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Wollongong University Laboratory Microgrid: A Design for Flexibility

Craig G. McLauchlan
University of Wollongong, cmclauch@uow.edu.au

Jason R. David
University of Wollongong, jasond@uow.edu.au

Duane A. Robinson
University of Wollongong, duane@uow.edu.au

Sean T. Elphick
University of Wollongong, elpho@uow.edu.au

Jonathan Knott
University of Wollongong, jknott@uow.edu.au

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Abstract

Microgrids are becoming increasingly important to electrical power distribution. They offer the possibility of increased reliability and lower power costs for both customers and network operators, however there are significant challenges that must be addressed before this potential can be realised. Laboratory experimentation where concepts can meet with real world complexities in a controlled environment is a crucial part of meeting these challenges. The design and implementation of a useful laboratory microgrid is a complex and expensive process and to be successful it must be done with care. This process was recently undertaken at the University of Wollongong, and the key features of the microgrid design are described within this paper along with proposed experiments to be undertaken in the near future.

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Wollongong University Laboratory Microgrid: a Design for Flexibility

Craig McLauchlan*, Jason David†, Duane Robinson*, Sean Elphick† and Jonathan Knott‡
*Sustainable Buildings Research Centre
†Australian Power Quality and Reliability Centre
‡Institute for Superconducting and Electronic Materials
University of Wollongong, Australia
cmclauch@uow.edu.au, jasond@uow.edu.au, duane@uow.edu.au, elpho@uow.edu.au, jknott@uow.edu.au

***Abstract*—Microgrids are becoming increasingly important to electrical power distribution. They offer the possibility of increased reliability and lower power costs for both customers and network operators, however there are significant challenges that must be addressed before this potential can be realised. Laboratory experimentation where concepts can meet with real world complexities in a controlled environment is a crucial part of meeting these challenges. The design and implementation of a useful laboratory microgrid is a complex and expensive process and to be successful it must be done with care. This process was recently undertaken at the University of Wollongong, and the key features of the microgrid design are described within this paper along with proposed experiments to be undertaken in the near future.**

***Index Terms*—Microgrids, Test facilities, Laboratories**

I. Introduction

A. What is a microgrid?

Microgrids are networks of small, distributed electrical power generators operated as a collective unit [1], [2]. They consist of a collection of localised generation, loads, control architecture and hardware, resulting in a miniaturised distribution grid. Microgrids can be contained within a single building, spread across several buildings or implemented as a precinct. The end result is an energy supply system with the ability to choreograph its own generation, demand and energy storage which in many cases, is fully capable of islanding itself from the wider electricity distribution network. Ultimately a microgrid may be considered as a highly efficient, often renewable energy dense, network connection capable of providing complex support to the electricity supply network.

B. Benefits of microgrids

Microgrids can be considered as one of the key building blocks of truly smart grids. There are significant advantages to be gained through the proper integration of microgrids into existing electricity supply networks for both customers and the network operators [3]. Microgrids offer customers the ability to reduce operating costs and carbon emissions whilst potentially increasing power quality and reliability. For network operators microgrids can significantly simplify downstream loads and even provide network support if the correct infrastructure and control systems are in place. Consequently, microgrids have the potential to become a network asset able to relieve network congestion, aid restoration, and improve reliability, resilience and efficiency. One of the major benefits of microgrids is that they can offer deferment of highly expensive network upgrades or augmentations.

Microgrids also offer potential benefits with respect to power quality if they can be implemented in an intelligent manner. In particular, the use of power-electronics-interfaced generation provides potential for improved mitigation of power system disturbances. Four quadrant inverter systems can be sources and sinks of reactive power and hence provide network support. In addition, smart inverters may be able to act as quasi-active filters, allowing for mitigation of harmonic distortion and voltage unbalance. When energy storage is included, microgrids also offer the potential to operate as uninterruptible power supplies, resulting in improvements in power supply reliability.

C. Microgrid experimentation to meet challenges of future networks

There are many challenges to implementing the networks of the future [4], [5]. These networks will need to be flexible enough to integrate a wide number of generating sources while maintaining adequate reliability and quality of supply. Addressing these challenges requires a range of approaches - ranging from the theoretical to the applied. These approaches are a continuum between desktop studies and simulations through to full scale field trials. Laboratory scale microgrid experimentation, which is the focus of this paper, forms a vital intermediate step between desktop studies and simulations and full-scale field trials. Laboratory-scale microgrid experimentation allows theoretical concepts to meet with real-world complexities in a controlled environment. This provides the opportunity to identify and solve issues where the cost and risk preclude this from being done at full-scale on the grid.

The changing electricity supply paradigm at distribution level - from centralised, often fossil fuel powered generation, and one way power flow, to supply from renewable energy technologies and high penetration of dispersed generation - is leading to many technical and economic challenges for both the distribution network operators and customers. From the distribution network operator perspective these challenges include:

- *Bi-directional power flows*: The most significant impact of reverse power flow in distribution systems designed for one way power flow is typically voltage rise. Increased voltage levels can have adverse impacts on customer equipment and in many cases cause tripping of solar photovoltaic (PV) inverters [6]. In certain cases, there also may be some impacts on protection systems due to reverse power flow.
- *Modelling (beyond a balanced system)*: Modelling of the complex technologies (e.g. inverters) associated with renewable energy generators remains an area requiring further work.
- *Low inertia of power electronics interfaced generation*: Low inertia results in potential difficulties with protection and fault ride-through. In the case of protection, the inability of power electronic devices to provide significant fault current can lead to difficulties in detecting faults. This becomes an obvious safety issue. The inability of power electronic devices to ride-through and/or recover after system faults can lead to system stability issues.
- *Uncertainty of renewable-based generation*: The intermittency of some renewable energy generation systems produces considerable difficulties in maintaining system stability and security.
- *Lack of available case studies and industry experience*: As the energy supply mix is evolving rapidly, a deep level of experience and understanding of the operating characteristics and capabilities of new technologies is yet to be achieved.

Challenges from the customer perspective include:

- *Cost of installation*: Although the cost of renewable generation technology and, to a lesser extent, energy storage has fallen in recent years, careful consideration still needs to be given to the cost/benefit ratios and payback periods related to installation of these devices.
- *Logistical challenges*: There can be many logistical challenges related to integration of renewable and distributed technologies. These include adequate space for the devices required and the need for wiring upgrades and retrofits.
- *Control algorithms to be integrated (e.g. to maximise generation usage, provide reliability, minimise cost, etc.)*: In order to best utilise any renewable energy of microgrid type systems, the methodology used for control needs to be carefully considered such that the investment made in the systems leads to outcomes that are superior to those that would be obtained by doing nothing and relying on traditional energy supply systems.
- *Lack of available case studies and industry experience*: Similar to the case for network operators, with new technology, little experience of the advantages and disadvantages exist, thus presenting a risk to first movers.

For both network operators and customers there are a number of fundamental challenges that need to be resolved as the number of microgrids connected to the network increases. These are outlined in [5], some of the more significant of these challenges include:

- *Changing levels of demand*: This requires careful balancing of generation versus load in order to maintain system stability.
- *Changes in probability of interference*: Interruptions or equipment maloperation.
- *Increasing use of advanced distribution automation*: Due to its impact upon the ever-changing distribution network impedance and its interaction with harmonic currents. This is evidenced by increased power electronic interfaced generation shifting network impedance resonances to lower frequencies [7]–[10], which likely leads to increased low-order harmonic voltages causing concern for both network and customer alike in the future.
- *Increased power electronics interfaced generation and load*: Power electronic devices by their very nature can be a source of waveform distortion. If distortion levels are too high, undesirable impacts on equipment may arise.

Some of the above issues are similar to those that have been faced since the early development of modern power networks, while others are new challenges that require innovative thinking and approaches.

The electricity distribution system of the future will likely be a large collection of devices operated by algorithms driven by a mixture of imperatives, with resulting complex behaviour [11]. Fundamentally, there are three main concerns that will shape these algorithms: economic, environmental and technical, as shown in Table I. Devices at various levels and locations throughout the grid will execute algorithms that variously aim to save money, maximise use of renewables, provide reliable supply or optimise for other parameters.

TABLE I
CONCERNS DRIVING CONTROL ALGORITHM OBJECTIVES

Economic	**Environmental**	**Technical**
Maximise energy saved	Maximise use of onsite generation	Operate to protect the battery
Maximise money saved (time of use charges)	Maintain acceptable environmental conditions	Operate to ensure battery charge above level to ensure reliability of supply
A weighted combination of these		

The resulting operation of interconnected devices and interacting technologies will be complex, thus it is crucial that control algorithms are developed to properly choreograph the behaviour of an individual device with others on the grid. This will allow it to meet its own imperatives without compromising the grid as a whole. While simulation will be an important step, there are real-world complexities that algorithms must be able to tolerate which cannot feasibly be simulated with confidence. Therefore laboratory-scale microgrid testing facilities like the one described in this paper will be an important tool in developing an understanding of the operating capabilities of microgrids and the algorithms necessary to implement them.

II. DESIGN OF THE MICROGRID

A laboratory microgrid research platform has been developed at the University of Wollongong (UOW) and is located at the Sustainable Buildings Research Centre (SBRC). The UOW facility has been designed to create an environment where testing of equipment and control systems can be undertaken simply with real world complexity at low risk. This has resulted in some key design principles:

- *Flexibility*: The microgrid research platform has been designed to consist of a series of modular components that can be reconfigured to suit a variety of tests with a *plug-and-play* mindset.
- *Authentic when needed*: Some testing will require real world loads and generation, whereas other tests will need precisely known laboratory load and generation. Both are available in the test facility. Where possible industrial and commercial components have been used for authenticity.
- *Accommodation*: All of the components of a real microgrid are available to configure around any Device Under Test (DUT) to simulate a complete microgrid. Any load, generation, protection and automation can be provided to fill in the missing components around a DUT.
- *Measurement*: The microgrid research platform includes a significant amount of inbuilt measurement systems. However, there is also scope for the easy installation of specialist instruments as required.
- *Safety*: The research platform has been designed to facilitate the safe connection of devices during testing.

The UOW Laboratory Microgrid research platform has been designed as a modular system of components that can be configured to suit any test regime. Shown schematically in Fig. 1, the research platform is set up for connection of real world loads and generators in a microgrid environment and is capable of undertaking testing power flows in the order of 30 kVA. The major components within the microgrid test platform and their significant features are as follows (numbering refers to components indicated in Fig. 1):

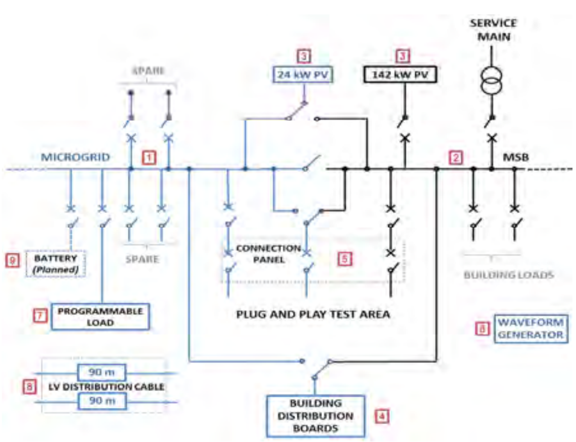

Fig. 1. Schematic representation of the laboratory microgrid at UOW.

Fig. 2. Microgrid switch board (MGB) of laboratory microgrid.

Fig. 3. Main switch board (MSB) of laboratory microgrid.

1) *Microgrid Switchboard (MGB)*: The MGB as shown in Fig. 2 is the heart of the Laboratory Microgrid research platform. It is an LV industrial switchboard with extensive switchable interconnections. These include: portions of the SBRC building PV panels; building Distribution Boards; the Connection Panel (CP) and a bus tie to the SBRC Main Switchboard (MSB). The MGB includes spare connection points, four of these are fitted with 160-250 A adjustable breakers and power meters to be ready to go for testing, and there are a number of spare spaces beyond these. The MGB board is fitted with electrical metering and test points for current and voltage sensing for specialist instrumentation if required.
2) *SBRC Main Switchboard (MSB)*: The MSB shown in Fig. 3 is an LV industrial switchboard connected to the service main that supplies the SBRC Building. It is connected to Building Distribution boards, the majority of the SBRC PV Array and the Connection Panel. It can

Fig. 4. SBRC photovoltaic system.

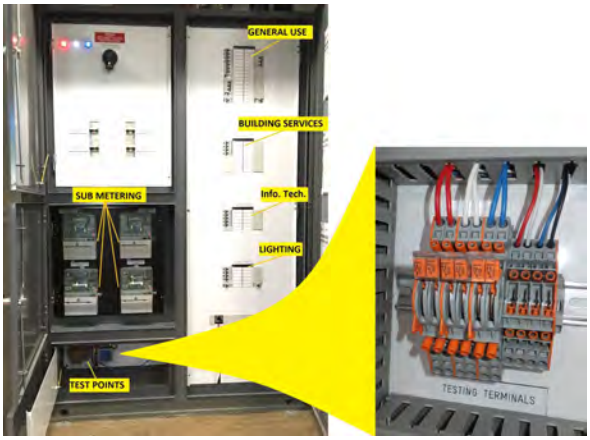

Fig. 5. Building distribution board and test points.

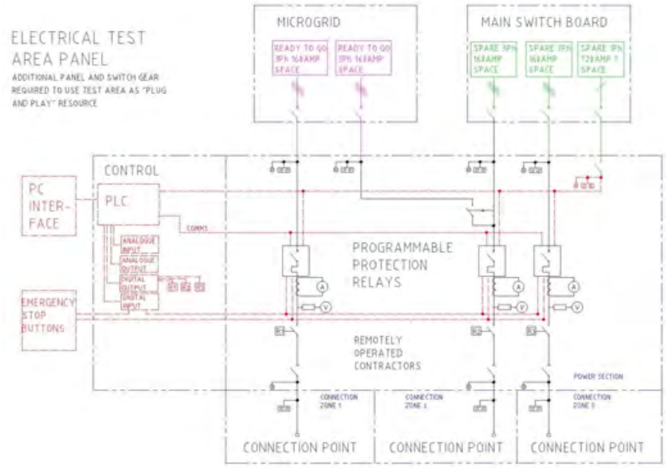

Fig. 7. Schematic representation of the microgrid connection panel.

be interconnected by bus tie to the MGB. The MSB is arranged to connect to whatever load is not connected to the MGB. The MSB includes a number of spare spaces for loads as wells as the same electrical metering and test points as the MGB.

3) *SBRC Photovoltaic Array*: The PV array as shown in Fig. 4 is divided into three sections of 4 kW, 33 kW and 122 kW peak, for flexibility. These can be connected in a variety of configurations between the MSB and MGB.
4) *SBRC Building Distribution Boards*: There are four distribution boards throughout the building, each of which can be supplied by either the MSB or MGB via a changeover switch. Each board is divided and sub metered by end use: lighting; information technology equipment; building services; and general outlets (as shown in Fig. 5). Each board is fitted with the same electrical metering and test points as the MGB.
5) *Connection Panel (CP)*: The CP shown physically in Fig. 6, and schematically in Fig. 7, is an industrial switchboard designed to facilitate easy testing within the microgrid. Its features include:
   - Three connection points, one fed from the MSB, one from the MGB and one switchable between either as shown in Fig. 7. Each connection point is designed for simple isolation, verification and connection. For safety there is both mechanical and electrical interlocking, along with shrouding shown in Fig. 8.
   - A Programmable Logic Controller (PLC) is mounted in the panel complete with spare inputs and outputs (Fig. 9). Each connection point has a dedicated MiCOM P341 Interconnection Protection Relay (Fig. 10). Taken together the PLC and relay allow for the automation and protection components under test.
   - The PLC also operates the CP and Adjustable Load Bank (ALB) (refer below) and is connected to a Human Machine Interface (HMI) panel shown in Fig. 9 and a safety relay.
   - The safety relay is connected to an emergency stop button system and door switches on selected access panel doors to avoid unsafe conditions and allow safe emergency shut down of testing.
6) *30 kVA Fully Regenerative Arbitrary Waveform Generator (AWG)*: The AWG provides precisely controlled accurate bi-directional power flow. This can effectively provide any required waveform, including switch-

Fig. 6. Microgrid plug and play connection panel.

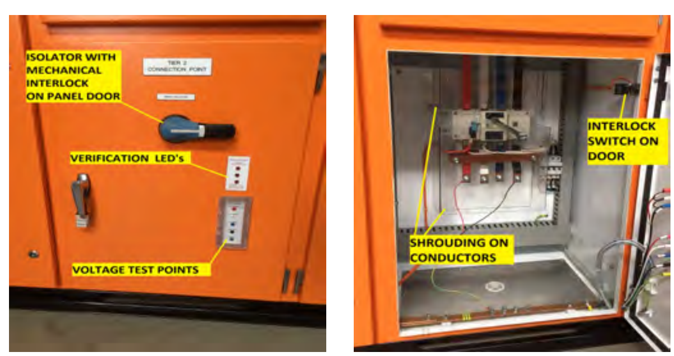

Fig. 8. Microgrid connection panel exterior and internal features.

Fig. 9. CP programmable logic controller and human-machine interface.

Fig. 10. Connection panel protection relay, power meter and test points.

ing transients, harmonic distortion, sags and swells, frequency variation, or simply a high-accuracy, low-distortion ideal supply where necessary for standardised testing. Fig. 11 shows the output of the AWG simulating a 1050 Hz ripple control signal superimposed on the 50 Hz supply. This was used to test for flicker with dimmable LED lighting.

7) *30 kVA Programmable Passive Adjustable Load Bank (ALB)*: The ALB includes resistors, capacitors and inductors as shown in Fig. 12 and schematically in Fig. 13, noting:
   - Components are selectable in increments that can absorb up to 30 kVA of power at a variety of power factors, i.e. up to 30 kW and 27 kVAr either leading or lagging.
   - Components are divided into three sections that can be separated, e.g. by cable, to simulate a distribution feeder with lumped loads at the start, middle and end.

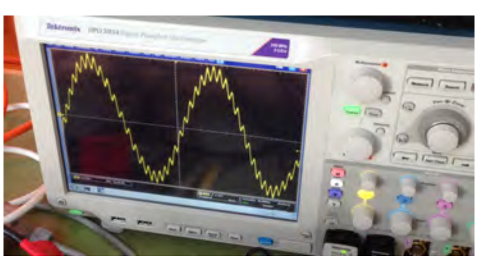

Fig. 11. Waveform generator output - ripple control signal on 50 Hz.

Fig. 12. Adjustable load bank (ALB).

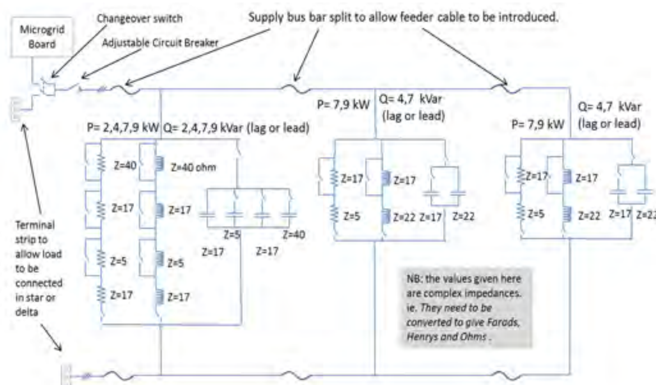

Fig. 13. Schematic representation of the adjustable load bank (ALB).

   - The ALB is connected to the PLC and HMI panel for ease of operation.
   - The ALB is fitted with metering and test points for current and voltage sensing for specialist instrumentation if required.
   - For safety, the ALB is connected to the safety relay in the CP and also has door switch interlocking.

8) *LV Distribution Aerial Bundled Cable (ABC)*: 200 m of LV ABC cable in two sections. This cable allows emulation of an LV feeder using a sample of cable that is deployed in Australian LV Networks.

9) *Battery Energy Storage System*: Battery system of 30 kW/50 kWh capacity is planned and will facilitate experimentation related to performance and integration of energy storage systems.

III. Potential Experimentation with the Microgrid Laboratory Research Platform

The successful completion of UOW's Laboratory Microgrid research platform provides a unique facility for a wide range of experimental testing, e.g. testing of control algorithms for an automatic changeover switch could be set up as shown in Fig. 14.

The specific control objectives can be motivated by a variety of economic, environmental and technical concerns. Different

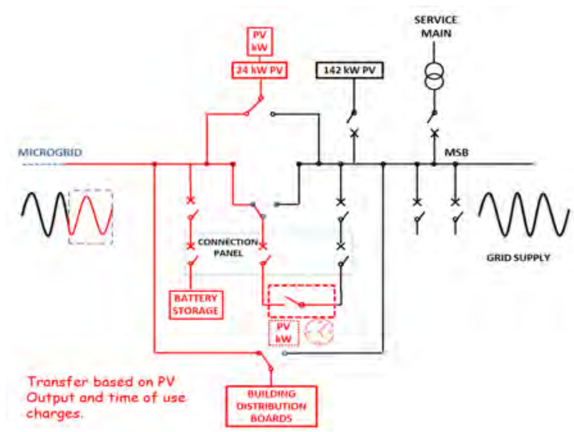

Fig. 14. Microgrid configured for testing of changeover switch control.

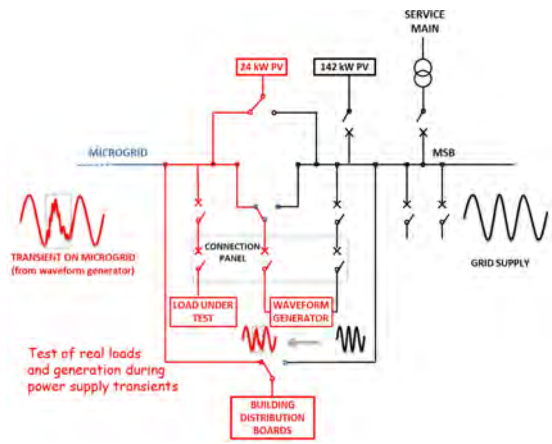

Fig. 15. Microgrid configured for testing impact of PQ issues on equipment.

concerns will result in different control objectives (refer to Table I), which will in turn require a specific experimental setup. Fig. 14 shows testing of a theoretical algorithm that includes a cost function that attempts to find an optimum balance between maximising the output from the PV array, while minimising the power purchased from the grid based on *time-of-use* charges. The choreography of the changeover switch and the battery storage would need to be tested under combinations of building load, weather dependent PV output, and various *time-of-use* schemes to ensure robustness and suitability of the algorithm before implementing on operational buildings.

Another potential test setup for the microgrid is to examine the impact of power quality disturbances on connected equipment. In this case, the MGB board would be supplied via the CP by the AWG, programmed to deliver the required disturbance as shown in Fig. 15. The equipment under test would also be connected to the MGB via the CP along with the appropriate amount of load from the SBRC Distribution Boards and PV generation as needed by the specific test. These and many more tests are possible given the flexibility and modularity built into the UOW Laboratory Microgrid research platform.

IV. Conclusion

Microgrids are likely to form an important part of the electricity supply systems of the future. However, there are significant challenges that need to be addressed with respect to the integration of microgrids before they become widespread. This paper has described the design and implementation of a novel laboratory microgrid research platform at the University of Wollongong.

This facility will provide an environment where testing of microgrid equipment and control systems can be undertaken simply with real-world complexity in a low-risk environment. The novelty of the installation is based on the accessibility and modularity of design. A wide range of testing capability has been accounted for with some potential examples presented in Section III. It is anticipated that the relevance of the installation will continue to grow as the technologies controlling the population's electricity usage continues to evolve.

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