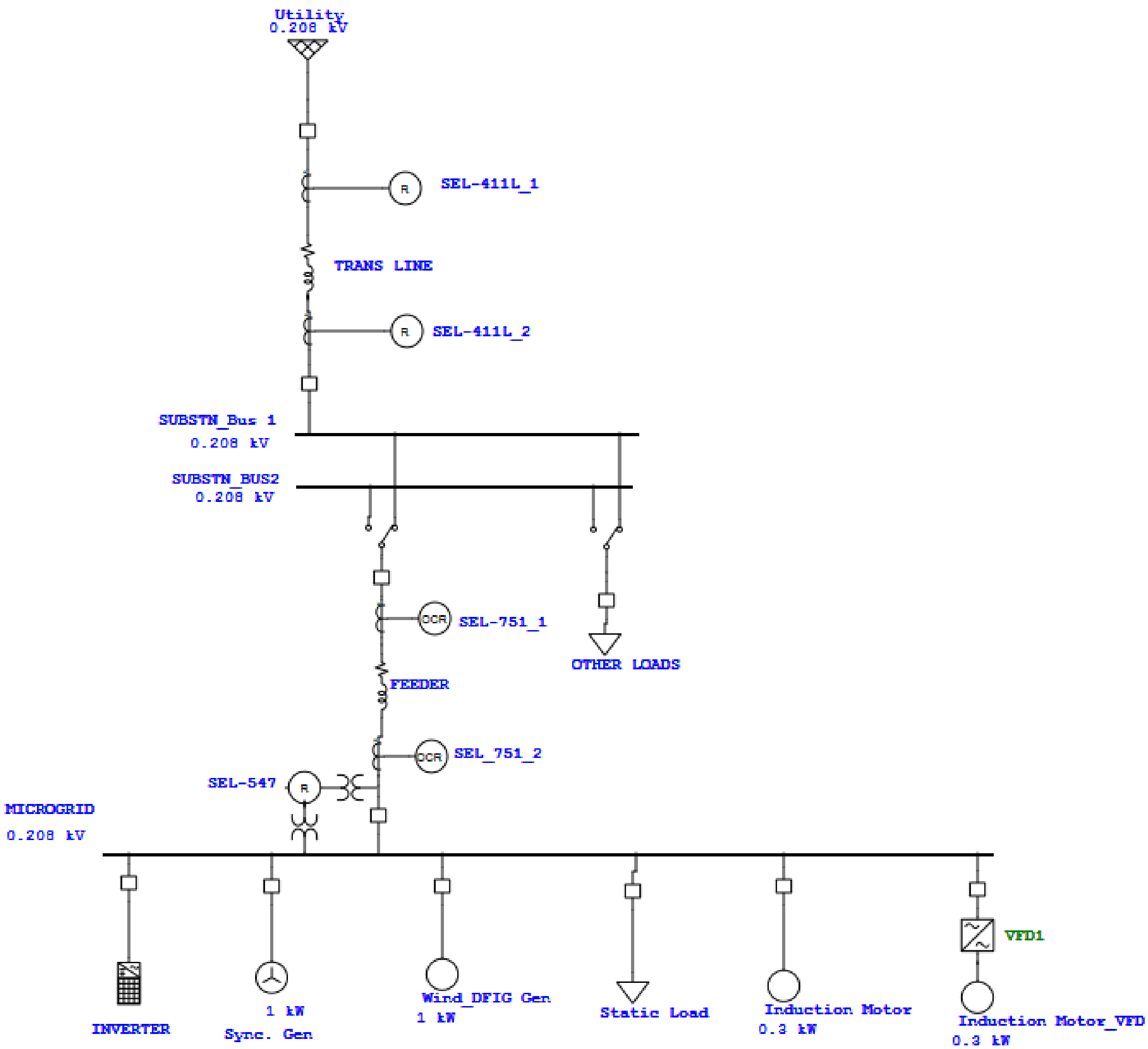

Fig. 3. Microgrid testbed configuration

A utility connection is provided by an AC power source that operates at 208V. Power is supplied through a module that emulates 93-mile transmission line. This line is protected using SEL-411L relays using instantaneous and time overcurrent, as well as directional overcurrent and differential protection (ANSI designations 50/51, 67, 87). The relays contain a reclose function (ANSI 79) when the relays operate on differential protection. The transmission line terminates at a double-busbar substation. This substation serves the microgrid through an underground feeder module, as well as other loads. The underground feeder module emulates 7.8-miles cable line and has overcurrent protection (ANSI 50/51) from SEL-751 feeder protection relays. The SEL-

751 relays have overcurrent protection settings that selectively coordinate with the SEL-411L relays. Figures 4 and 5 illustrate the layout of the testbed and SCADA screen.

Fig. 4. Testbed layout

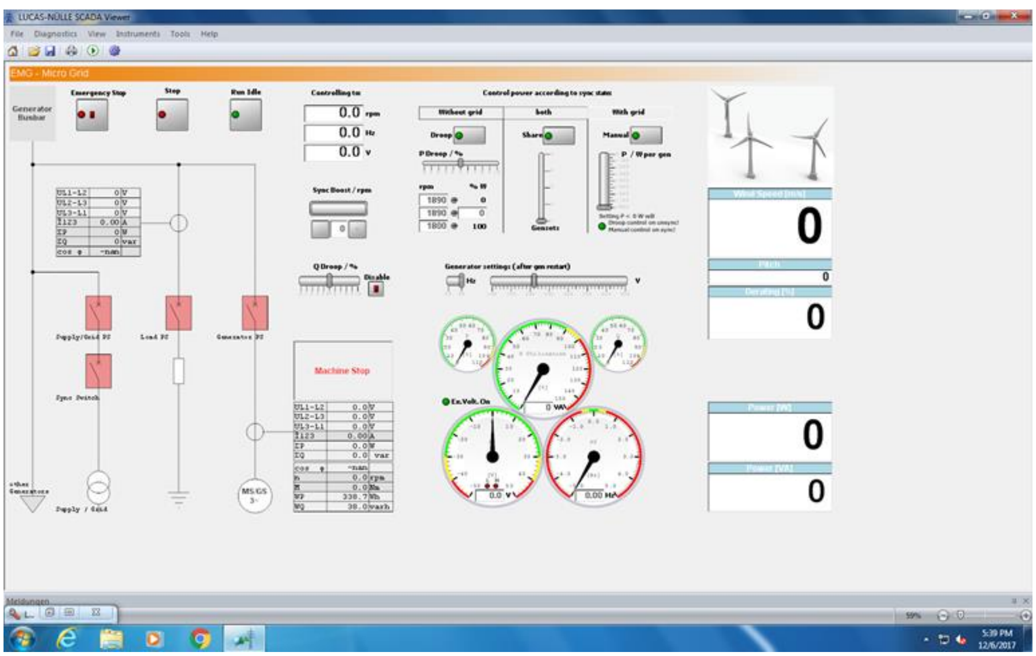

Fig. 5. SCADA control panel for microgrid

Initial setup was to prove that the utility and CHP generator could share the load and test the control system associated with the microgrid HMI. Early on, a problem with power system stability was encountered. When the generator was synchronized to the utility, power levels began to oscillate until the system became unstable and protective devices tripped. After troubleshooting the system and consulting with LN engineers, it was discovered the LN control system software was tuned for a 50Hz instead of 60Hz used in North America. As a result of extensive testing and troubleshooting together with engineers from LN, modification was applied to a coefficient in feedback loop of the control system software. Figure 6 illustrates power oscillations encountered before modifications were made. After modification, stability of the system was achieved. Multiple iterations of testing showed the utility carrying the majority of the load without aid from the generator. However, when service from the utility was disconnected and the relays opened the breaker, the generator was able to reliably supply power to the system.

The next step was integration of the DFIG wind module as part of the microgrid. Various tests were conducted to verify the generator and DFIG had the capability to share the load without the utility. Reclosing functions were added to the relays protecting the feeder line in order to conduct tests with simulated faults, then reconnect to the utility. As successful results were achieved, more functions were added, such as deployment of SEL-411L relays with their protection functions. Figure 7 illustrates event oscillography of the upstream SEL-411L relay during a fault (line currents at the top of the figure and phase currents at the bottom). The fault was between the two terminals and the relay tripped on differential current. Fault location was near the substation Bus 2 terminal shown in Figure 3, resulting in minimal voltage drop. Vertical red dashed line indicates the initiation of the fault (function 87L has activated).

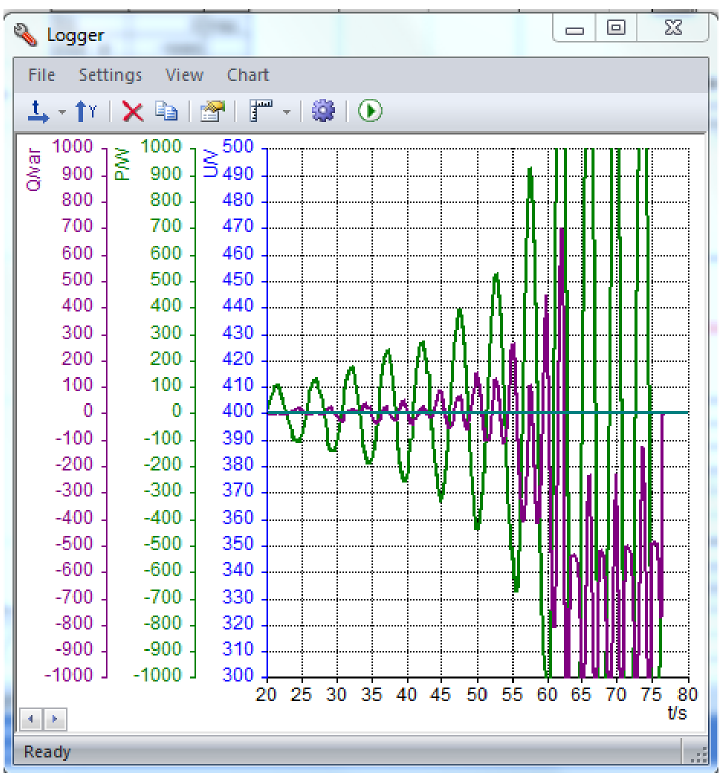

Fig. 6. Power swings during unstable operation

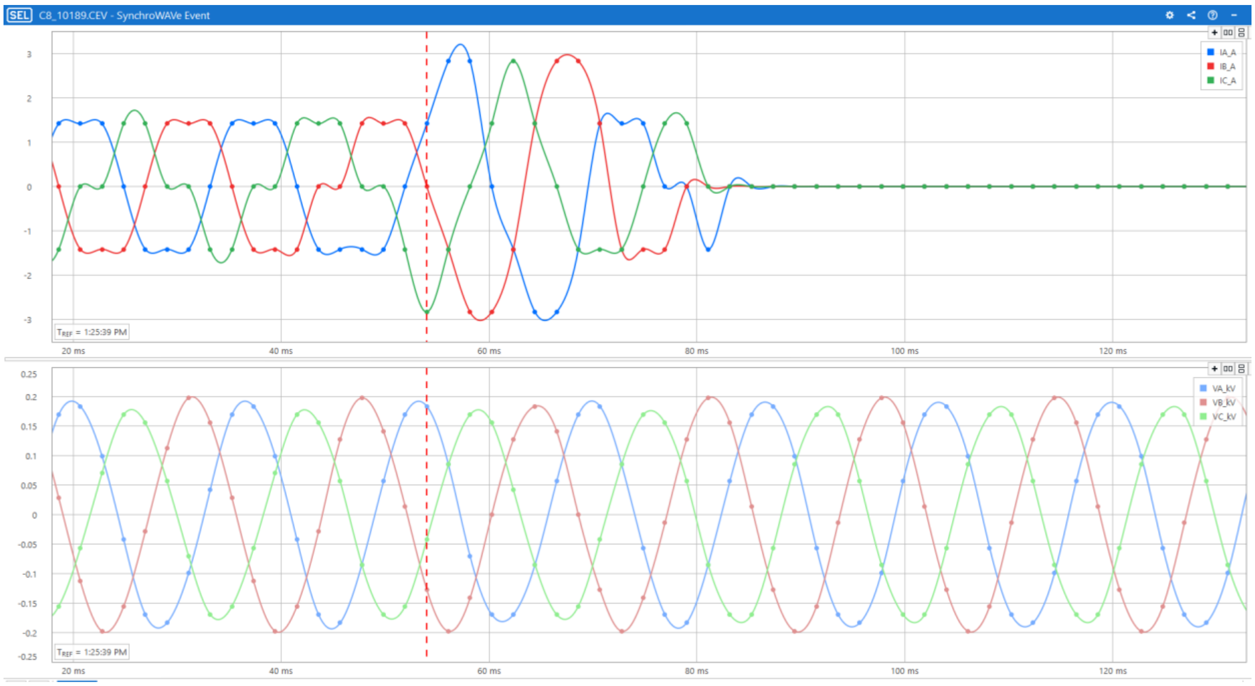

Fig. 7. Event oscillography of SEL-411L relay

Assessment and Evaluation

The testbed project was one of the projects in a senior design two-semester sequence, now in its second cycle. Besides technical component, students were assessed in team building skills (ETAC ABET outcome 3e), project management skills (IEEE Program Criterion 4), design and research skills (ETAC ABET outcomes 3d and 3f), documentation and presentation skills (ETAC ABET outcome 3g), as well as ethical, social, and professional development skills (ETAC ABET outcomes 3h, 3i, 3j, and 3k). Direct measurement assessment tools were used, including peer assessment of team contributions, NSPE-based ethics exam, papers on engineering ethics, social issues, project management test, as well as bi-weekly grades assessing organization, degree of completion, subject knowledge, technical merit, and documentation. Table 1 illustrates evaluation of assessment results for the senior design class overall and for the testbed project teams.

The difference in outcomes for overall class and testbed team during 2016 – 2017 academic year is insignificant, while during 2017 – 2018 the testbed team attained considerably better results in project management, design and research, and documentation categories. There are too many factors that can explain the difference (quality of students, high level of enthusiasm towards the project, smaller team size among others).

Students were very excited to work with the state-of the art equipment and face many challenges ranging from tackling stability issues, system integration, SCADA programming, and integration of SEL relays. Most of these issues were not part of the regular coursework in the program. Students engaged with experts from industry to clarify several issues that they encountered. Such

interaction is an important part of their undergraduate experience and a required component of the senior design sequence at SUNY Buffalo State.
Students reflected on the project in highly positive way:

"The Microgrid senior design project has been an excellent opportunity to apply theoretical principles and knowledge gained during Electrical Engineering Technology classes. Completion of the various Lucas-Nuelle training labs assisted in teaching theoretical principals and developed a working knowledge of the equipment required to build a functional microgrid. Lucas-Nuelle also provided the SCADA and Panel Designer software that were crucial to the development of the SCADA and HMI required to operate the microgrid. Working with the Lucas-Nuelle built-in PLC developed a working knowledge of PLC coding which were also crucial to the operation of the microgrid. I have also learned a lot about the Siemens PAC family of power quality meters. They have been critical to the functional operation of the project, as their measurement data is used to execute the various automation and switching functions performed by the microgrid."

"The project I have been involved with focused on the creation of a microgrid which emulates a system utilizing a diverse range of power generation sources along with modern techniques for monitoring, controlling and protecting modern power systems. The project encompasses multiple aspects of the power systems discipline and has provided a means for study beyond the scope of the typical classes. Particularly, my duties with the project involved working SEL-based protection. Through this I have been able to develop skills in relay protection. I have also been exposed to the communication and data aspects of power systems which is critical for the automation and control of the future grid. This experience has brought positive feedback from my supervisors at my current internship and has led to full-time employment. It is my opinion that this project is one of the greatest factors shaping the trajectory of my career and has provided incalculable benefits to my education."

"Feedback from industry professionals viewing the project has been very positive with frequent expressed interest and enthusiasm. The microgrid provides an opportunity to apply real world industry knowledge and principals. For that reason, I consider the Microgrid Senior Design Project a critical component to my future success and believe that other senior design projects should provide as much hands-on opportunity to apply industry practices and actual industry hardware as possible."

The fact that the testbed project was selected twice for funding by GridEd/EPRI by itself attests to the significance and quality of the project. Three students, who completed the project, were accepted to the graduate schools (Johns Hopkins University, University at Buffalo), one student was hired by National Grid utility company, four students were hired by energy service company, and one by engineering consulting firm. This also attests to advanced skills and knowledge acquired by the students during the project. Students presented the results of the project at SUNY Buffalo State Student Research and Creativity Conference, ASEE St. Lawrence Section Conference in 2017 and 2018, as well as at DISTRIBUTECH conference in January 2018.

Table 1

		Number of students	Ethical, Social, and Cont.	Team Building	Project management	Design and Research	Documentation	Presentation
2016-2017	Class overall	23	93.08	89.74	82.585	90.685	89	90.945
	Testbed team	6	94.8	88.235	82.29	86.63	90.585	90.2
2017-2018	Class overall	24	94.64	90.13	84.31	88.46	85.91	91.24
	Testbed team	3	98.7	91.43	92.86	98.88	94.392	94.33

Conclusions and future work

The project provided an insight for undergraduate students at SUNY Buffalo State in the design and analysis of the modern grid. The testbed assisted in the validation of theoretical concepts aimed at increasing reliability, efficiency, and sustainability of tomorrows energy systems. This project provided valuable information for studying the effects of DG resources on system operation and reliability. Data collected offer information on the considerations for the practical application of distributed resources. Experiments assisted in the development of educational material for power engineering and smart grid design and were shared with Lucas-Nuelle, the manufacturer of the equipment and associated software, to expand their portfolio of possible laboratory exercises. The microgrid project serves as a testbed for emerging concepts and as an educational tool for the design and operation of the modern power systems.

Efforts are ongoing in deployment of battery storage to be used with photovoltaic system, investigation of synchrophasors for control and monitoring of the system, power quality measurements, as well as incorporation of price signals for transactive energy part of the project.

Acknowledgments

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- Center for Grid Engineering Education (GridEd) and EPRI provided financial support for student teams in the amount of $10,000
- Lucas-Nuelle provided technical consultations and updated software and firmware for their equipment to meet the goals and challenges of the project
- USDidactic donated equipment and supplies to be used for the project
- SEL Inc. and Robinson Sales provided equipment and technical consultations
- Operations Technology, Inc. for providing ETAP Power Lab educational licenses.

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