1 INTRODUCTION

A microgrid is a small group of generation sources and loads that operate together as one system. Typically, a microgrid has a control system that controls each device (generator or load) inside it, allowing the microgrid to present itself to the grid as a single device. A microgrid may operate connected to the grid, standalone from the grid, or may support dynamically connecting to and disconnecting from the grid. A microgrid that has dynamically disconnected from the grid is operating in islanded mode.

The Australian Energy Storage Knowledge Bank’s (AESKB) Mobile Test Platform is a portable microgrid system with embedded battery energy storage system (BESS). Figure 1 shows the simplified electrical layout of the Mobile Test Platform, in a general configuration.

Figure 1: AESKB Mobile Test Platform simplified electrical system, general configuration.
The top half of Figure 1 shows the flexible AC switchboard. There are two three-phase busses: the main bus and the generation bus. The main bus includes automated control and protection switchgear that allows for the connection to an upstream LV grid, and to a downstream feeder (load/customers). The protection devices are a set of three automated circuit breakers (Q1, Q2, Q3) controlled by two protection relays. The first is a grid intertie relay that controls the upstream grid circuit breaker Q1 and the generation bus circuit breaker Q2. The second is a feeder protection relay that controls Q3, allowing for the downstream feeder and loads to be disconnected.

The intertie relay can close the generation bus circuit breaker to connect generation sources (including the inverter and battery) to the grid and load. The intertie relay can also open the grid circuit breaker to disconnect from the grid, causing the system to form an islanded microgrid. In this example the generation bus becomes the sole source of power for the downstream feeder and the customers/loads connected to it.

![Figure 2: (a) AC switchboard, (b) Automated circuit breaker, (c) Bi-directional Inverter.](image)

Microgrid operation with islanding is possible because of the “PaDECS®” high level control system. The PaDECS® control system is a flexible, distributed “Internet of Things” (IoT) that interfaces with and controls all devices in the microgrid system. It coordinates operation of the battery, inverter, and both protection relays. Dynamic “bump-less” segregation (leaving the grid to form an island) and reintegration (reconnecting to the grid) is only possible with the careful coordination of all these devices in the microgrid system.

To allow for the system to form an islanded microgrid, the inverter operates in voltage source mode where it emulates a generator and produces the reference voltage and frequency for the islanded microgrid. Without the voltage source inverter providing these references, the microgrid voltage and frequency would become unstable and cause the microgrid to shut down.
2 ANTI-ISLANDING

In the event of a grid supply disruption or failure (e.g. black out), grid connected inverters are required to stop operating and shut down. This safety requirement is called *Anti-Islanding* and requires inverters not to maintain or form an electrical supply of their own. An Inverter must not provide power or voltage is such a scenario.

In Thebarton, South Australia, the Mobile Test Platform was deployed in a grid connected configuration with downstream load bank, shown in Figure 3. Using this configuration, anti-islanding of the inverter was tested.

![Mobile Test Platform](image)

*Figure 3: Mobile Test Platform configuration in Thebarton South Australia.*

2.1 ANTI-ISLANDING WITH 10kW LOAD

To test anti-islanding, the following method was used:

1. The load bank is turned on and draws power from the grid.
2. The inverter is then enabled, then set to produce most of the power consumed by the load. This removes most of the load on the grid, but the inverter is still connected and synchronised to the grid.
3. The upstream grid connection is manually tripped, disconnecting the inverter and load from the grid.

Figure 4 shows the active power for the inverter (measured at node F in Figure 3), the grid (measured at node K), and the load (measured at node N).
The inverter provides most of the load power for approximately 1.5 minutes. After the grid supply was tripped, all power in the microgrid system stops. Importantly, the inverter power stops, as required.

Figure 5 shows the positive sequence voltage magnitude, as measured by the phasor measurement unit (PMU) of the embedded data logging system. For this test, the PMU was set to produce 25 measurements per second, allowing for fast changes to be captured. The inverter voltage was measured at node E of Figure 3, and the grid voltage was measured at node J. The positive sequence represents the normal operating voltage of the three-phase system.

After the supply was disconnected, the voltage inside the microgrid drops in less than one second.
2.2 **Anti-Islanding with 110kW Load**

The anti-islanding test was repeated for 110kW, using the same method as the 10kW test. Figure 6 shows the power in the microgrid, with the inverter providing most of the load power for approximately 4 minutes. After the grid supply was tripped, all power in the microgrid system stops.

![Figure 6](image-url)

*Figure 6: Total active power at the inverter (node F), grid (node K) and load (node N) connections during the 110kW anti-islanding test at Thebarton SA.*

Figure 7 shows the voltage measured from the phasor measurement unit (PMU). Again, after the grid supply is disconnected, the voltages at nodes J and E drops in less than one second.

![Figure 7](image-url)

*Figure 7: Voltage magnitude during the 110kW anti-islanding test at Thebarton SA.*
The microgrid in the Mobile Test Platform is capable of intentional islanding operation. The system can perform bump-less segregation and reintegration, where the high-level control system coordinates the dynamic disconnection/reconnection of both embedded generators and loads from the grid. The term bump-less refers to the fact that generators and loads inside the microgrid continue to operate normally during the transition. Loads do not experience any outages or interruptions, and do not even notice that the grid has been disconnected.

Referring to the electrical layout in Figure 3, the system starts operation in a grid connected mode where circuit breakers Q1 (to main grid), Q2 (to generation bus/inverter) and Q3 (to downstream load) are all closed and power can flow through all of them. Upon receiving a command to segregate and form an island, the PaDECS® control system coordinates the transition of all devices to this new operating mode. This includes a change in protection settings and a change in the inverter’s operating mode.

The inverter transitions to providing the voltage and frequency reference for microgrid. This is done using a voltage and frequency droop curve, where voltage and frequency drop in response to the power being delivered by the inverter. Figure 8 shows the frequency of the grid connection (measured on the grid side of Q1, at node J) and the load (measured at the generation bus, at node H). When Q1 is closed, the frequency at both locations is the same. After segregation (Q1 opens), the generation bus frequency changes independently of the grid. Figure 8 highlights the frequency stability of the inverter when operating in islanded mode. After reintegration (Q1 closes), the frequency at both locations is the same again.

Figure 8: Grid and generation bus frequency during the microgrid islanding test at Thebarton SA.

Figure 9 shows the power flowing through the microgrid during the islanding test. Before segregation, the inverter was providing almost all power used by the load. After segregation the grid power drops to zero, but the load power remains constant. Just after reintegration, there is small peak in power exported from inverter to grid, lasting for less than a second. Throughout the process, the load power is constant and operates continuously and seamlessly during both transitions.
The electrical power measurements are made by measuring the voltage and current (of each phase) at each node in the system. In a grid connected mode, the voltage of the grid, load, and generation bus is the same because these buses are all directly connected. However, in islanded mode this is not the case. In the electrical diagram shown in Figure 3 there are two voltage nodes: node J located on the grid connection, and node H located on the generation bus. Depending on the state of the grid connection Q1 and generation bus connection Q2, the voltage at the load connection (at the node N) may be the same as either node J, node H, both node J and H or neither (case where both Q1 and Q2 are open, and there is no voltage at the load).

The power at the load (node N) is measured twice, with different voltage reference for each measurement. Figure 10 shows the same power plot as Figure 9, but with the load power measurement that uses the grid voltage (node J) as its reference. Because the grid voltage is disconnected from the microgrid during islanding mode, the resulting voltage and current waveforms drift out of phase and no longer produce a meaningful result. In this case, it appears the power is flowing back and forth (this is not possible though, because the load used can only absorb power and not generate power).
3.1 **Segregation in Detail**

Figures 11 to 14 show the moment of microgrid segregation in detail. This data is measured using the data logging system’s phasor measurement unit (PMU). A phasor measurement unit uses advanced analysis techniques to provide more information than conventional electrical measurement techniques.

After segregation, the grid and load voltages separate (Figure 11). Both the inverter and load voltage drop because of the voltage droop curve used by the inverter in islanded mode. The inverter voltage is lower than the load voltage because of the isolation transformer. Frequency also drops (Figure 12), due to the frequency droop curve of the inverter.

Figure 13 shows the phase of the voltages at the grid connection and the generation bus (corresponding to the voltage at the load). Both voltages are synchronised before segregation, having the same phase angle. Because the frequency is near but not exactly 50Hz, the phase angle slowly changes. After segregation, the drop in inverter frequency (which sets the generation bus and load frequency) results in a relative phase angle that changes more quickly, and is no longer synchronised to the grid.

Figure 14 shows the Rate of Change of Frequency (ROCOF). Again, both the grid and load voltages have the same value until segregation. Just after segregation, there is small impulse/negative peak in the ROCOF waveform, showing the sudden change in frequency.

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**Phasor Measurement Unit**

The phasor measurement unit uses a GPS locked timing reference to provide power system measurements that are synchronised to universal coordinated time (UTC). The resulting measurements are called *synchrophasors*, because they produce magnitude and phase measurements (the components of a phasor) with respect to the ideal power system frequency of exactly 50Hz (synchronised to UTC via the GPS receiver).

For a voltage waveform, the synchrophasor magnitude is just the voltage. The synchrophasor phase is the relative phase angle difference between voltage waveform and an ideal 50Hz sinewave (aligned to UTC). For an exact 50Hz waveform, the phase will be constant. For a waveform not at 50Hz, the phase angle will slowly change. For example, a 49.9Hz waveform will have a synchrophasor phase that is changing at a constant rate and repeats every 10 seconds (the phase angle is wrapped into a range of -180° to 180°).

The key benefit of synchrophasors is the ability to see fast changes in the phase angle, and to look at the phase angle alignment of different parts of the power system. Frequency (rate of change of phase) and Rate of Change of Frequency (ROCOF) are derived from the phase angle measurements. They can provide deeper insight into the operation and stability of a power system.
Figure 11: Voltage magnitude during segregation.

Figure 12: Voltage frequency during segregation.

Figure 13: Voltage phase during segregation.

Figure 14: Voltage Rate of Change of Frequency (ROCOF) during segregation.
3.2 REINTEGRATION IN DETAIL

Figures 15 to 18 show the moment of microgrid reintegration in detail. Again, this data is measured using the data logging system’s phasor measurement unit (PMU).

Before reintegration can take place, the voltage source inverter must synchronise with the grid. Synchronisation requires the inverter’s voltage waveform to match the voltage level of the grid and be in phase with the grid waveform. If the connection to the grid (Q1) is closed without being synchronised, very large currents and power may briefly flow between the inverter and grid and may damage components of the microgrid. Normal and desired power flow between the grid and the microgrid is also not possible if the voltages are not synchronised.

Figure 16 shows the frequency of the grid and the load (set by the inverter). Before reintegration, the two frequencies are different. Because of this, the phase angle between them is constantly changing. The grid and load voltages are repeatedly coming into and going out of phase. After receiving a command to reintegrate, the system waits until the grid and inverter voltages are in phase, after which Q1 can be closed to connect the generation bus and load back to the grid.

At the point of reintegration, the generation bus voltage increases to match the grid voltage (Figure 15) and the generation bus frequency drops to match the grid frequency (Figure 16). The Rate of Change of Frequency (ROCOF) plot in Figure 18 shows an impulse/negative peak in the generation bus frequency, caused by the sudden drop in frequency required to match the grid frequency. The ROCOF measurement is very sensitive to small changes, and is useful for detecting events and changes in the power system.
Figure 15: Voltage magnitude during reintegration.

Figure 16: Voltage frequency during reintegration.

Figure 17: Voltage phase during reintegration.

Figure 18: Voltage Rate of Change of Frequency (ROCOF) during reintegration.
4 CONCLUSION

A microgrid is a group of generation and load devices that can operate together as a single system. When equipped with suitable generation devices, protection devices and control system, a microgrid can dynamically disconnect from the grid to operate in islanded mode.

The Australian Energy Storage Knowledge Bank’s (AESKB) Mobile Test Platform is a portable microgrid system with embedded battery energy storage system (BESS). It includes a state of the art high level control system and all components required to operate in an islanded configuration.

This report has examined both the anti-islanding protections and deliberate islanding modes of the microgrid system with battery storage. Dynamic and seamless segregation and reintegration was shown, with a detailed look at the power system behaviour of both transitions. The microgrid successfully disconnected from and reconnected to the grid while under load and without any interruption to that load. Such behaviour is desirable in microgrid systems, and demonstrates how the reliability of the power system for consumers inside a microgrid can be improved using battery energy storage technology.