Paper ID #26084

Student-Led Study of Energy Flow and Storage in an Emergency Microgrid

Dr. Herbert L. Hess, University of Idaho, Moscow

Herb Hess is Professor of Electrical Engineering at the University of Idaho. He earned the PhD Degree from the University of Wisconsin-Madison. His research and teaching interests are in power electronics, electric machines and drives, electrical power systems, and analog/mixed signal electronics. He has published over 130 papers on these topics and on engineering education. He has taught senior capstone design since 1985 at several universities. He contributed a host of technology advances to the US Armed Forces in his 32-year military career. He was elected an ASEE Fellow in 2018.

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Abstract

Students investigate the feasibility of forming a microgrid in the downtown area of a larger city in the Pacific Northwest. The objectives of this study are twofold: 1) Create a microgrid to provide for prioritized urban loads and 2) prepare students who will likely design and install several microgrids in the region in the next few years. Generation is two hydroelectric units and a nearly equal amount of distributed photovoltaics. The grid is defined and its elements identified and modeled in PowerWorld®. Simulations reveal that all loads cannot be served all the time with available generation. The nature and size of priority loads vary most with seasons and also with time of day. Battery storage is not effective because the public utility cannot afford enough of it. Simulations show that steady state stability is readily achieved and maintained, including voltage and frequency stability. Graduate students led the study and, under their direction, undergraduates contributed greatly to the work: They defined the project, they brought resources from their education to bear for characterizing, modeling, analyzing, and improving the proposed microgrid, and they effectively and efficiently modeled with system with state-of-the-art modeling tools. Assessment indicates that the student team achieved the proposed outcomes and enabled the public utility to move forward to the next step toward eventual installation. Students who performed this study have all been employed within the public utility industry or directly supporting industries, receiving no shortage of job offers.

Introduction and technical framework

A microgrid is a small-scale power grid that can isolate from the main grid and still be able to supply local loads sustainably using local distributed energy resources and self-contained control. The major components of a microgrid are electrical loads, generation resources, a microgrid controller, and an optional electrical energy storage system. Microgrids can be intentionally created, often in remote places, or they can be isolated and islanded in convenient locations during the prolonged grid outages. In either case, microgrids provide energy to loads sustainably within the microgrid footprint. [1] There is great resilience to be gained from establishing microgrids.

This paper describes a feasibility study performed by a student team for forming a microgrid in the downtown area of the City of Spokane, Washington, under emergency conditions created by loss of power transmission. Such a regional interruption on November 17, 2015, provided strong motivation for this project. The technical objective of this study is to investigate the feasibility of operating a microgrid, determining the level of improvement in resilience that this microgrid could provide within the city's core. At hand, there are two hydroelectric generators totaling 13 Megawatts operating "run of the river", without the energy storage afforded by a dam. Rooftop solar generation adds a similar amount a generation capacity. Energy storage consists of a relatively small set of vanadium flow batteries. Loads are typical high priority urban loads such as hospitals, police and jail, government offices, and a downtown business district. In this study, we address issues pertinent to the reliability of an established microgrid, not its establishment or its long term economics.

From many years' public utility distribution and transmission data, a unified model of the downtown microgrid can be created. Using this model, steady state and transient studies may be performed. Voltage control, frequency stability, and power flow were important parts of this investigation. Voltage stability proves amenable to conventional means of reactive power control, such as tap changers and distributed capacitance. Renewable resources (hydro and solar) provide the sole sources of energy for this microgrid and its means of frequency control. Renewable resources' well-known seasonal and diurnal variations in availability encourage compensation from electrical energy storage. Conclusions of these studies provide understanding and insight into establishing, operating, and maintaining an urban microgrid. [2]

Academic and pedagogical framework

This is a student project. As such, there are appropriate learning methods and expected learning outcomes. Graduate students led the study and, under their direction, undergraduates performed most of the tasks of characterizing, modeling, analyzing, and improving the proposed microgrid. This is consistent with a methodology published in 2008 for similar projects [3,4]. Within those papers, a complete system for defining the project's goals, objectives, and outcomes is presented in the context of a graduate student mentor and a team of several undergraduate students. The method was developed over the previous several years [3]. The method was refined and documented in practice several times over the ensuing decade, for example [5.6,7,8,24,25]. The method proved to be successful in providing theses for graduate students that clearly contained more than theses performed in similar subjects without senior capstone design team contributions. The quality of those theses are usually superior, for example [2,9,10,11,12,13]. Papers generated from those theses were more likely to receive recognition and higher marks in peer reviews. Hence, we again employed these methods in the project at hand.

The project's staffing was organized in the typical fashion with a major professor chairing a committee of three professors for a Master's degree with thesis. A graduate mentor was appointed and, through a documented self-selection process, a team of undergraduates was appointed [14,15]. For a senior capstone design project, the desired educational goals, objectives, and outcomes are several and described on the same interdisciplinary course website [16]. The outcomes are more focused for the specific project at hand than the broad five-department, seven-program outcomes of the course website. These outcomes include:

- Students design an engineering system of some complexity in a manner that produces a result that is shown to meet a client's need.
- Students in a team environment bring together several aspects of their education to produce a useful solution to an engineering problem.
- Students create and apply engineering models in the process of stating and solving an engineering problem.
- Graduate student mentors lead a team to complete an engineering design project.

As a learning outcome for a senior design project (and a Master's thesis), the second one above is the most important.

Understanding the distribution system

The technical aspects of the project consisted of several tasks. First, to characterize the microgrid, it is necessary to identify energy resources and critical loads, obtain network data, and collect historical generation and load resource data. A microgrid, as defined earlier in this paper, is a controlled, coordinated unit within recognizable boundaries, not merely a piece, planned or random, of a distribution system with distributed energy resources (DER). [1] In the case at hand, the largest city between Minneapolis and Seattle along the northern tier of states plans to establish an urban microgrid downtown to serve critical loads during emergencies. Hydropower has served as the reason for inhabiting this location since the dawn of Native American cultures. Two hydroelectric turbines, already operating for nearly a century, sit along the continent's second largest natural urban waterfall. Within the downtown core, existing and planned photovoltaic arrays nearly match the energy capacity of the hydroelectric generators. Normally, hydroelectric generators on the Columbia River provide most of the city's power through a long 500kV line. Possible interruption of this line's electrical power flow, as happened in December 1996 and recently in November 2015, creates an incentive for an urban microgrid. A 115kV distribution loop and a set of substations, as illustrated in Figure 1, serve downtown electrical demand. Breakers B1, B7, B8, and B13 delineate an urban microgrid. [2]

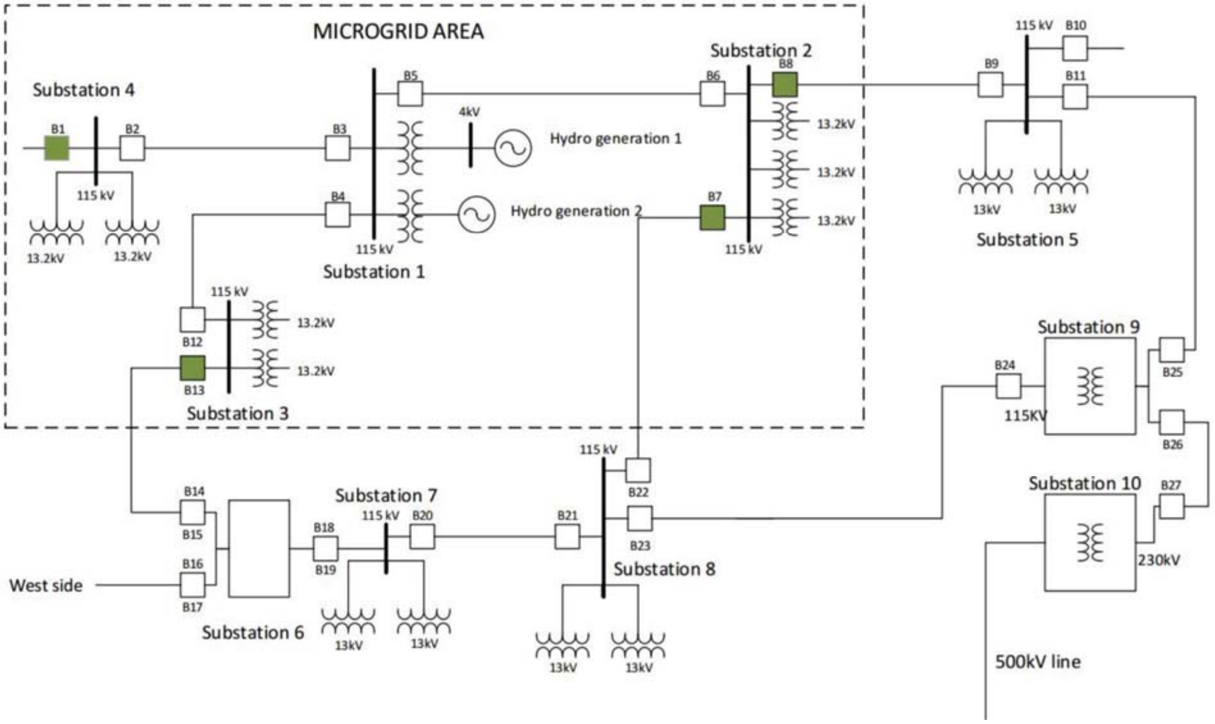

Figure 1. Downtown Electrical Distribution Loop

Within the city, there is no dam for water and hence, no economical energy storage. River flow rates are remarkably consistent with the yearly rotation of the seasons since recordkeeping began in 1891. Flow is more than ten times greater in the spring months of April, May, and June than in the autumn months of August, September, and October. Solar radiation is likewise consistently seasonal, being nearly ten times greater in May through September than in November through February.[17] This pattern of renewable energy maxima and minima presents an imperfect opportunity for balancing energy resources by season as shown in Figure 2.

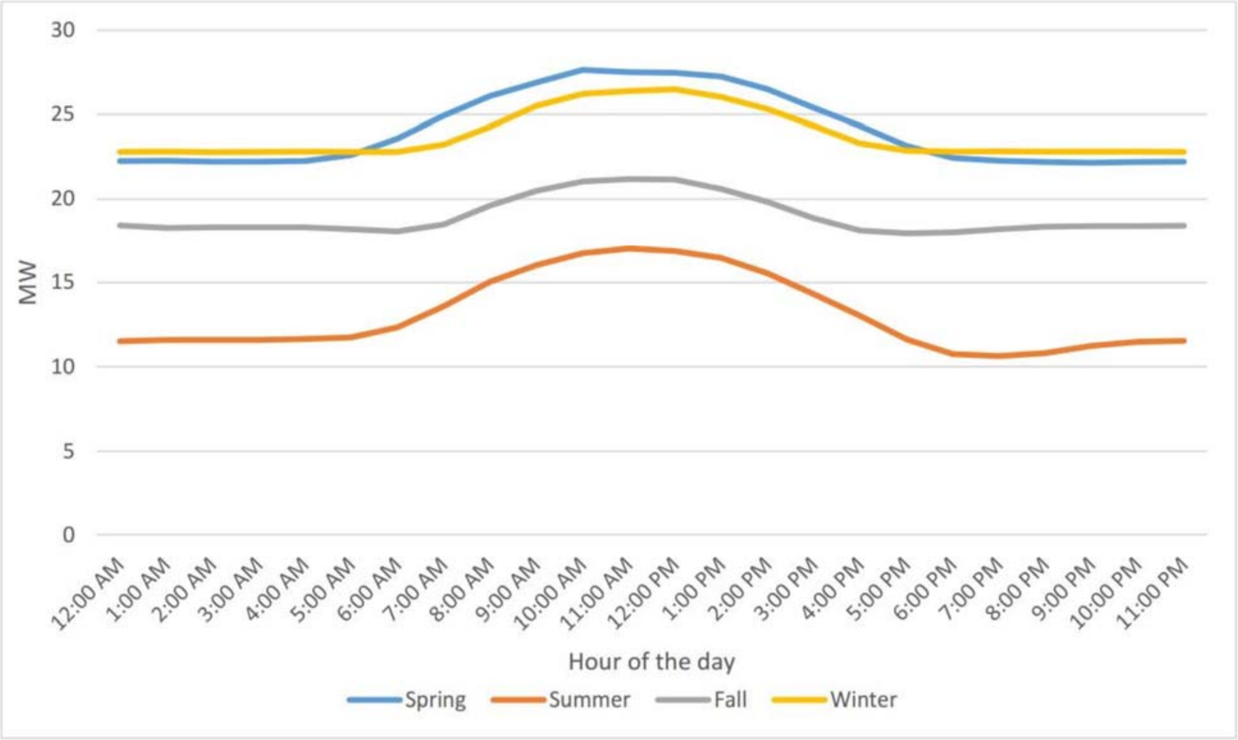

Figure 2. Combined Hydroelectric and Solar Energy Capacity by Season and Time of Day

There are nine critical loads within the downtown microgrid area, such as hospitals, jails and police stations, government buildings at every level, emergency communications, public utility control and dispatching, etc. Metering data for each load dates back to when each was created. Three years' data sufficiently characterizes each load. All have their own switchgear on site and are remotely controlled. All nine loads show similar seasonal and daily characteristics with strong summer and afternoon peaks. The public utility installed vanadium flow batteries for energy storage in locations outside the downtown area. Performance of those batteries may soon lead to another installation nearby. Even then, the public utility can only afford to store about 1.5MWh of energy capacity with a peak response of about 1.5MW of power. [2]

Modeling the microgrid

The second task is to create a validated model of the microgrid. Appropriate models exist for each element of the microgrid but in different simulation packages. Generator and transmission line models are in PowerWorld® as part of the larger Western Electricity Coordinating Council (WECC) transmission model [18]. Most of the local distribution network is modeled in

SynerGEE® [19]. Though tedious to do so, this SynerGEE® section was converted to PowerWorld®, producing a unified PowerWorld® model [18,19]. This became the most time-consuming portion of the project.

Most of the critical loads are at the ends of distribution lines. Feeders that supply higher priority loads also have many lower priority loads as well. Some switchgear in appropriate places can isolate and serve higher priority loads, but additional switchgear will be necessary to reduce distribution to higher priority loads alone. As such, the model must include the influence of lower priority but difficult to shed loads.

Models for individual elements are of the standard variety. Lines are modeled as impedances with values known to the electric utility. One of the two generators has known models derived from testing during the most recent maintenance interval. These models include the machine itself, its exciter, its governor, and its connections to the grid. The other generator's parameters are not known. A complete set of estimates were adapted from known parameters of other, similar generators within the public utility's territory. Frequency control is by droop methods.

Transformers have standard models, including tap changers. [2] PowerWorld® uses a CBEST model for batteries [2]. Constant power models are assigned in PowerWorld® for all loads. Loads are priority designated by number from one (highest) to nine (lowest). Loads are aggregated as much as possible to simplify the analysis. More than one feeder supplies each critical load. Sometimes, a load may be recalculated if a feeder that supplies it goes out of service. A final PowerWorld® model is shown in Figure 3.

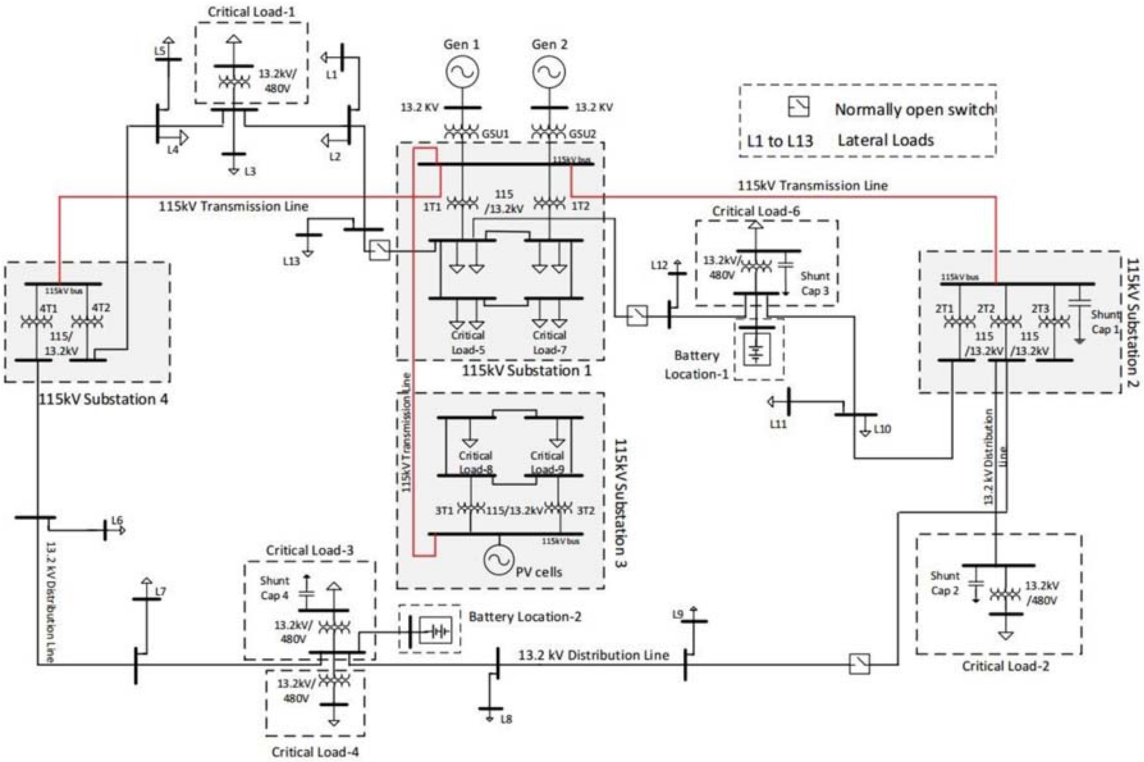

Figure 3. Final PowerWorld® Model of Microgrid

To establish the microgrid's steady state feasibility, the third task is to perform PowerWorld® simulation using the models as described. Historical data from the past three years enables creation of operating specifications. It quickly became obvious that not all loads may be supplied all the time. Loads must be scheduled for shedding or reclosing based on their own demand and on available generation. Generation that depends on river flow varies significantly by season. Photovoltaic generation varies by season and time of day. Loads have priority based on time of day and to the degree that they are deemed "essential". Available generation always falls short of critical load demand. This shortfall is greater in the summer. Battery storage could make up some of the shortfall, discharging during peak demand times during the day and recharging near sunrise and sunset. For two seasons, Figure 4 shows the use of generation, load shedding, and storage to meet demand [2].

Steady state stability analysis performed within PowerWorld® shows that appropriate load shedding and capacitor placement in coordination with available generation maintains system steady state stability. This is true in all four seasons. Only different loads are shed in each season.

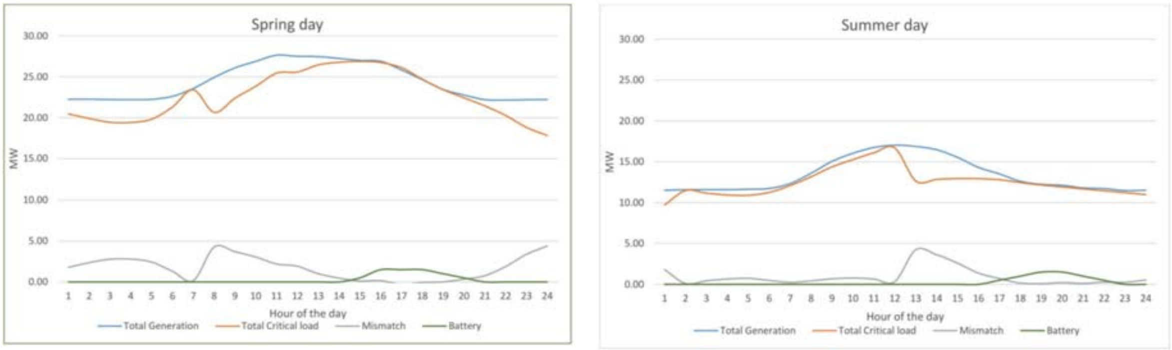

Figure 4. Comparing Load and Generation, Spring and Summer including Load Shedding

Master control technology and its adaptation to microgrid control techniques were studied. Voltage magnitude and frequency are fundamental to master control of a microgrid [2]. Based on those results, the team developed voltage and frequency control schemes for centralized and decentralized control of the microgrid. The results are in [2] and will be the subject of a future paper.

Academic and pedagogical methods

Under the mentorship of the graduate students, the team created appropriate models as described in the technical sections of this paper. Methods of forming teams, mentoring and advising their projects, and of evaluating their progress are in accordance with practices and standards for the University of Idaho.[26,27] All team members were already familiar with Matlab®, Simulink®, and PowerWorld® from their coursework. At the six-week point in the first semester, the team gave a poster presentation showing the definition of their project and a preliminary outline of a solution to the problems that they had defined. At the ten-week point, the team gave a formal oral technical presentation of their project definition, organization, modeling, and their proposed solution methods. Sponsors, professors and peers were invited to give feedback. Their progress was evident and encouraging. The sponsors were impressed with the team's progress. At the end of the first semester, the team appeared to be on track. The team was functioning as a team. That is, in itself, an accomplishment. Other teams without graduate student mentors were not so well along, either technical progress or for working together. The students defined the project well and their solution outline made sense. The students recommended that the project be reduced in scope from its initial statement. The team had coordinated the revised scope with the industry sponsor. Their recommendation was adopted.

Models were of the conventional and effective sort as defined already in detail in the technical sections of this paper. The students had begun simulations of some of the models and had already achieved some promising initial technical results. It was clear that they had brought their knowledge and skills from several places within their education and experience to define a working, competent model of the system at hand and to outline a proposed solution to the problem of creating a microgrid.

However, the sponsor had not provided appropriately formatted data for modeling the main part of the electrical utility system at hand. Their data was in both SynerGEE®, for those parts of the system not within the downtown core, and in PowerWorld® for the main downtown core. The sponsor wanted an interactive model. That meant everything formatted for the same software. It was early second semester before the team finally accomplished that task. This eventually turned out to be one of the project's greatest technical achievements: creating a way to efficiently restructure data that is originally in SynerGEE® into a whole system stated in PowerWorld®. The team had successfully used their modeling tools to adapt existing but difficult to use information into a form that all team members could use in their modeling work. The team designed a solution within a complex system to meet a specific client need. They had done it by bringing their skills in power engineering, data structures, knowledge of the two software packages (learning SynerGEE® and applying their already strong knowledge of PowerWorld®), and their skills in client interface. They did it with the graduate student's guidance and leadership and the team's hard work.

In the second semester, the team pushed forward to organize and model the generation inputs of both types: hydrdoelectric and photovoltaic. Hydroelectric resources were well defined, but photovoltaic resources were not. They organized hydroelectric resources by season, time of day, and load demand. They used projections gathered from the National Renewable Energy Laboratory to create a model predicting reasonable levels of solar energy generation [17]. By their second design review seven weeks into the semester, their project was on track to provide what the customer expected as deliverables.

At the eleventh week in the semester, they presented another poster describing their progress. They had overcome the software problems well enough to identify two "show stopper" issues in the power grid structure. The first problem was that the downtown grid had too few automated circuit breakers to enable sufficiently fine division of loads into a desired prioritized list. They proposed delaying that to the next year's project. The sponsor approved this and eventually hired a consulting firm to create a new concept of the loads' organization. The second problem they solved with their own initiative. Hospital backup generators were not compatible with the microgrid concept. This denied the microgrid a strong third source of generation. The students found the manufacturers of those backup generators and, in coordination with those manufacturers and their technical data, the students specified equipment that would enable those generators to join the microgrid. They had learned how to address a problem like this during their first semester when encountering the data incompatibility issue. With their graduate student mentor providing guidance, they now applied the skills learned then to this new problem of enabling backup generators. With appropriate coordination in the design process, the students provided the technical details of their solution to the sponsoring public utility and to the customers, two local hospitals. Solving these two problems was a strong validation of this paper's stated learning outcomes for the project and the two-semester course sequence.

The students' final presentations were twofold in scope: Two written reports and two oral presentations before a technical audience that included executives and engineers of their sponsor, their professors, and their peers. The team made two written presentations in the form of a written project report by the undergraduates [15] and a thesis by each graduate student [2,10]. The sponsor replied that all written reports met expectations and provided the sponsor with strong basis for further funding of follow-on projects. One oral presentation was the undergraduate students' final oral project report. The other presentation was the team's final project report at the sponsor's headquarters in Spokane, Washington. These were likewise received as satisfactory by academic and industry reviewers.

Upon completion of their two-semester senior capstone project, the undergraduates received their baccalaureate degree and, a few months later, the graduate students completed the project for their theses [2,10]. In this project, as in its predecessor projects administered in this framework, the results have consistently been a somewhat greater set of accomplishments for the graduate students than their peers and a definitely greater attractiveness in the job market for the undergraduates above their peers. Specific outcomes as presented earlier in this paper were verified by a combined audience of sponsors, professors, peers, and the students themselves.

Sponsors' Perspective

This work was sponsored by a grant from Avista® Utilities, the public electrical utility headquartered in the same city. With the approval of the state Public Utilities Commission, the utility established an educational research grant program in 2015 to encourage the state's universities to adapt emerging technology to improve service and price to the ratepayers within five years of a given project. Such a grant program is definitely unique for this several-state region. To date, nearly a dozen projects have provided technology that has benefited the ratepayers, as required in this research and education program's charter. Topics similar to the project at hand have included the following:

- the emergency microgrid at hand, [14,15]
- reconfiguring distribution networks as hybrids of public utility and renewable generation, [20]
- automatic generation control, [21]
- creating a transactional energy distribution system at the retail level. [22]

This project, like several projects of a similar nature, was administered in a manner described in the educational paper of 2008 [3]. An external sponsor, in this case a public electrical utility, provides funding for equipment and for one or two graduate students. These graduate students serve on a typical research assistantship to enable them to afford to undertake their studies. A team of three undergraduates, seniors in their final year of study, were assigned to this project as their senior capstone design project. The undergraduates performed much of the modeling and analysis under the supervision of the graduate students. The utility's interest is in identifying new technologies that benefit the ratepayers, as mentioned already in this paper, and in identifying students who will be promising young engineers within their company. The success rate of undergraduates in obtaining job offers is quite high among who perform well in these sponsored projects.

Deliverables included a working model of the downtown microgrid in steady state operation and written and oral reports to the public electrical utility. From the point of view of the utility, the project was successful. The sponsor received a plan for a downtown microgrid of such quality that they were then confident enough to fund follow-on work with greater resources through their private consultant firms. This may not seem significant on its face, but any academic person who has ever worked with industry knows from experience that funding a follow-on project with greater funding levels is a strong vote of confidence in the work that has been completed, in its findings, and in its recommendations for the next steps in the work.

Summary of assessments

As described in the previous section, the project achieved the given pedagogical outcomes. Its structure, provided by the paper of 2008 and reinforced by projects over the following decade as described, provided a framework for this project's success. Each review or presentation in a fixed structure provided evidence of project ongoing success. The students achieved their learning outcomes through appropriate faculty and graduate student mentoring, bringing their own skill sets to bear on a complicated problem, and finding a useful solution. They identified the next round of projects to follow on, itself a strong indicator that the learning outcomes had been achieved. Sponsors, faculty, peers, and the students themselves all described the outcomes as achieved and successful. The public utility funded follow-on projects, quite a vote of confidence. The projects that were funded were those that the students recommended. The (now ongoing) next project consolidates development of both this project and a concurrently designed microgrid in a neighboring district within the city's center. The strength of the students' work was directly responsible for advancing this project to the next stage, in the opinion of the sponsor, faculty, and students.

The graduate students completed the project and wrote both theses [2,10] and two papers [8,23] that were accepted at a national conference in electric power engineering. One thesis was completed shortly after the end of this project. It is considered one of the stronger Masters theses in this subject. In the opinion of the paper reviewers, it documents the issues of microgrids in ways not foreseen previously. He is now employed in an industry that supports the public utilities. His company is the world leader in digital relaying and protection equipment design and manufacturing. All undergraduate students who worked on this project are now employed locally within electrical public utilities and their support industries, such as consulting and electrical distribution and transmission equipment manufacturing. There was no shortage of job offers for any of the students.

Conclusions

This paper describes a student project performed in the methodology of our 2008 paper [3]. A graduate student mentor led the project with four undergraduate students providing the main portion of the technical work. The students organized an investigation into establishing a microgrid in an urban downtown area. Appropriate boundaries were delineated and the distribution system within those limits and its contents are identified. They created appropriate models and adapted other models. It was a complicated project that they organized well. They discovered problems with modeling and with integration of emergency generators and solved them. They discovered problems with structure of the incumbent grid and arranged for the sponsor to postpone compartmentalizing them. Simulation of the entire microgrid yielded specifications for load shedding because generation could exceed total load demand. Seasonal variations and diurnal cycles were addressed effectively. Cost makes battery storage less than effective. This microgrid was shown to be stable in steady state and quite capable of supplying its critical loads to the degree that this investigation determined. The students met the expected pedagogical outcomes: defining the project well, bringing their resources from several sources in their background to bear on solving a complicated problem, creating and using models well, all under the mentorship of a graduate student. All students have graduated and have found employment within industries closely related to this project. The sponsor has funded follow-on projects using the students' recommendations as primary basis for defining the next round of projects.

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