# Basic Operation of a Battery Energy Storage System (BESS)

Gabriel Haines

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## 1 Introduction

A Battery Energy Storage System (BESS) is a type of energy storage device the uses batteries as its underlying storage technology. A battery energy storage system is more than just a battery, and requires additional components that allow the battery to be connected to an electrical network. A bidirectional inverter is the main device that converts power between the AC line voltage and the DC battery terminals, and allows for power to flow both ways to charge and discharge the battery. Other components of a BESS may include an isolation transformer, protection devices (e.g. circuit breakers), cooling systems, and a high-level control system to coordinate the operation of all components in the system.

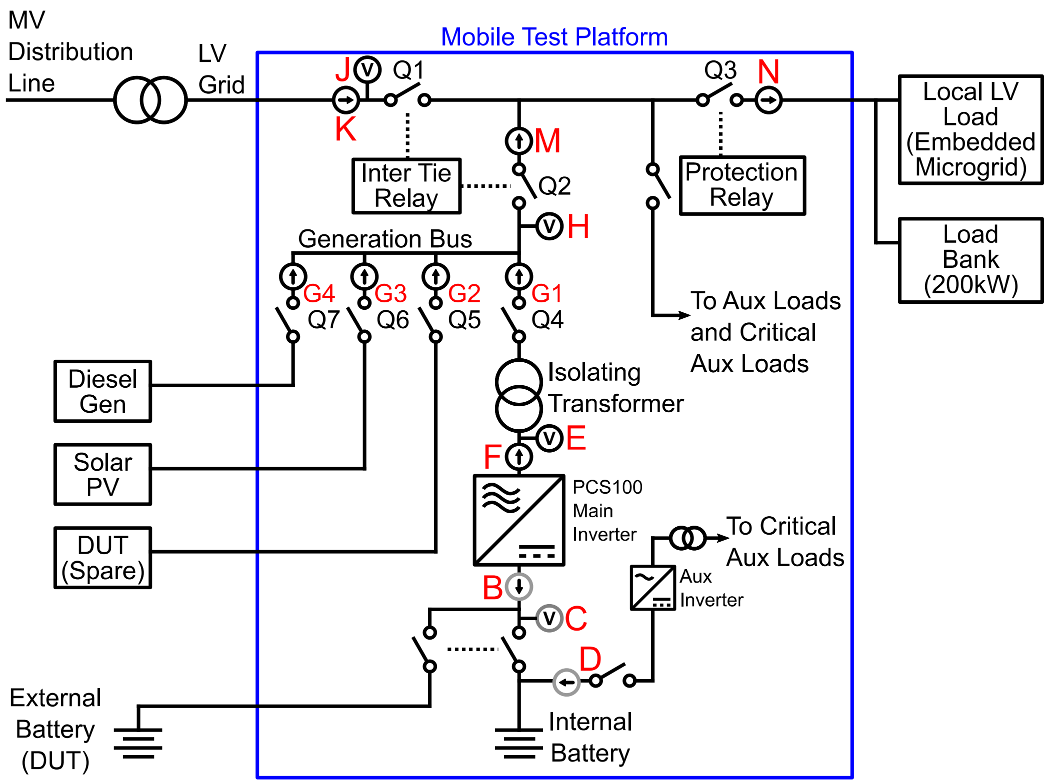


*Figure 1: AESKB Mobile Test Platform simplified electrical system, general configuration.*

Figure 1 shows the simplified electrical layout of the Australian Energy Storage Knowledge Bank's (AESKB) Mobile Test Platform, shown in a general configuration. The portable shelter houses a battery energy storage system that includes a flexible AC switchboard with protection devices (top half of Figure 1), an inverter with isolation transformer, an internal battery, flexible "Internet of Things" (IoT) high level control system with supervisory control and data acquisition (SCADA) interface, and a high speed multi-channel data logging system.

The AC switchboard comprises of 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.

*(a)* *(b)* *(c)*

*Figure 2: (a) AC switchboard, (b) Automated circuit breaker, (c) Bi-directional Inverter.*

The internal battery is LG CHEM 273kWh Li-Ion battery, comprised of three racks of battery modules, located in a dedicated battery room of the shelter. The mobile test platform also allows for the internal battery to be bypassed and an external battery used. The battery is connected to the generation bus via the ABB PCS100 inverter (270kW) and isolation transformer. The inverter can convert AC power to DC (rectifying) to charge the battery, or converter DC power back to AC (inverting, or rectifying in reverse) to discharge the battery and provide AC power.

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. In comparison, a typical domestic solar PV inverter can only operate in a DC to AC mode (one-way power flow) and can only operate in *current source* mode, requiring an existing stable grid voltage to operate. These types of inverters cannot operate without an active grid connection (cannot island) and cannot operate during black outs.

The “PaDECS®” flexible IoT high level control system uses a distributed architecture to interfaces to all devices in the Mobile Test Platform, including the battery management system (BMS), the inverter control system, both protection relays, and a remote SCADA interface that allows for the network operator to remotely control the system. Although the system can be manually controlled by the remote SCADA interface, the advanced control system also includes autonomous control modes that can respond to the grid (for example, peak load lopping, voltage support etc).

*(a)* *(b)* *(c)*

*Figure 3: (a) Battery system with three racks, (b) PaDECS® IoT control system local terminal, (c) Voltage and current transducers.*

Embedded throughout the mobile test platform is a high speed multi-channel data logging system that records electrical measurements, temperatures and external weather. The transducers are shown in Figure 1 with “V” for voltage transducers and “→” arrows for current transducers. Each set of transducers are given a Node designation, shown in **red** in Figure 1. All AC nodes (E, F, G1, G2, G3, G4, H, J, K, M, N) include 3 transducers (1 per phase of the 3-phase system), for a total of 33 transducers. The DC Nodes include only 1 transducer per Node (B, C, D) for a total of 3 transducers.

Table 1 provides examples of the polarity of power measured at each node in the system, for different scenarios.

*Table 1: Typical operating scenarios and the polarity of active power at each location.*

| **Scenario** | **Active Power Polarity** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Grid (K)** | **GenBus Tot. (M)** | **GenBus Inv. (G1)** | **Inverter AC (F)** | **Inverter DC (B)** | **Battery DC (Calculated)** | **Load (N)** |
| Battery charging from grid. | + | - | - | - | + | + | |
| Battery exporting to grid. | - | + | + | + | - | - | |
| Battery islanded, supplying load | | + | + | + | - | - | + |
| Battery islanded, absorbing from load (and/or peak shaving) | | - | - | - | + | + | - |
| Grid supplying load (battery off) | + | | | | | | + |
| Grid absorbing from load (reverse power flow) | - | | | | | | - |
| Grid and Battery supplying load. | + | + | + | + | - | - | + |

# 2 BASIC BESS OPERATION

## 2.1 20KW CHARGE TEST

The Mobile Test Platform with battery energy storage system was first operated in Bayswater Victoria, and was deployed in the following configuration:

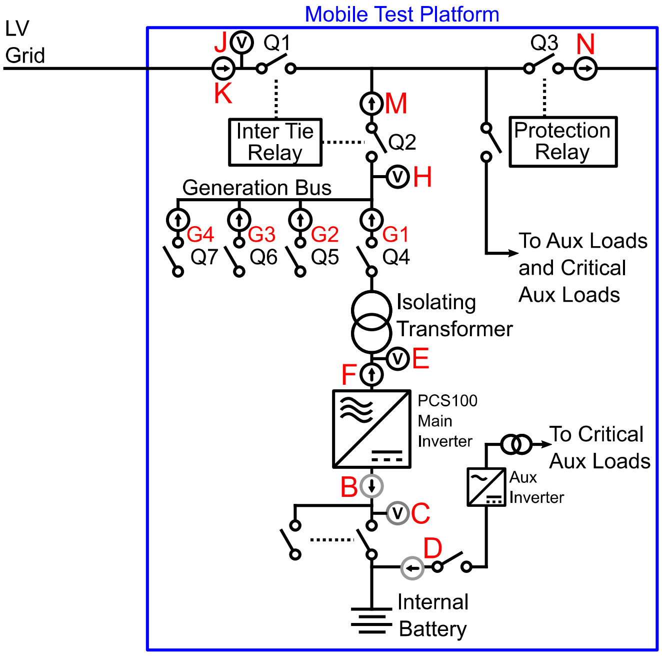


*Figure 4: Mobile Test Platform configuration in Bayswater Victoria.*

Figures 5 to 7 show the operation of the system for a 20kW charge test. This was a simple demonstration of the basic operation of the system, where the inverter was told to turn on with zero power consumption, then to charge the battery at increasing power levels. The 20kW operating point represents operation at about 7.4% of the rated power of the inverter.

Figure 5 shows the DC power into the battery (calculated from nodes B and D in Figure 4). At the start of the test the inverter was told to draw zero power from the grid. Because the inverter requires power to operate, this was taken from the battery and results in short dips of negative battery power. Soon after the inverter was told to draw power from the grid to charge the battery, with power level increasing in steps up to 20kW. The actual DC power delivered to the battery was less than the 20kW the inverter consumes from the grid, because the inverter is not 100% efficient and includes some losses.

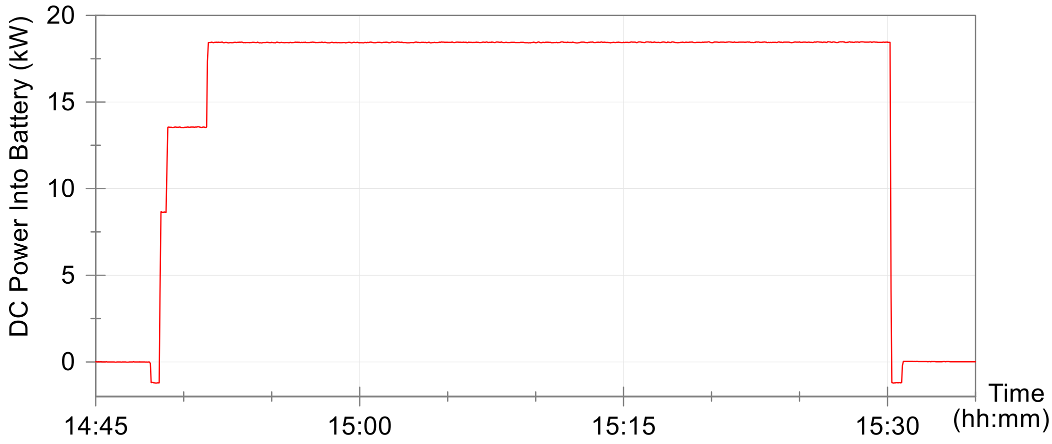


*Figure 5: Power into the battery during the 20kW charge test at Bayswater Victoria.*

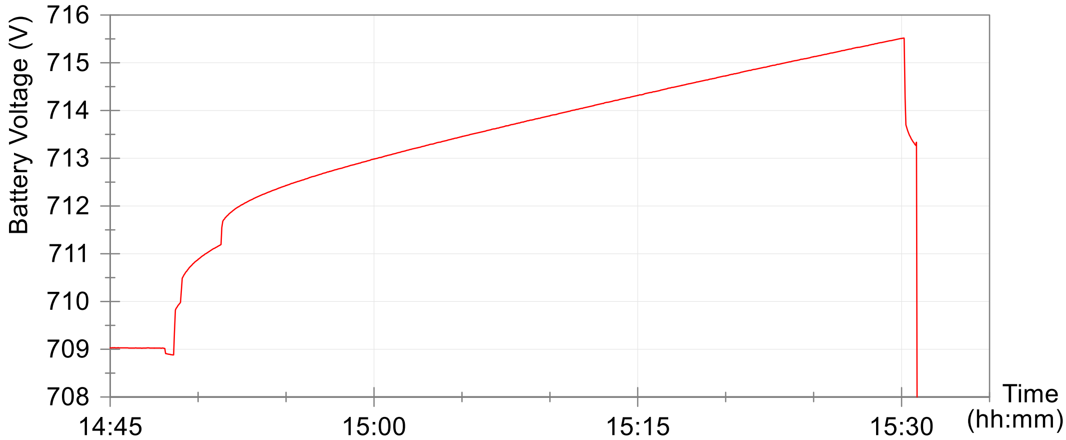


*Figure 6: Battery voltage during the 20kW charge test at Bayswater Victoria.*

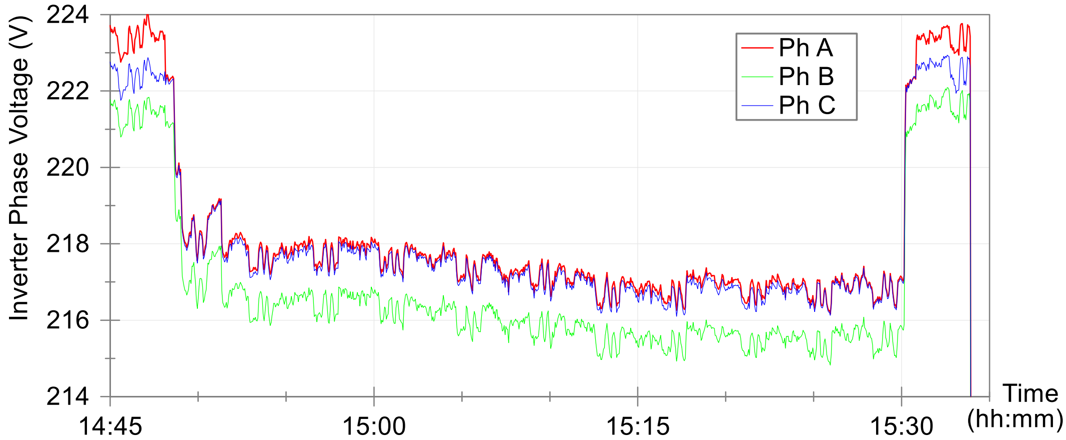


*Figure 7: Inverter phase voltages (RMS) during the 20kW charge test at Bayswater Victoria.*

The battery voltage (Figure 6, measured at node C in Figure 4) rises at an approximately constant rate for the duration of the constant power charging. Figure 7 shows the inverter AC terminal voltage for each phase, measured between the transformer and the inverter (node E in Figure 4). There was a small voltage drop once the charging starts and the inverter starts to load the grid connection.

## 2.2 Full Power Discharge Test

In Thebarton, South Australia, the Mobile Test Platform was deployed in a grid connected configuration with downstream load bank, shown below:

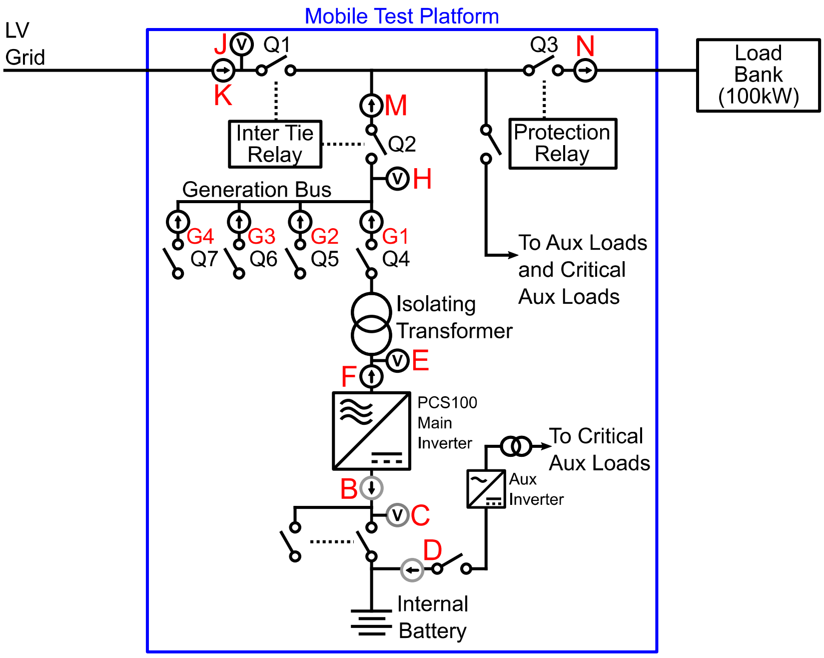


*Figure 8: Mobile Test Platform configuration in Thebarton South Australia.*

In this configuration, the full output power of the inverter and battery was tested, with results shown in Figures 9 to 12. The test starts by charging the battery for 15 minutes to just over 91% State of charge. The full power discharge test starts just after 17:30 by turning the 100kW load bank on. Initially, this only consumes power from the grid. After the load bank was running, the inverter was then enabled at run just under full power. The inverter outputs 258kW, with 113kW sent to the load and 143kW exported to the grid. The missing 2kW represents losses in the isolation transformer between the inverter and both the grid and load connections.

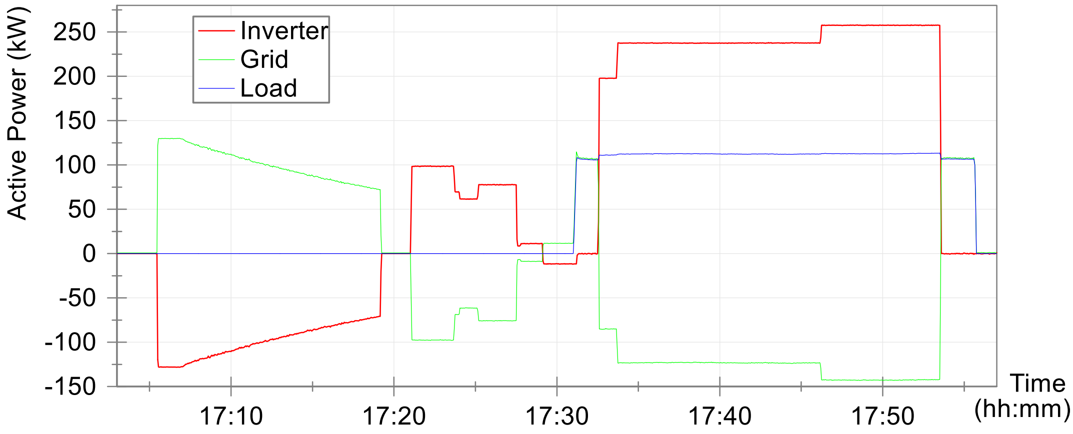


*Figure 9: Total active power at the inverter (node F), grid (node K) and load (node N) connections during the full power discharge test at Thebarton SA.*

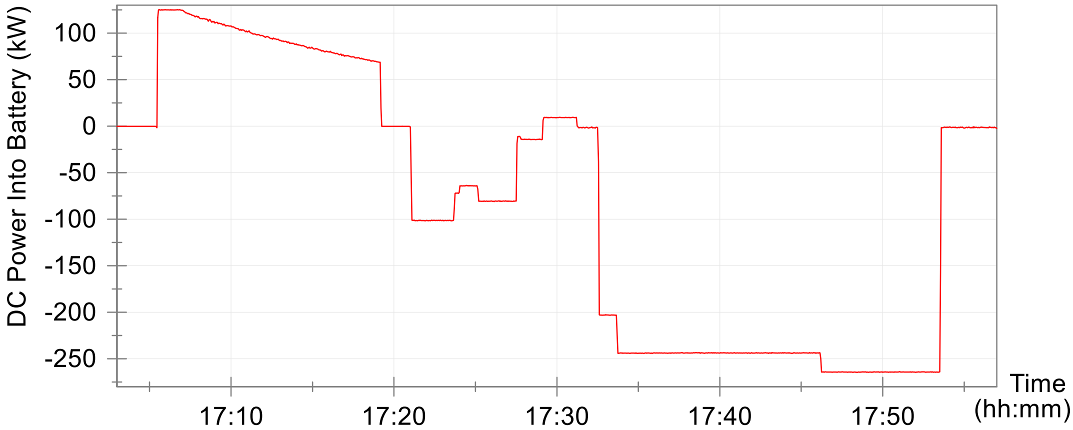


*Figure 10: Battery power during the full power discharge test at Thebarton SA.*

During the test, the peak DC power (calculated from nodes B and D of Figure 8) was measured at -264kW, representing power flowing out of the battery. Because of inverter and transformer losses, not all battery power is delivered to the grid. The battery power that doesn't reach the grid and load connections is lost as heat and must be removed by the air conditioning systems for the battery, inverter and transformer.

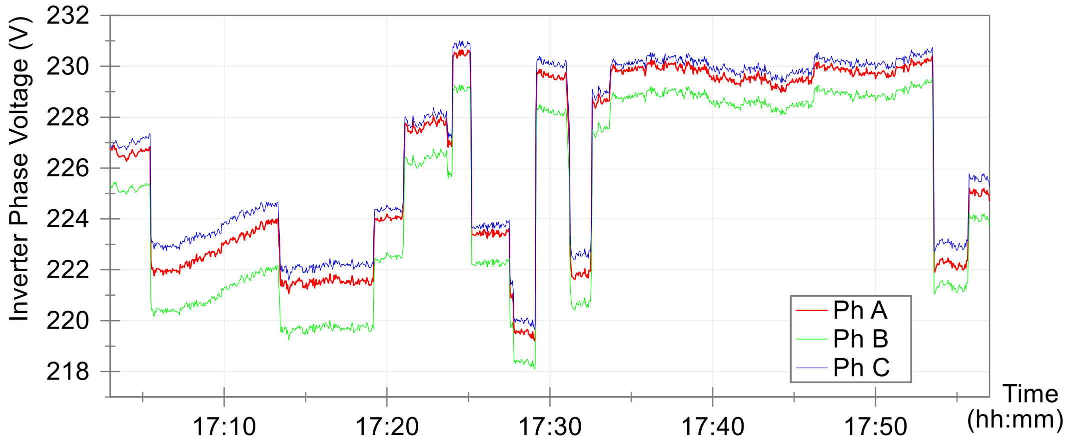


*Figure 11: Inverter terminal voltage (RMS) during the full power discharge test at Thebarton SA.*

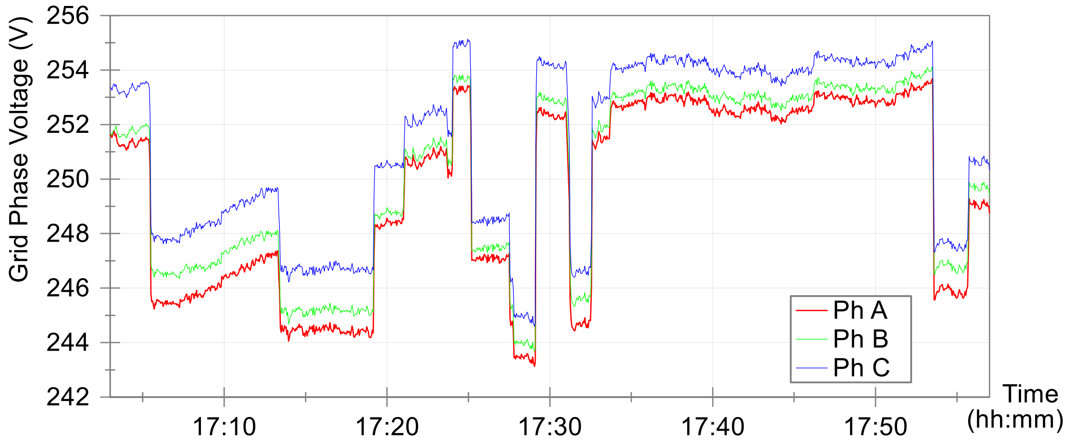


*Figure 12: Grid voltage (RMS) during the full power discharge test at Thebarton SA.*

Figure 11 shows the inverter AC terminal voltage for each phase, measured at node E in Figure 8. Similar to Figure 7, this shows a drop in voltage as the inverter loads the grid connection to charge the battery. When the inverter discharges the battery to the grid (and load) the voltage increases. Figure 12 shows the grid voltage (measured at node J in Figure 8), which shows a similar shape but different voltage level because of the isolation transformer.

# 3 State of Charge and Cell Voltage

For the full power discharge test described by in Figures 9 to 12, the total battery voltage, individual cell voltage and state of charge was measured. Figure 13 shows both the Battery voltage and the state of charge. The battery voltage was directly measured at the inverter DC terminals (node C in Figure 4), but state of charge was calculated by the battery management systems (BMS) in each battery rack.

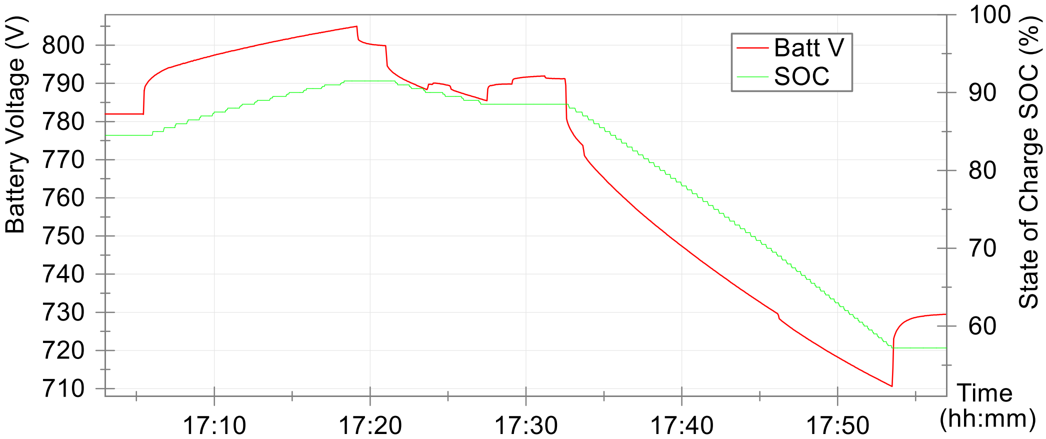


*Figure 13: Battery voltage (Red) and State of Charge (SOC, Green) during the full power discharge test at Thebarton SA.*

State of charge uses a complex model to more accurately estimate the stored energy in the battery. Although battery voltage is loosely correlated with state of charge, it does not provide an accurate estimate by itself. For example, at the instant the inverter starts to charge the battery, the battery voltage jumps almost 10V, however the state of charge cannot instantly increase (the energy required to do so has not yet been delivered to the battery, and that energy takes time to flow into the battery).

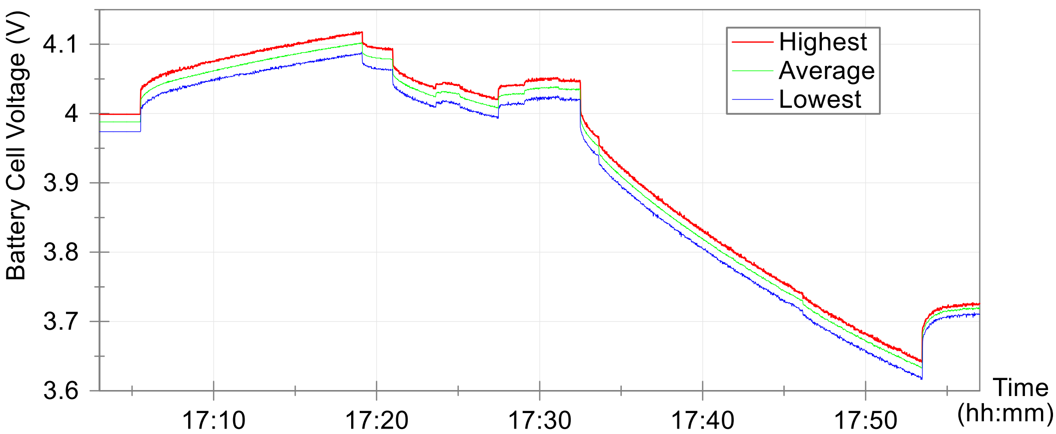


*Figure 14: Battery cell voltage during the full power discharge test at Thebarton SA.*

Figure 14 shows the cell voltages for the battery, with the maximum, average and minimum cell voltages plotted over time. All cell voltages are individually measured by each battery module, and the data is collected by each battery rack's battery management system (BMS).

A large, high power battery is made from a collection of low voltage cells. The cell voltage is determined by the battery chemistry (Lithium Ion for this battery) and shares the same nominal cell voltage as other batteries of that same chemistry. For the LG CHEM battery used, each cell has a nominal voltage of 3.7V. The cells are connected in series, where the individual cell voltages add up to a voltage large enough to be used in a grid connected energy storage system. Each LG CHEM battery module uses 14 cells in series, resulting in a nominal module voltage of 51.8V. Each battery rack then uses a stack of 14 modules connected in series to produce a nominal voltage of 725V. Per rack, there are a total of 196 Lithium Ion cells connected in series.

*Figure 15: One rack of the LG CHEM Lithium Ion battery, showing the 14 battery modules.*

Each battery rack has the same total voltage (sum of 196 cells) and stores 91kWh of energy (126Ah @ 725V). Three racks are connected in parallel to provide a total of 273kWh of energy. Each battery rack is rated for "1C", meaning each 91kWh rack is rated to discharge its energy in 1 hour (or longer), or rather, is rated to operate at a power of up to 91kW. For a given energy capacity, a lower C rating means a lower power rating, and a higher C rate means a higher power rating. For example, a rating above "1C" means a battery can discharge its kWh capacity in less than an hour.

The C-rate of a battery is an over simplification of its general power rating and does not represent the actual power rating under all conditions and states of charge. For example, a battery cannot be charged at full power when it is at 99% state of charge and must be charged at a much slower rate. Figure 16 shows the battery power for the same time period as Figure 10, but includes the instantaneous charge and discharge power limits. These limits are determined in real time by each rack's battery management system and the battery section controller that overseas all battery racks. Charging of the battery starts above 100kW, but automatically drops below this as the state of charge rises. This drop in charge power is automatically controlled by the high level PaDECS® control system, that coordinates the inverter's power commands in response to the battery's state of charge. As state of charge rises (near 90%), the battery's charge power limit drops. The limit doesn't rise again until the state of charge drops.

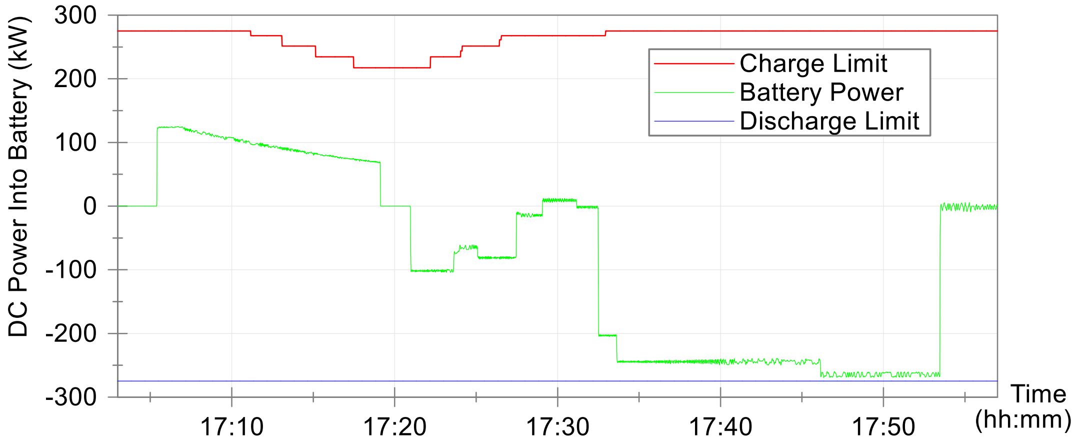


*Figure 16: Battery power, charge and discharge limits from the battery section controller (BSC) during the full power discharge test at Thebarton SA*

Because of these power limits, a grid connected battery cannot function effectively if the state of charge is too high or too low. Grid applications including energy arbitrage (charge when cheap, discharge when expensive), voltage support, reactive power support and peak shaving require a state of charge that allows high power charge and discharging at any time.

# 4 Efficiency and Capacity

Efficiency describes how much power and energy is lost or wasted by a system in the context of how much power and energy it delivers. For a battery energy storage system, each component in the system has losses, and these losses depend on how the system operates.

## 4.1 Inverter Efficiency

Inverter efficiency represents the instantaneous power loss with respect to the power flow through the inverter (when charging or discharging). Figure 17 shows the inverter efficiency for the 20kW charge test in Bayswater VIC, and Figure 18 shows the inverter efficiency for the full power discharge test at Thebarton SA, and includes both charging and discharging.

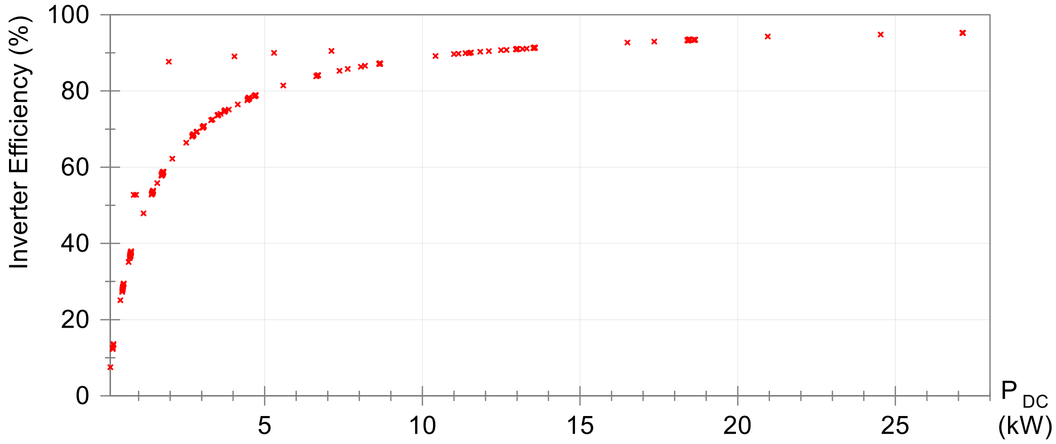


*Figure 17: Inverter efficiency during the 20kW charge test at Bayswater Victoria.*

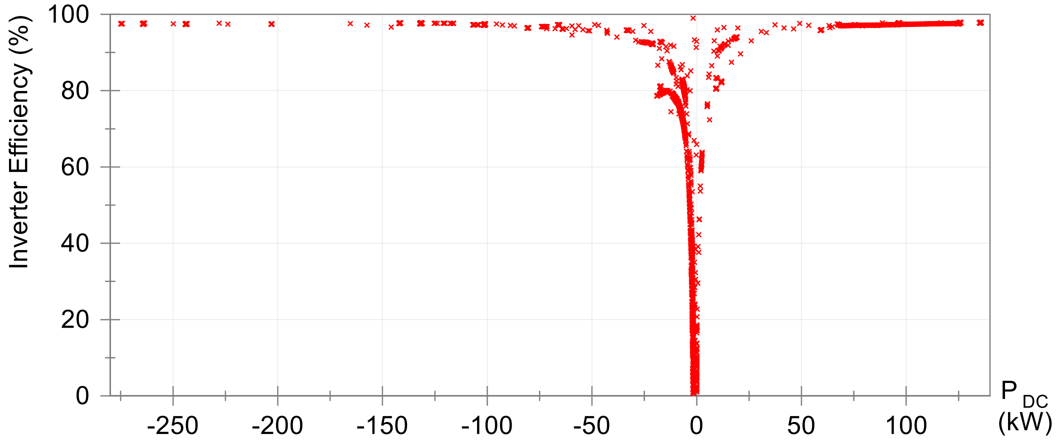


*Figure 18: Inverter efficiency during the full power discharge test at Thebarton SA.*

Figure 17 shows the efficiency when the inverter runs below 7.4% of its rated power and demonstrates poor efficiency (high loss relative to power output) when operated at low power levels. This is typical behaviour for all inverters, and highlights the importance of correctly sizing the inverter for the application to minimises losses. Figure 18 shows a relatively flat, high efficiency operating region from 10% rated power (>92% efficient) to 100% rated power (>97.5% efficient).

## 4.2 Energy Capacity

The capacity of an energy storage system is measured using an energy meter while fully discharging the battery. Figure 19 shows the battery voltage and state of charge from the start of the full power discharge test (91.5% SOC), to the end of the full discharge test (0% SOC) on the following day. Figure 20 shows the energy meter plots for the inverter AC connection and the battery/inverter DC connection, taken over the same time.

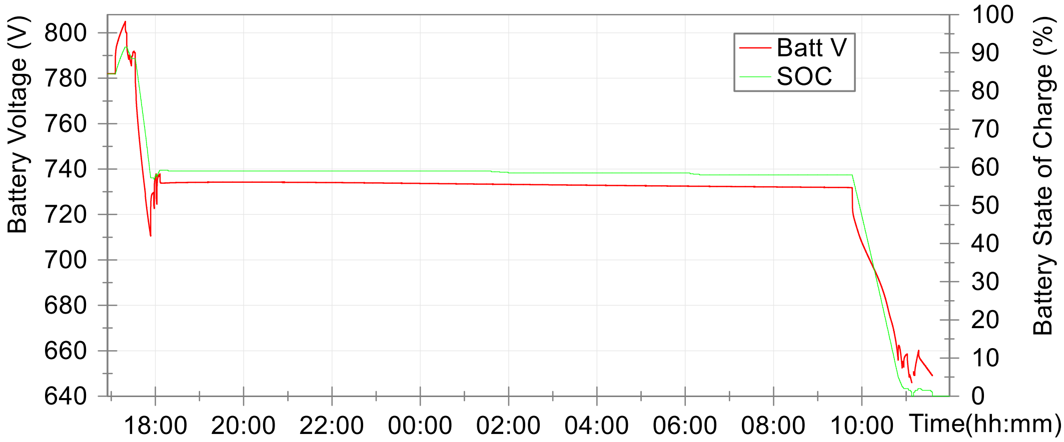


*Figure 19: Battery voltage (Red) and State of Charge (SOC, Green) during the full discharge test at Thebarton SA.*

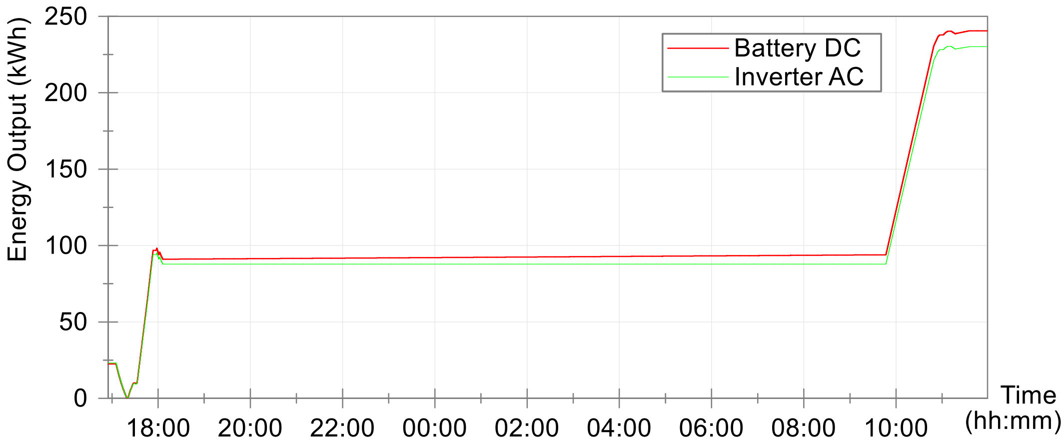


*Figure 20: Battery and inverter accumulated energy during the full discharge test at Thebarton SA.*

Table 2 shows the results for the test. The energy delivered by the inverter's AC connection was lower than the energy delivered by the battery. This is because of inverter losses, but also because of the auxiliary inverter's standby current (which caused a small drop in state of charge overnight). This test shows that 91.5% state of charge corresponds to 240kWh of energy in the battery, or 230kWh that can be delivered by the inverter.

*Table 2: Energy capacity measured by the full discharge test.*

| SOC (%) | Inverter AC Energy (kWh) | Battery DC Energy (kWh) |
|---|---|---|
| **91.5** | 0.421 | 0.416 |
| **0** | 230.443 | 240.314 |
| **Net Difference:** | 230.022 | 239.898 |

# 5 CONCLUSION

A grid connected battery energy storage system includes several components and sub systems that make it possible for a DC battery to be connected to the AC electrical grid. Key components include a bidirectional inverter, battery, transformer, protection devices, cooling systems and high-level control system.

The Australian Energy Storage Knowledge Bank's (AESKB) Mobile Test Platform is a portable energy storage system that includes theses key components deployed in a flexible and customisable way. The embedded data logging system allows for the operation and behaviour of energy storage systems to be measured and evaluated.

This report has examined the behaviour of an energy storage system, with focus on the operation of the bidirectional inverter and battery system. Charging and discharging modes were shown, highlighting the battery's internal cell voltage and state of charge changes during those modes of operation. Inverter efficiency and battery system capacity were measured, and provide insight into the power and energy that can be delivered by in a real system using battery energy storage technology.