Design of a microgrid laboratory for electrical power education

Piyush Shukla, Tajrian Akther, Zorica Nedic & Andrew Nafalski

University of South Australia
Adelaide, Australia

ABSTRACT: The focus of the project reported in this article was the carrying out of a technical and economic feasibility study for the design of a microgrid test-bed facility at the University of South Australia (UniSA), in Australia. The designed microgrid meets the electrical and thermal load demands of the building where the test-laboratory facility will be located. Activity for the study was the investigating of various power resources, and comparison of the cost of energy (COE), net present value (NPV) and emissions of the microgrid in three different configurations, i.e. grid-only, islanded-microgrid and parallel to grid operation, all available in modern power systems. The study was carried out with a microgrid simulation tool, HOMER, developed by the National Renewable Energy Laboratory, USA.

INTRODUCTION

Electrical power systems are undergoing a major transformation. Outdated operation and infrastructure are being replaced by new modern equipment to cope with increasing demand and to support modern techniques of power generation and distribution. The modern power grid is equipped with smart sensors and measuring devices, advanced control methods and integrated communication systems; and it is moving from being a centralised to a decentralised power source, with a two-way flow of power.

The power source of a grid is composed of a large number of distributed resources that are connected at the supply, as well as the demand, end. Renewable energy resources are important as society continues toward a non-carbon energy supply. The contribution from renewable energy resources will grow and it is expected to become a critical factor. Electric power companies face challenges in planning and operation, because of the shift of fundamentals that have guided them up to now. Integration of renewable resources into the main grid brings a new set of challenges and problems.

These additions to electrical power systems have profoundly altered the methodologies associated with power system analysis and troubleshooting. These changes in power systems have changed it from being vertically integrated into a distributed system of parts that requires new theories, models and algorithms for electrical power system analysis. As educational institutions include new material on topics, such as smart grids, microgrids, distributed resources, and renewable energy resources the need for a laboratory environment equipped with such educational tools has become apparent, as is the need to train and educate power engineers.

To educate and train electrical engineering students on the principles of modern power systems, a new era power laboratory is required, at any educational establishment. A laboratory of that type should be equipped with incorporated components, such as industrial drive systems and workstations integrated with machines; and have the capacity of carrying out simulations of power generation sources, storage facilities and power electronics in a single facility.

It is essential that this laboratory is practical; operates under industry standards; and have the capacity for provision of hands-on learning experience about the characteristics and attributes of modern power system. A microgrid test-bed facility at the University of South Australia (UniSA) can help students to understand the details of modern power generation and the behaviour of various renewable resources.

As the laboratory is fully computerised and its components interfaced, it will be easy to introduce remote operation, with the collection of vital learning analytics data, such as illustrated by Considine et al for the remote laboratory NetLab [1].

MICROGRIDS

Microgrids are the building blocks of modern power systems and crucial to making the present grids smart and reliable. The idea of a microgrid is not new and the inception of it can be traced back to early networks, which operated independently before they were integrated into national grids. The idea of current microgrids revolves around improving power security and reliability; and includes high renewable penetration. Most of all they should be cost-effective. Microgrids are a possibility, because of the low cost of renewables, power electronics and increasing need for reliable power [2].

A microgrid refers to a distributed energy generation that utilises different technologies, such as fossil fuel generators, photovoltaic cells, fuel cells, wind turbines and energy storage systems. They operate in a controlled way and may or may not be connected to the main grid at a point of common coupling. It is a privately owned network that caters for a local load. Microgrids can operate within a community, village or business. According to the US Department of Energy:

> *…a microgrid is a group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected and islanded modes* [3].

The main components of a microgrid include distributed energy resources, energy storage systems, switching devices, protection, communication and an automation system. Microgrids are effective and reliable as they use a distributed generation approach, where the demand is met through smaller disparate resources, which distribute the impact of any unexpected load evenly, unlike a centralised generation system.

In contrast to a regular power system, microgrids prevent losses in transmission and distribution by adopting a distributed generation scheme, where the generation is in closer proximity to the load. Lastly, the modular approach in a microgrid to power generation makes it customisable to cater to local need. A microgrid is not defined by the number of power sources involved, size or load, but has two key features: it is controlled locally and can function with or without the main grid [4]. Microgrids have a complex control mechanism to control voltages, frequency and reactive power.

LOAD PROFILES AND AVAILABLE RESOURCES

As the microgrid test laboratory facility will be located at UniSA, the microgrid was sized to meet the electrical and heat load requirement of Sir Charles Todd - Building SCT and to export any access power to the University network through the point of common coupling.

From the daily average load profile of the building (Figure 1), it can be seen that the average demand increases in the morning (about 8 to 8:30 am), reaches maximum about 1:00 pm and starts decreasing afterwards. The load profile of the building is typical of any small business, with most consumption during working hours and minimum during non-working hours. From the load data obtained, the average load of the building was found to be 32.39 kW with a peak load of 99 kW and an average daily consumption of 777.36 kWh/day.

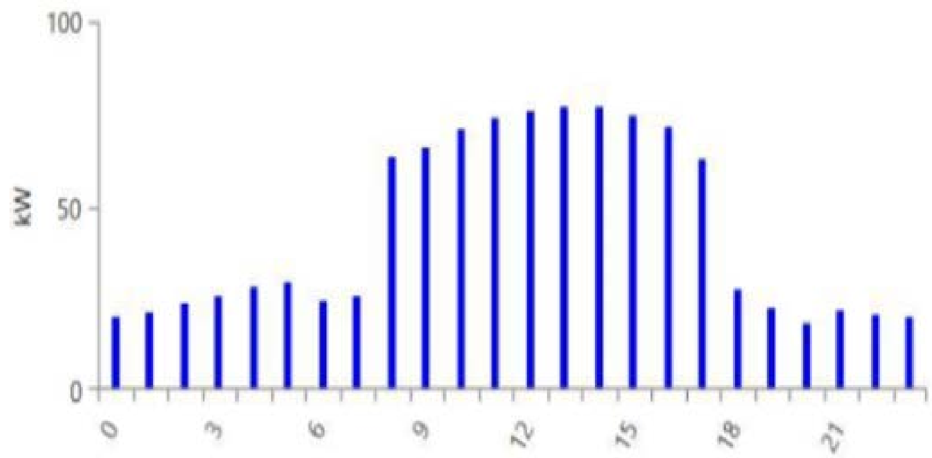

Figure 1: Electrical load profile.

The thermal load in the building comprises mostly space heating (for offices, study rooms, classrooms, and so on) and hot water usage. As the thermal load data for the building was unavailable, a synthetic thermal load profile was generated based on the average load consumption of 100.92 kW and a peak consumption of 316.56 kW. These figures were auto generated in hybrid optimisation of multiple *electric* renewables (HOMER), based on a commercial-size building. Since the thermal load will be consistent in every scenario, these figures were accepted as per HOMER Energy [5].

One of the main considerations before proposing photovoltaic (PV) or wind energy generators as part of hybrid power generation was an investigation of the site profile to ensure availability of renewable resource. To ensure viability of a PV system, solar irradiance data for the University campus was downloaded from NASA's surface meteorology and solar energy database [6]. The annual average in kWh/m^2/day, referred to as peak sun hours or PSH, was found to be 4.64 with maximum occurring in January at 6.85 and minimum during the month of June at 2.31.

For the wind part of the system, historical meteorological wind data were investigated to ensure sufficient availability of wind power to justify the installation of wind turbines. The data downloaded from the NASA surface meteorology and solar energy database showed that for most months the average wind speed was above 6 m/s, and the annual average wind speed was found to be 5.90 m/sec. Both wind and solar data indicate that these resources are viable for power generation.

SYSTEMS COMPONENTS AND MODELLING

Conventional generators provide reliability for a hybrid system. These generators provide energy when intermittent resources are either not available or are unable to keep up with the demand, because they are not dependent upon unpredictable natural conditions. Other than providing reliable uninterrupted energy, these generators also provide a mechanical inertia to the system and have fast response to any load variation.

To extract maximum energy from a fossil fuel generator, a combined heat and power generation unit, commonly known as a Cogen (cogeneration) unit can be used. The overall efficiency of a combined heat and power unit can be 65-80% [6]. As the Cogen unit will form the base of this microgrid and will serve as the last resort (in off-grid mode), when none of the intermittent resources is available, it was sized to meet the peak load requirement of the building.

From the list of generators available in the HOMER Genset catalogue, a 125 kW Cummins 125GGHJ was selected to be able to serve as a Cogen generator. It was modelled with a heat recovery ratio of 60%. As the Cogen has natural gas as a fuel source, the average price of gas for industrial customers (including transmission) for Australia was taken from a study done by the Australian government [7][8]. The average gas price was found to be $8/GJ or 30.31 cents/m^3 and this price was used in the simulations [8]. The price of the Cogen unit was estimated at $350,000 [9].

A 50 kW PV system was modelled using Sun Power E20-327 modules. These modules have a factory-integrated microinverter that enables module level DC to AC conversion. Microinverters can reduce the effect of shading and dust on system performance. The total price of the PV system was estimated as $80,000 [10].

The selection of wind turbines (each with a converter to be connected to the AC bus of the microgrid) in the HOMER menu included three AWS HC HAWT (horizontal) each rated at 3.3 kW and four AWS VAWT (vertical) each rated at 1.5 kW. This makes the combined capacity of the wind farm 15.9 kW. These turbines were chosen, because of their lower cut-in speed (2.7 m/s for the HAWT and 3.1 m/s for the VAWT) and smaller turbine diameter (4.65 m for the HAWT and 3.2 m for the VAWT), which makes them campus-friendly.

To provide a solution to cope with the fluctuation from other power sources and variable load, Tesla Powerwall 2 batteries were included in the model. These batteries feature a fully integrated AC battery system for residential and commercial use [11]. Key parameters for modelling the system in the software, HOMER, are shown in Table 1 and the system model is shown in Figure 2.

Table 1: Key modelling parameters.

Component	Investment ($)	Rating	Lifetime	O & M ($)
CHP-Genset	350,000	125 kW	60,000 hours	2/hour
PV-System	80,000	50 kW	25 years	1,000/year
HAWT	24,750	9.9 kW	20 years	200/year
VAWT	15,000	6 kW	20 years	200/year
Batteries	87,000	132 kWh	10 years	n/a

As the trend in society continues towards a no-carbon energy supply, the contribution of variable renewable energy resources will grow and is expected to become critical. Energy generation from conventional resources is not a sustainable choice, both economically and environmentally.

As every microgrid is unique, optimal solutions will differ and will depend on the flexibility of the grid, because of the generation mix. An investigation for this project was the feasibility of a hybrid renewable energy laboratory for the UniSA Mawson Lakes campus. With the grid-only cost of energy (COE) assumed as $0.20/kWh, the COE for the islanded-microgrid was found as $0.25/kWh and $0.26/kWh for the grid-connected microgrid. Although the COE for the grid-only scenario was the lowest in this study, the cleaner energy provided by the microgrid coupled with reliable interruption free power for the building can easily outweigh the extra cost.

Simulations show that a microgrid can not only easily replace a grid, but can be cost effective by providing clean energy over time. A microgrid also operates best with different resources and minimising the load on one centralised resource.

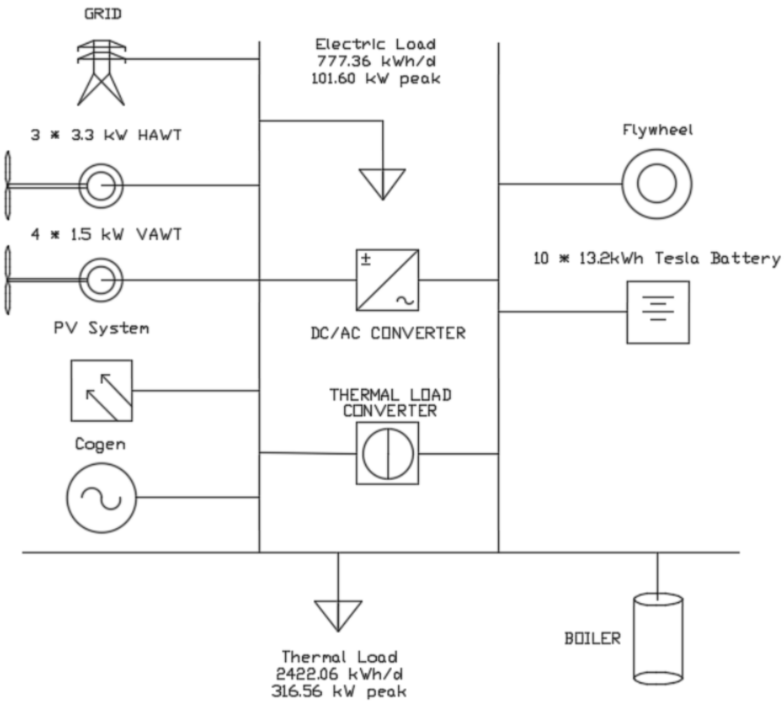

Figure 2: The microgrid model in HOMER.

RESULTS AND DISCUSSION

Provided in Table 2 is an overview of the simulation results for the three scenarios: grid only; islanded microgrid; and grid-connected microgrid. Although cost of energy was found lowest for grid-only connection and was very close for the islanded and grid-connected microgrid scenarios, any increase in the electricity charges could change that. If the electricity prices increase by $0.05, that will be the breakeven point (assuming all other costs remain the same) making the microgrid a more viable option.

Table 2: Comparison of contribution from various sources to meet the electrical load.

Components	Grid only (%)	Islanded microgrid (%)	Grid-connected microgrid (%)
50 kW solar panels	n/a	25.70	27.80
125 kW CHP	n/a	64.60	8.80
9.9 kW HAWT	n/a	7.08	7.57
6 kW VAWT	n/a	2.62	2.83
Grid purchases	100.00	n/a	53.00
Total	100.00	100.00	100.00

Load of the boiler was met solely by the power purchased from the grid in the grid-only scenario. The islanded microgrid the combined heat and power (CHP) generator contributed to almost 35% of the total load (see Table 3); that is 35% of the heat that would have else escaped or lost if it was not recovered by the CHP unit. This justifies the installation of the CHP unit and making the most of the fuel. As in the case of electrical load, the CHP unit did not make much contribution in the grid-connected microgrid towards the thermal load, because it was cheaper to buy the required electricity from the grid and run the boiler.

Table 3: Comparison of contribution from various components to meet the thermal load.

Components	Grid only (%)	Islanded microgrid (%)	Grid-connected microgrid (%)
125 kW CHP	n / a	34.20	4.99
Boiler	100.00	65.80	95.10
Total	100.00	100.00	100.00

Lowest carbon emissions or total emissions were observed for the islanded-microgrid configuration (Table 4). The natural gas generator used for CHP generation was the deciding factor in emissions comparison. Even though the CHP unit was operating continuously, the efficiency of it was far better than electricity bought from the grid, which led to lesser emissions in the case of the islanded microgrid.

Table 4: Comparison of annual emissions.

Emission types (kg/yr)	Grid only	Islanded microgrid	Grid-connected microgrid
Carbon dioxide	383,728	288,763	308,515
Carbon monoxide	0	479	64.1
Unburned hydrocarbons	0	0	0
Particulate matter	0	13.5	1.81
Sulfur dioxide	777	0	412
Nitrogen oxides	380	1,006	336
Total emissions	384,885	290,262	309,329

Although carbon-taxes or penalties were not considered in the modelling, it would have made a significant difference in bringing down the net present cost and cost of energy in the islanded microgrid case as a result of lesser emissions. Additional emissions that were noticed due to the generator, were carbon monoxide, particulate matter and nitrogen oxides, which were not present in the grid-only simulation results. This will need further investigation as to how harmful these emissions are and how they can be controlled.

IMPLICATIONS FOR ENGINEERING EDUCATION

As mentioned in the introduction, power systems have had major transformation, incorporating more and more components of modern hardware, control, measurement, telecommunication and computer systems. All this happens with an amalgamation of traditional and renewable power sources, and their increasing presence in dispersed locations, linked or isolated from the main grid. Consequently, if new power engineering graduates are to be employable, they need to develop knowledge and skills in this new and fast-developing field of renewable energy sources, and their integration and management, as well as smart-grid technologies.

For smart-grid engineering, the present educational requirements include a broad range of disciplines to be mastered, both theoretically and practically. These include: automatic control, power electronics, computer engineering, telecommunications, system theory, energy conversion, signal processing, transmission and distribution of energy, and engineering physics. Non-technical skills include marketing and economics, public policy and standards [12].

Teaching smart-grid technologies is much more demanding than teaching traditional power systems. The teaching must include how to integrate many new technologies and how to manage uncertainties in scheduling intermittent renewable energy sources within the requirements of the so-called *legacy* conventional power systems. This includes the comprehensive protection system developed over the past century that is based on different principles, which brings more uncertainty into the performance and controls of modern power systems that include a high penetration of the renewable sources [12][13].

There are many examples of universities upgrading curricula and laboratories to support the teaching of microgrid and modern power system technologies [12-16]. A strategy of upgrading a traditional power laboratory to teach smart micro-grids is outlined by Gaouda et al [13]. This will lead to the enhancement of students' hands-on skills in the process of migrating from teaching only traditional power systems to the integration of smart-grids within the existing power grid. The integrated solution of the smart-grid requires teaching topics, such as cyber security and the vulnerabilities of infrastructure, such as devices and systems connected to the Internet.

The hands-on microgrid laboratory of Patrascu et al [14] is a good platform for educating electrical power engineers [15]. It allows students to vary parameters of traditional and renewable energy sources and to evaluate different energy sources, power converters, loads and energy storage elements. Educational institutions are modifying electrical engineering programmes and courses, giving more focus to the implementation of smart-grid technology. New developments are placed in the context of discussions of the social, economic and environmental implications of the new technologies.

An interactive platform to assess advanced distribution automation (ADA), with applications and solutions is presented by Celeita et al [16]. In the paper, comprehensive student feedback is proffered on using a smart grid flexibility to link theory with practice, enhance the learning outcomes and encourage class innovation. Student evaluation in regard to microgrid laboratory solutions on a five-parameter model reveal that the two most chosen and growing over the years are flexibility and realism, followed by faster development time and lower risks and costs.

In the laboratory design presented in this article, students will benefit from the physical nature and direct hands-on access to a microgrid and will understand the limitations of computer simulation programs. Simulation programs are more cost-effective than operating a physical laboratory facility, but do not provide a good physical understanding and actual testing.

As the power resources in the laboratory will include renewable resources, such as PV, wind turbines and fuel cells along with traditional power generation sources, such as a generator, the situation will expose future engineers to all the technologies, their interaction with one another, and it will introduce protection and control of every element.

CONCLUSIONS

As the world continues towards a no-carbon energy supply, the contribution of renewable energy resources will grow and is expected to become critical. It is evident that energy generation from conventional resources is not a sustainable choice, both economically and environmentally.

As every microgrid is unique, optimal solutions will differ, because of the generation mix and will depend upon the flexibility of the grid. The study for this project was an investigation of the feasibility of a hybrid renewable energy laboratory at the University of South Australia. With the grid-only cost of energy (COE) assumed as $0.20/kWh, the COE for the islanded-microgrid was $0.25/kWh and $0.26/kWh for the grid-connected microgrid. Although the COE for the grid-only scenario was found cheapest in this study, the cleaner energy provided by the microgrid coupled with reliable interruption-free power for the building can outweigh the extra cost.

The simulations show that a microgrid can replace a grid and can be cost effective by providing clean energy over time. A microgrid also operates best using different resources and minimising the load on one centralised resource.

This investigation of the technical and economic performance of the proposed microgrid laboratory provides confidence that the laboratory running on a university campus will not only serve as an example of a microgrid, but also as a hands-on educational environment. It is to be seen if funding will be provided for such a laboratory, because power laboratories of this scale prove costly. However, if it comes to fruition, future graduates will acquire knowledge and skills that will be of high importance for their work in a modern power engineering industry.

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