White paper

Battery/diesel grid-connected microgrids: a large-scale, industry-based case study of future microgrid capabilities

1 The GESS is installed in an industrial estate in northern Melbourne, Victoria, Australia, and provides support to a local end-of-line feeder

2 The GESS is fully portable, and all system components are transportable. The system is housed in six twenty-foot shipping containers and two transportable skids.

Introduction

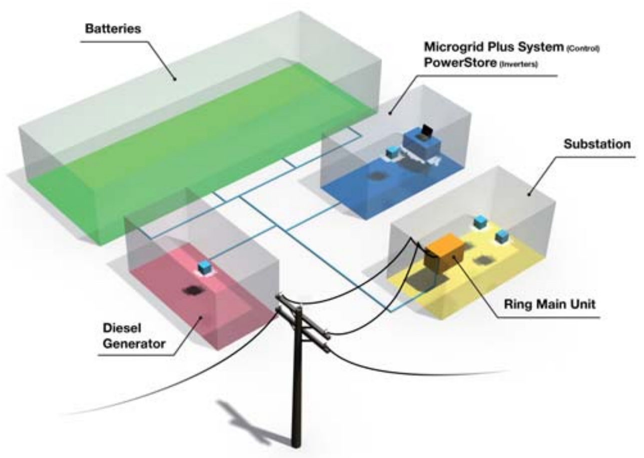
As large scale battery technology and economies of scale continue to improve, many industrial utilities are investigating the use of battery technology as the basis for Grid Energy Storage Systems (GESS). Based in Victoria, Australia, AusNet Services, the state's largest energy delivery service owning and operating approximately $11 billion of electricity and gas distribution assets that connect into more than 1.3 million Victorian homes and businesses, began investigating GESS in 2013. AusNet Services chose to trial the technology to explore the ability to manage peak demand with the potential to defer investment in network upgrades.

Through a competitive tender process, AusNet Services awarded the contract to design, construct and deliver a GESS to a consortium led by ABB Australia and Samsung SDI, with ABB in Australia providing the integration technology and design and Samsung SDI taking the role of battery supplier.

The GESS consists of a 1 MWh 1C lithium battery system which interfaces to the microgrid through a 1 MVA PowerStore™ (an inverter-coupled energy storage system), a 1 MVA PowerStore™ diesel generator, a 3 MVA three-winding transformer and a SF_6 gas-circuit breaker-based ring main unit with associated power protection systems. The system is fully portable and redeployable and is installed on an industrial lot in a number of transportable shipping containers and transportable skids.

Situated in the northern suburbs of Melbourne, the system is located at an end-of-line distribution feeder in an industrial estate. With the design of the system commencing in early 2014 the system was commissioned in December 2014, and a two year trial is now underway. The GESS is the first Australian system of this type and size, and the trial aims to explore the benefits to peak demand management, power system quality and network investment deferral that large-scale, grid-connected energy systems can provide.

Through the installation and commissioning process a full set of site acceptance tests were conducted. These tests demonstrated the capabilities of the GESS with respect to power system supply and stability, islanding and reconnection to the larger grid and management of the various system components (passive and proportional load sharing between the PowerStore, battery management and charging etc.). This whitepaper presents these results and discusses the future applications for the demonstrated technology. The results of the two-year trial period will be published at its completion.



3 System Overview

Aims of the GESS

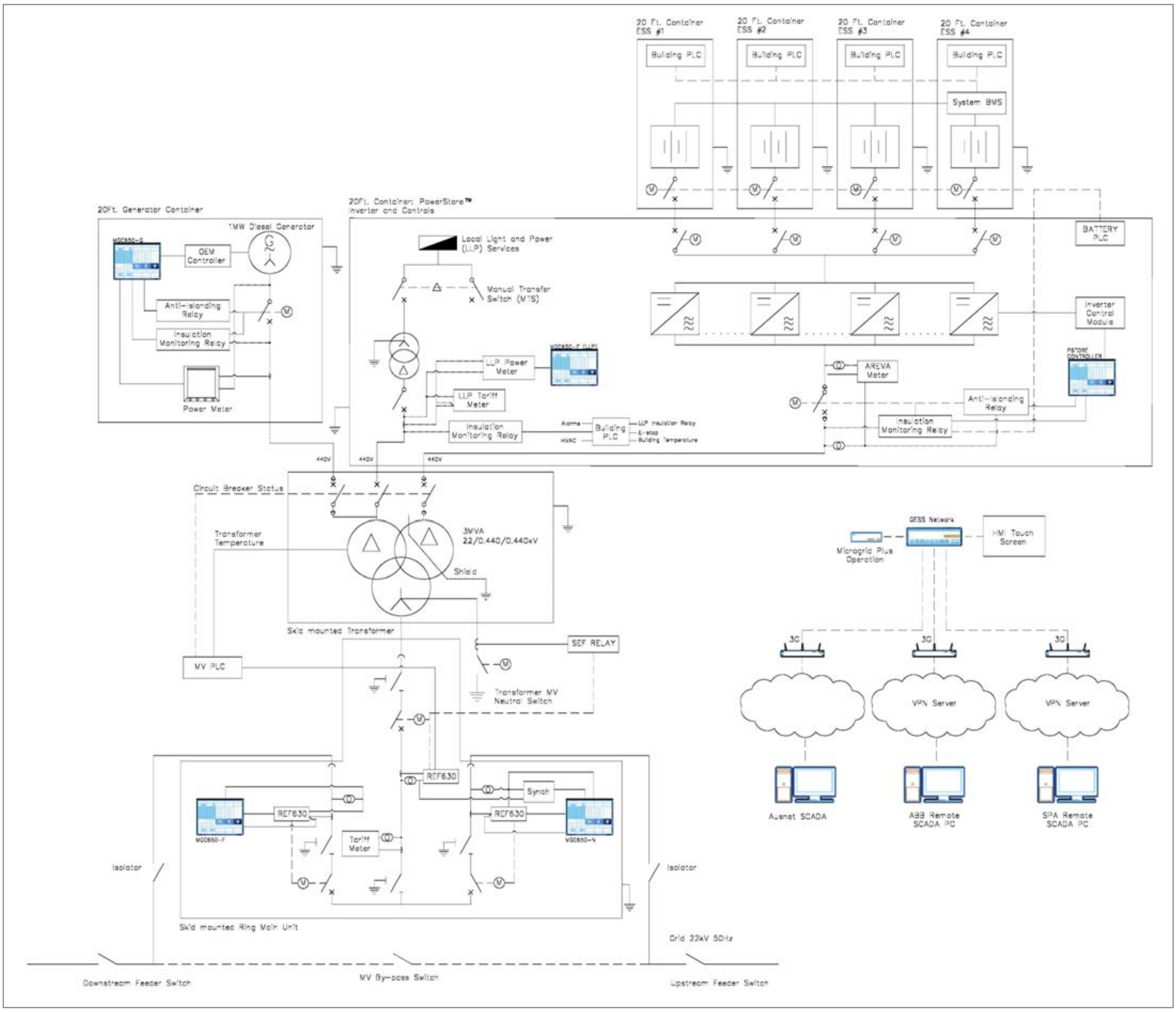
AusNet Services aims to trial a non-network option to manage peak demand and defer network augmentation. This trial will investigate the capabilities of grid-connected microgrids to provide peak demand support. By embedding a generation source close to the load, AusNet Services plans to study the effects this will have on postponing network investment involved with upgrading feeder lines to support increased loads. It is envisioned that such an embedded generation source can also be used to provide peak load support by reducing the upstream feeder requirements during peak consumption periods by supplying the loads locally. Given the capabilities of the GESS with regards to power system quality AusNet Services also plan to investigate the effect on local system quality and stability that the GESS will provide, such as power factor, voltage support, harmonics, flicker and negative sequence voltage.

Additionally, the islanding capabilities of the GESS are being investigated by AusNet Services to improve system supply and stability in the case of larger network faults. In the event of a fault the GESS would island the downstream feeder, creating an islanded microgrid which the GESS would supply until its energy reserves are depleted or the fault is cleared. When the fault is cleared the GESS would reconnect to the grid and transfer the supply back to network and begin recharging the batteries on a scheduled, preset programmed time of day.

ABB has successfully installed a number of high-penetration microgrid installations in a variety of remote locations throughout the world utilizing a flywheel-based ABB PowerStore (see Figure 4). The GESS also extends the technology used in these installations in two ways: through increasing the energy storage content of the 4.4 kWh flywheel-based systems previously used and expanding the grid-connected and islanding capabilities of the system.

4 Previous ABB PowerStore Installations (clockwise from top right): Coral Bay; a wind/diesel microgrid that achieves 95% wind penetration. Ross Island; 70% wind penetration and frequency conversion between a 60 Hz and 50 Hz grid is achieved through an ABB microgrid solution including a PowerStore. Marble Bar and Nullagine; the worlds first high-penetration solar photovoltaic diesel power station achieving 60% penetration. Kalbarri; a PowerStore STATCOM minimizes disturbances in voltage of an end-of-grid network to which 2 x 800kW wind turbines are connected.

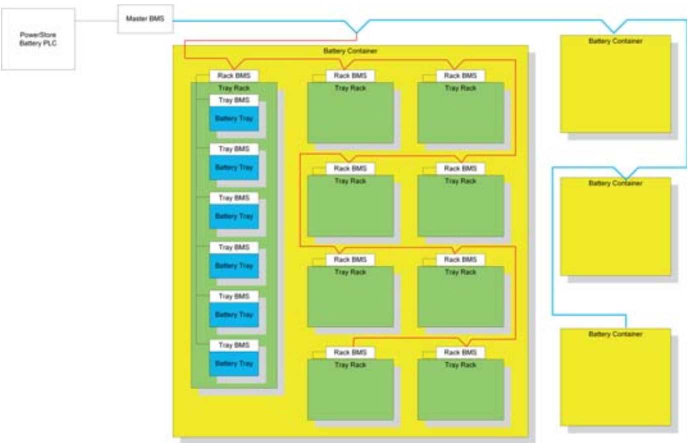
System Outline



5 GESS Single Line Diagram

The GESS consists of three main components: a 1 MWh 1C Lithium-ion battery energy storage system coupled to the grid through a 1.372 MVA inverter, a 1 MVA backup diesel generator, and a grid connection substation consisting of a 3 MVA transformer and sulfur hexafluoride (SF_6) filled ring main unit and power protection devices. All the system components are portable, with the generator, batteries and PowerStore housed in shipping containers, while the transformer and RMU are housed on skid-mounted platforms.

The battery-based system comprises a lithium-ion battery system supplied by Samsung SDI. It consists of 4 self-contained shipping containers with integrated HVAC and fire suppression, and has several layers of battery management systems to monitor and manage the lithium cells and ensure system safety as seen in Figure 6. Effective battery management systems ensure safe operations and mitigate fire risk. Lithium-ion based batteries were utilized because of their high energy density and power ratings. The 1 MWh 1C batteries are capable of symmetric charge and discharge ratings of +/- 1 MW, and can transition from charge to discharge very quickly, allowing for robust system operation (hence the 1C rating because a 2C system would be able to provide 2 MW but only for half an hour). Additionally, the batteries used have a wide depth of discharge range of 3%-100% and a known and predictable degradation of the state of health that allows for the total capacity of the GESS at end-of-life to be guaranteed. The batteries themselves are installed in modular trays allowing for replacement of any single tray of cells without the need for extensive servicing. During commissioning a series of environmental and abuse tests were conducted to prove the performance of the battery system under specified conditions.



6 GESS and Samsung SDI Battery Management System Hierarchy

Connected through a 1,000 VDC bus, the batteries are interfaced to the grid through an ABB PowerStore. Housed in a self-contained shipping container with integrated HVAC, the PowerStore utilizes a bank of IGBT-based ABB PCS100 inverters with a symmetric power rating of +/-1372 KVA. The PowerStore provides fully bidirectional real and reactive power management, allowing the system to provide power system supply in the same manner as a traditional generator and power system stability correction with a similar effect as a traditional STATCOM. With near full waveform control and millisecond response time, the PowerStore is able to very effectively respond to network conditions and inject or absorb both real and reactive power as required.

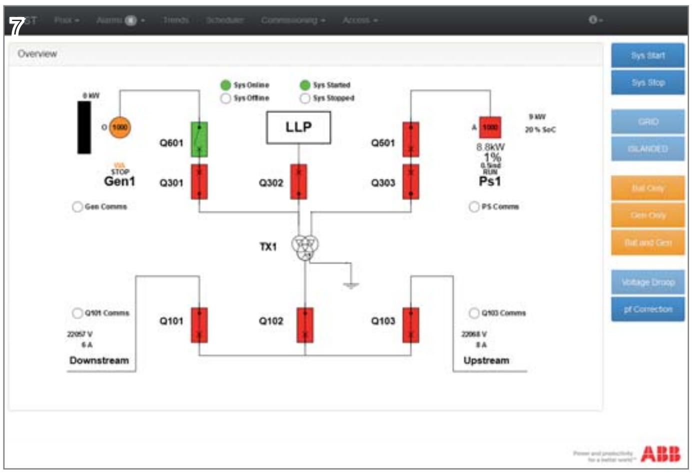
A 1 MVA diesel generator with generator controller, integrated ventilation and fuel tank provide an additional source of generation that can extend the discharge duration and power output of the GESS, recharge the batteries in case the state of charge of the batteries is low, or to support the microgrid individually.

Both the PowerStore and generator are interfaced to the 22 kV grid through a three-winding air-cooled resin core transformer with a primary connected neutral switch and a three-breaker SF_6 filled ring main unit. Intelligent Electronic Devices (IED) consisting of three ABB REF630's provide protect and monitor the grid connection. Additionally, an ABB Synchrotact allows the GESS to synchronize and transition from islanded operation to grid connected via 'bumpless' transitions. Local light and power is provided through an additional tap on a secondary winding and an isolation transformer. In the event of the loss of local supply, the GESS is able to 'self-supply' the 240 VAC auxiliary control supply from the batteries themselves, providing at least eight hours of backup communications and control supply.

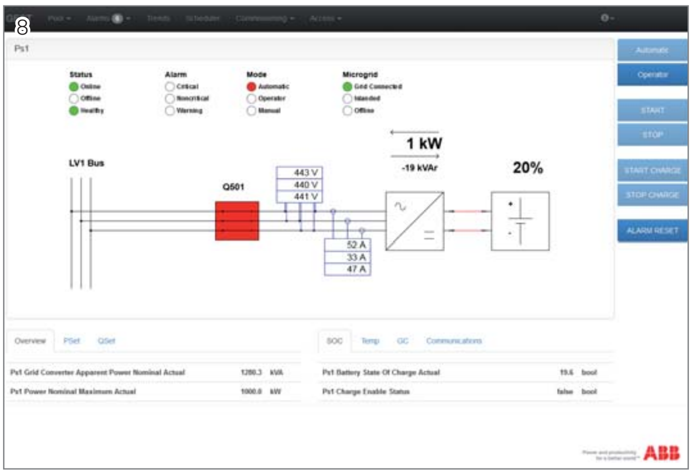
ABB's Microgrid Plus control system manages the GESS and ensures that consistent grid supply and stability is maintained. With a uniform hardware platform the distributed Microgrid Plus control system (MGC600) interfaces to each major piece of plant through a dedicated controller (designated MGC-G for generator, MGC-F for feeder, MGC-N for network etc.) which collects and publishes power system information to the entire network. Individual MGC controllers act in a distributed manner to send commands to their associated plant item (e.g. power setpoints, breaker open commands, synchronization, commands, etc.) resulting in the entire GESS performing as a cohesive whole, without the need of master/slave relationships. Remote monitoring and management is provided through ABB's M+ Operations (a HTML 5 based web interface) and also through an RTU connection to AusNet Services' control system. An example of the overview screen can be seen in Figure 7 with the battery screen seen in Figure 8. Both connections communicate externally via a 3G cellular connection. A redundant ring fiber network provides the local network backbone of the GESS.

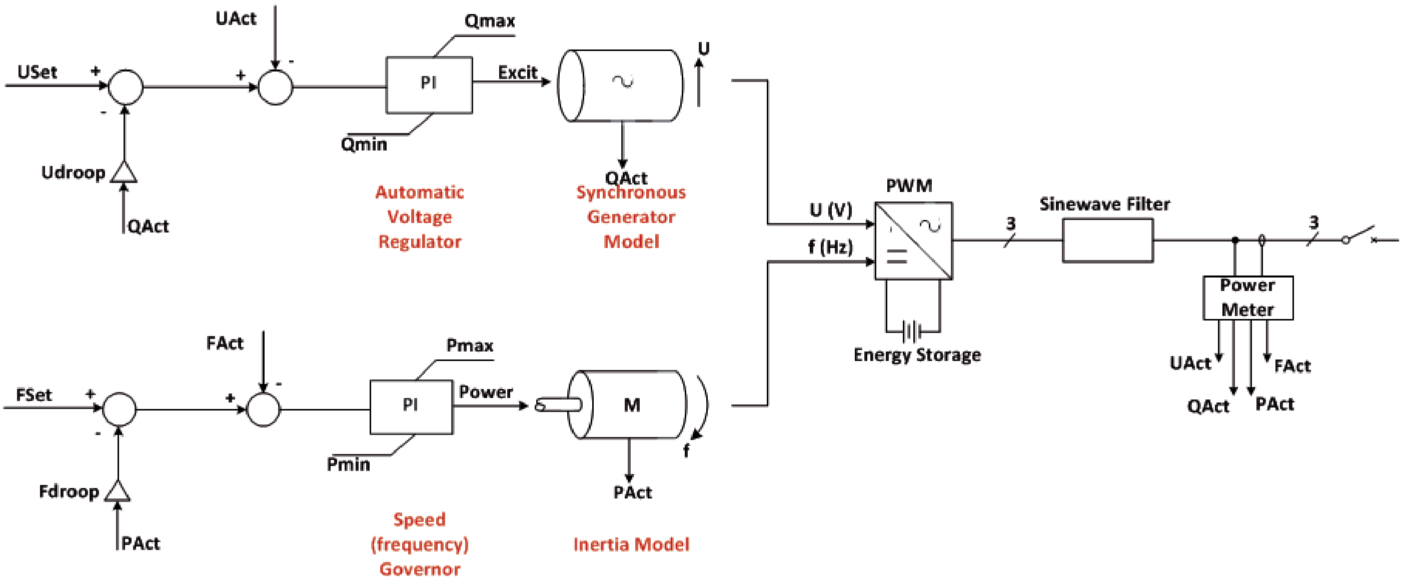
System protection is ensured through a set of complementary methods. The Samsung BMS communicates any alarms to the Microgrid Plus control system which in turn will cease operation in the event of critical alarms. Anti-islanding protection is implemented to ensure that in the event of an upstream feeder opening, the GESS does not attempt to supply to the entire network. Various power system protection functions are implemented by the REF630 relays and a backup sensitive earth fault relay installed on the transformer primary neutral connection. Insulation monitoring relays provide protection in the event of any local cable faults.

7 GESS M+ Operations Overview Screen



8 GESS M+ Operations Battery Screen





9 Software AVR and Governor models used in the PowerStore Virtual Generator Mode

System Functionality

The heart of the GESS is an ABB PowerStore, an IGBT-based PCS100 inverter system which interfaces the Samsung lithium battery energy storage system to the grid. The PowerStore operates in the GESS in Virtual Generator Mode (VGM) as a voltage source inverter. When in VGM the PowerStore inverters supplied by the batteries operate as a synthetic generator, similar to a traditional diesel generator but with exceptional response time and expanded power system supply and stability capabilities as described below.

Using software models of a diesel generator's Governor and AVR (as seen in Figure 9) in VGM, the PowerStore provides isochronous (droop) frequency and voltage control in the same manner as a diesel generator. Through the commissioning process, the PowerStore control parameters are tuned on site to match the characteristic response of the diesel generator. This allows the PowerStore to passively and proportionately load share both real and reactive power with the generator when both the PowerStore and generator are operating. The PowerStore is also able to use these models to generate in parallel with other generators on the network.

The software AVR and governor models utilized by the PowerStore also enable it to act as a grid-forming generation source (a stiff voltage source) that other synchronous generators, such as wind turbines or solar inverters, can use as the network voltage and frequency reference of a microgrid. This includes being able to provide supply to the microgrid by using solely the PowerStore. Additionally, the PowerStore responds to faults in the network in the same way as a synchronous generator, supplying up to 2 p.u. fault current for two seconds.

The functionality of the system can be summarized as seen in Table 1.

Table 1 GESS Functionality

Functionality	Power type supplied	Power provided by	Control Options
Islanded operation	See below (as per control options)	Battery inverter and/or diesel generator	• Bumpless transition to grid connection • Microgrid shutdown • Microgrid startup • Reactive power supply • Stiff voltage source • Battery charging • Spinning reserve
Grid connected operation	See below (as per control options)	Grid, battery inverter and/or diesel generator	• Bumpless transition to islanded operation • Reactive power supply • Peak lopping • Battery charging
Reactive power supply	Reactive power (capacitive and inductive)	Battery inverter, when sufficient, then diesel generator	• Voltage droop • Power factor correction
Stiff voltage source	Active power and reactive power through fast absorption and injection of current	Battery inverter	• None
Peak lopping	Active power supply	Battery inverter and/or diesel generator	• None
Battery charging	Active power consumption	Grid and/or diesel generator	• Timed charging • Charging at minimum feeder load
Spinning reserve	None (generation sources are brought online or offline as required)	Microgrid Plus control system	• Schedule of generation sources

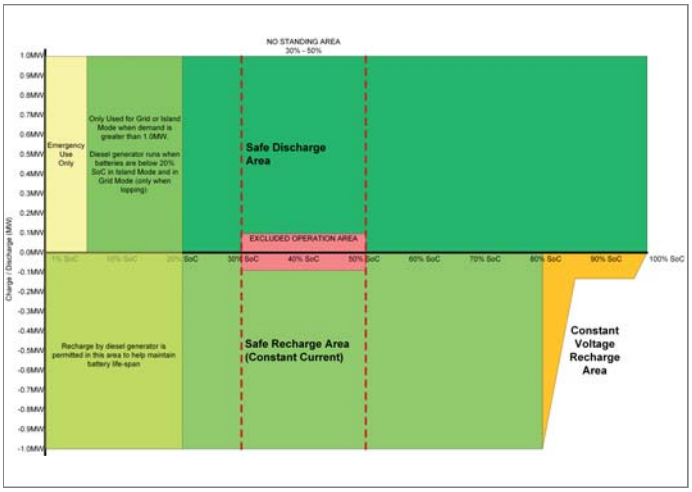
Peak lopping, whereby the load seen from the upstream breaker is limited, is achieved through use of a power setpoint. The Microgrid Plus control system monitors the downstream load and calculates the required power from the GESS. Using a generation schedule, the Microgrid Plus control system then instructs either the PowerStore or generator or both to provide power such that the upstream network load is equal to the setpoint. The Microgrid Plus control system can start and stop both the PowerStore and the generator and also ensures that there is sufficient spinning reserve present in the system.

Spinning reserve is maintained in the system by the Microgrid Plus control system. By constantly monitoring the power and energy flows through the system, the Microgrid Plus control system ensures that there is sufficient spinning reserve (both with respect to power and energy when the batteries are nearing their discharge limit) to ensure that any load steps can be accommodated. This functionality includes automatic 'black starting' of the backup generator when additional spinning reserve is required and likewise automatic shutdown of the generator when there is excess spinning reserve. Deadbanding and power throttling of the PowerStore is utilized to ensure that the minimum loading and minimum runtime of the generator is met. The Microgrid Plus control system uses a customizable schedule of generation sources to be set; this schedule details which generation source is to be brought online or offline as required by the power flows in the system to maintain a settable amount of spinning reserve in the system. Additionally, as the energy within the battery system decreases, the Microgrid Plus system controls the proportion of the load shared by each generator.

Additional power system supply and stability management functionality is also implemented. Voltage management is undertaken through the use of a voltage droop algorithm k whereby the PowerStore absorbs or injects reactive power proportional to the difference between the network voltage and a programmable setpoint. Management of the power factor of the upstream network breaker is undertaken through monitoring and injecting or absorbing reactive power as required. The GESS is also able to act as a typical network generation source with real and reactive power setpoints for upstream and downstream breakers able to be set and maintained, limiting the real and reactive power imported or exported to and from the microgrid. The PowerStore is also able to act as a current source inverter in Grid Support Mode with capabilities similar to a traditional STATCOM; however, this functionality is not utilized in the GESS.

The management scheme used to maintain the lithium batteries can be seen in Figure 10. In addition to excluding operation of the system when the batteries are at a low state of charge, the GESS also manages a 'no standing area', whereby the state of charge is not held between 30%-50% to extend the lifetime of the batteries; the system charges or discharges the batteries through this region ensuring that the system is not left 'standing' with a state of charge between 30%-50% as the lithium battery chemistry within state of charge region leads to a reduction in the state of health of the cells.

Charging of the batteries (using a constant current charging method followed by a constant voltage recharge scheme, depending on the state of charge) is undertaken through either a timed charging period or through minimum feeder load management. Both modes of charging can be supplied by the grid connection, the backup generator or both, allowing the batteries to be charged when the GESS is islanded or grid connected. The timed charging utilizes both a power and a time setpoint to specify when and at what power rate the batteries are charged. This functionality enables the GESS to utilize differences in the price of energy to charge at low-cost periods then discharge into the grid at higher price periods of the daily network cycle; however, this functionality is not utilized by AusNet Services.



10 GESS battery management scheme detailing charging and discharging regions. During operation the GESS does not maintain the state of charge of the batteries within the 'no standing area', instead charging or discharging through the region as required.

When charging at minimum feeder load, a minimum power setpoint is given to the Microgrid Plus control system that denotes the minimum power drawn from the upstream feeder. The downstream feeder supply is maintained and any difference between the upstream power setpoint and the downstream feeder power requirement is utilized to charge the batteries. Additionally, the GESS can perform peak lopping during charging while maintaining minimum feeder load if the upstream network power requirement is above a maximum power setpoint as described above. Because of the bidirectional power capabilities of the PowerStore provided by the PCS100 inverters, the system is able to inject or absorb reactive power even when real power is being consumed to charge the batteries.

Power system protection is managed by both the REF630 IED devices and the Microgrid Plus control system. Each IED has a number of protection groups that are able to be individually tuned as required. When the GESS transitions between the different modes of operation, the system calculates the number of generation sources that are online. The Microgrid Plus control system then instructs each IED to change the protection group setting, ensuring that appropriate parameter settings (fault current levels, ROCOF settings etc.) are selected. In this way the fault settings for the GESS match the available fault levels able to be provided by the online generation sources at any given point in time. Operation of the SF_6 breakers in the ring main unit is controlled by the REF630 IED's under instruction from the Microgrid Plus control system to ensure the power system protection is functioning safely and correctly. Anti-islanding protection relays monitor the network parameters to ensure that in the event of an upstream breaker opening the GESS is taken offline, ensuring, it does not attempt to supply the entire network.

Grid and Islanded Transitions

Located at the end of a feeder in the local network, the GESS allows for the downstream system to operate as an islanded microgrid (supplied wholly by the GESS) or as a grid connected system. The GESS performs 'bumpless' transitions between the 'Islanded' and 'Grid-Connected' modes, whereby no interruption or interference to the downstream or upstream supply or system quality is observed. Transitions between the grid-connected and islanded can be seen in Figure 11.

When transitioning from a grid-connected state to an islanded state, the output of the GESS is increased such that the real and reactive power flow across the upstream breaker is zero, i.e. the GESS is supplying the entirety of the downstream microgrid load. The Microgrid Plus control system then opens the upstream breaker through the associated REF630 IED, creating a microgrid system. The GESS supplies the system so long as there are energy reserves (battery state-of-charge and/or diesel fuel) available. When the GESS energy reserve is depleted or if commanded, the GESS can safely shutdown supply to the microgrid and likewise the GESS has the capability to initialize supply to the microgrid. The GESS can supply the microgrid through the inverter based PowerStore only, the generator, or both sources of generation, and the GESS has been sized so that it can supply the power requirements of the microgrid system when islanded.

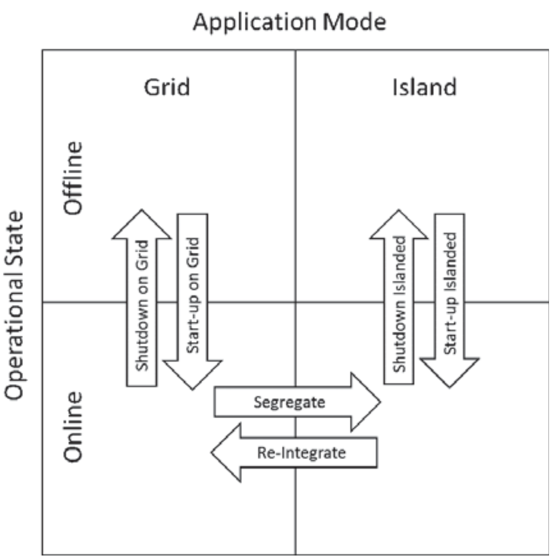
Transitioning back to a grid-connected system, the GESS synchronizes its supply (voltage, frequency, and phase angle) with the upstream network through an ABB Synchrotact. Using voltage and frequency adjustment signals from the Synchrotact, the Microgrid Plus control system adjusts the output of the PowerStore and generator accordingly until they are within acceptable limits. The ABB Synchrotact instructs the associated REF630 IED to close the upstream breaker only when the voltage, frequency and phase angle between the GESS's supply and the upstream network are within acceptable limits. During the synchronization and closure of the upstream breaker, the GESS continues to supply the downstream load resulting in a 'bumpless' transition. The GESS then can continue to providing grid supply and support, begin charging the battery bank or ramping down the output of the system to full transfer of the supply back to the grid.

During the transitions, the HV neutral switch on the primary winding of the transformer opens or closes as required. When the GESS is grid connected the neutral switch is open so that the upstream protection of the zone substation correctly operates. When transitioning to an islanded system the neutral switch is closed providing the microgrid and its associated power protection relays with a HV neutral reference. Transitioning back from an islanded system to a grid connection, the neutral switch is again opened to ensure there is only one neutral reference present in the system.

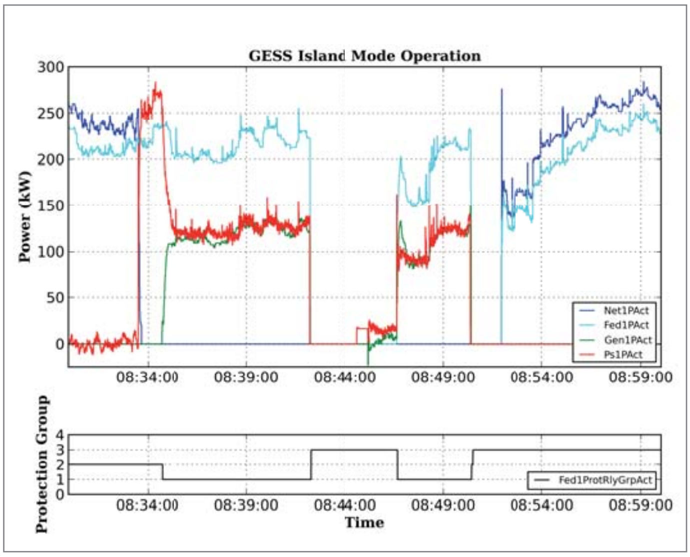
System Results

When transitioning from grid connected mode to island mode, as seen in Figure 12, the GESS increases its power output so that the power flow across the upstream breaker is zero and the GESS is entirely supplying the downstream feeder load. Figure 12 shows the PowerStore taking on the entire downstream load (the supply of the GESS auxiliary power accounts for the ~30 kW difference between Ps1PAct and Fed1PAct and between Net1PAct and Fed1PAct). When the power flow across the upstream breaker is zero, the upstream breaker is opened with the PowerStore solely supplying the microgrid. The generator is then started and the PowerStore and generator passively load share the downstream feeder load before a safe system shutdown is performed. When initializing the microgrid, the PowerStore starts first to provide a system reference for the generator to synchronize to. When this is completed, the downstream feeder breaker is closed and the GESS supplies the downstream feeder before another safe system shutdown is performed. Finally, Figure 12 shows the downstream network being reconnected to the upstream feeder.

11 GESS application modes and automatic transition sequences



12 GESS Island Mode Operation. Upstream feeder power (Net1PAct), downstream feeder power (Fed1PAct), generator power (Gen1PAct), PowerStore power (Ps1PAct) and power system protection group (Fed1ProtRlyGrPAct) during transition from grid connection to islanded microgrid, microgrid system shutdown, microgrid initialization and reconnection to the network



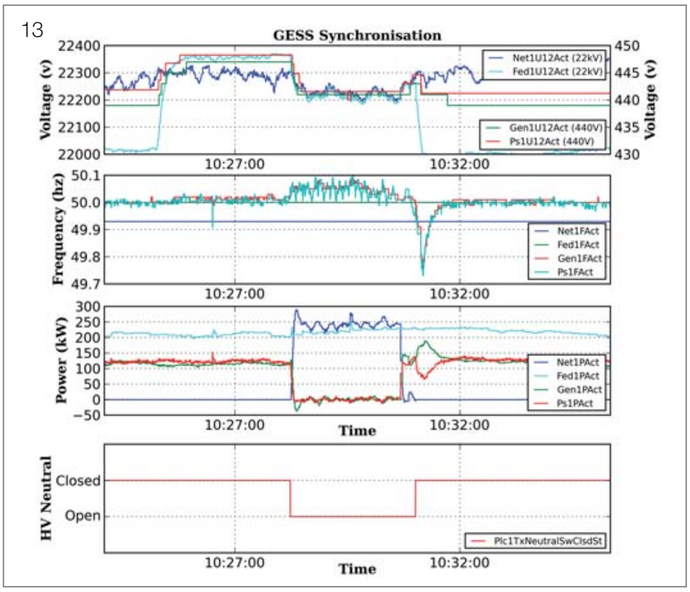
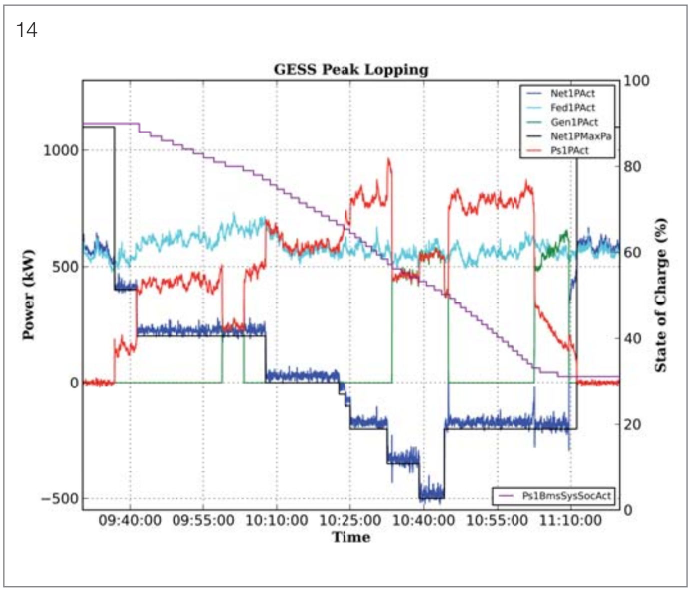


Figure 13 GESS Synchronisation. Upstream feeder voltage (Net1U12Act), power (Net1PAct) and frequency (Net1Fact), downstream feeder voltage (Fed1U12Act), power (Fed1PAct) and frequency (Fed1Fact), generator voltage (Gen1U12Act), power (Gen1PAct) and frequency (Gen1Fact) and PowerStoreTM voltage (Ps1U12Act), power (Ps1PAct) and frequency (Ps1Fact) and HV Neutral Switch status (Plc1TxNeutralSwClosedSt) during transition and synchronisation from Islanded to grid connected state then back to Islanded operation.



14 GESS Peak Lopping. Upstream feeder power (Net1PAct) and maximum power setpoint (Net1PMaxPa), downstream feeder power (Fed1PAct), Generator power (Gen1PAct), PowerStore power (Ps1PAct) and battery system state-of-charge (Ps1BmsSysSocAct) during peak lopping.

Figure 12 additionally, shows the changing of the protection groups of the GESS. The GESS has three (imaginatively titled) protection groups:

- Group 1: Both sources of generation online
- Group 2: One generation source online
- Group 3: No generation sources online

The Microgrid Plus control system coordinates the protection group setting of the REF630 power protection relays by instructing them to change protection group settings when generation sources change state from online to offline, and vice versa. The change of a protection group setting only occurs after the change of online/offline status of a generation source, so that the more conservative groups are not affected by transients. For example, Group 3 has more relaxed settings with respect to overcurrent and ROCOF to handle the transformer energization. The protection group only changes after the first generation source is online, ensuring that the energization is covered by Group 3 and the actual operation of the generation source by Group 2. Because of the commissioning process that tunes the PowerStore to the generator, Group 2 is identical for both operation of the PowerStore only or the generator only.

NB: For clarity only real power flows have been shown in Figure 12; however the same functionality has been demonstrated for reactive power.

When transitioning from an islanded state to a grid connected system and back again, as seen in Figure 13, the GESS adjusts the voltage and frequency output of the PowerStore and generator to ensure that the downstream feeder voltage and frequency are equal to the upstream network voltage and frequency plus/minus an acceptable deviation. This is performed by an ABB Synchrotact which, sensing the voltage waveform using voltage transformers placed either side of the upstream breaker, sends signals to the Microgrid Plus control system which adjusts the output voltage and frequency of the PowerStore and generator accordingly to synchronise the two networks. The actual breaker operation is handled by the REF630 to ensure that the power system protection algorithms operate correctly during the transition. Because the system also synchronises the phase angle of the two systems the synchronization can take a short period of time before the voltage, frequency and phase angle are within acceptable limits. Only then is the upstream breaker closed, the HV neutral switch opened and (in this case) the downstream feeder load transferred to the upstream network by ramping down the output of the PowerStore™ and generator. Transitioning back to an Islanded state follows the same method as described above; when the power flow across the upstream breaker is zero the upstream breaker is opened and the HV neutral switch is closed.

NB: The results presented show only the real power values for clarity. Additionally different sampling rates were utilized for various parameters (notably PS1U12Act, Gen1U12Act and Net1FAct).

When performing peak lopping, as seen in Figure 14, the Microgrid Plus control system injects power into the system from the PowerStore or generator to maintain the upstream feeder load at an upstream feeder maximum power setpoint while meeting the downstream feeder requirement. The setpoint can be set to positive values, whereby both the network and the GESS share the supply of the downstream load, or negative, where the GESS acts as a traditional network generation source supplying power to both the downstream load and upstream network. When both the PowerStore and generator are online, they passively and proportionally share the power load requirement. As Figure 14 shows, if the upstream demand is below the setpoint the GESS stops supply from both generation sources, as it is not required.

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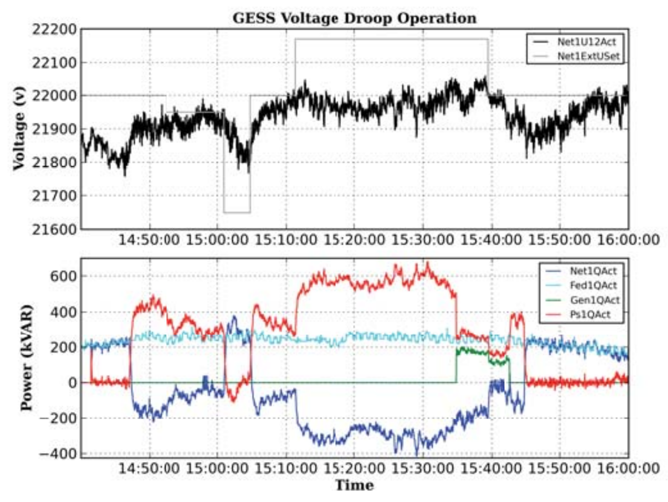

15 GESS Voltage Droop Operation. Upstream feeder voltage (Net1U12Act), voltage droop setpoint (Net1ExtUSet) and reactive power (Net1QAct), downstream feeder reactive power (Fed1QAct), generator reactive power (Gen1QAct) and PowerStore reactive power (Ps1QAct) during voltage droop operation

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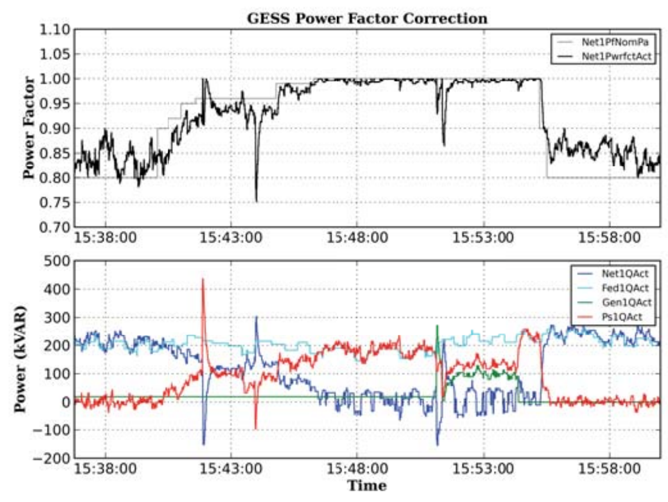


16 GESS Power Factor Correction. Upstream network power factor (Net1PwrfctAct), power factor setpoint (Net1PfNomPa) and reactive power (Net1QAct), downstream feeder reactive power (Fed1QAct), generator reactive power (Gen1QAct) and PowerStore reactive power (Ps1QAct) during power factor correction.

Additionally, Figure 14 shows the GESS system battery management scheme. As the GESS provides energy to the upstream and downstream network the state-of-charge of the batteries declines. When the state-of-charge of the batteries reaches a minimum setpoint (shown here at 35%) the microgrid system changes the proportional rate at which the generator and PowerStore load share, reducing the loading on the PowerStore to reduce the rate of discharge by increasing the loading of the generator. This proportional rate change is dynamic, increasing the loading of the generator as the state of charge of the PowerStore reduces.

NB: Only real power values are shown for clarity but the same behavior is demonstrated with reactive power.

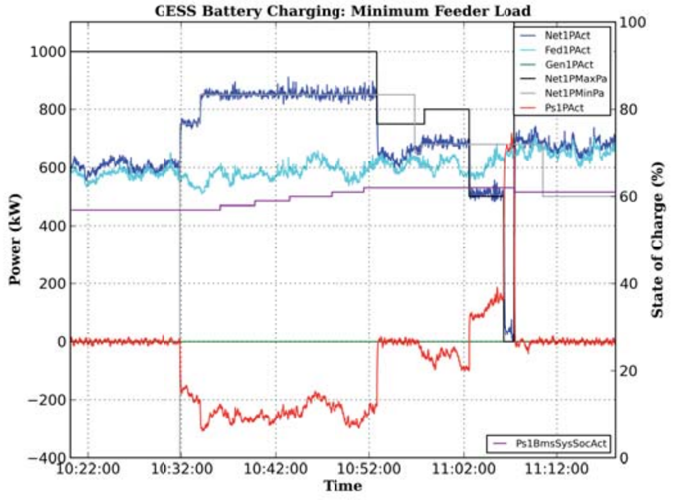
When operating in voltage droop mode, as shown in Figure 15, the system compares the network voltage to a set parameter, with the difference between the two values being used to determine the amount of reactive power injected or absorbed from the grid in order to stabilize the network voltage. Utilizing a 3% droop characteristic, Figure 15 shows the reactive power delivered to the upstream network and the downstream feeder by the PowerStore and the generator. Figure 15 shows the PowerStore and the generator proportionately sharing the reactive power requirements. When the network voltage is above the setpoint the GESS absorbs reactive power, while when the voltage is below the setpoint the GESS injects reactive power into the network to passively influence the network voltage.

Power factor correction, as shown in Figure 16, is performed by injecting or absorbing reactive power into the network in a manner similar to that employed by the voltage droop algorithm. By comparing the network power factor to a setpoint the GESS injects or absorbs reactive power to make the power factor seen at the upstream network breaker as close to the setpoint as possible, if the setpoint is greater than the power factor. The downstream feeder requirement for reactive power is also supplied by the system. Because of the synthetic generator models used in the PowerStore and the microgrid control system, this can be achieved with both the PowerStore and generator online, whereby they will proportionately share the power loading.

Charging at minimum feeder load, as shown in Figure 17, charges the battery while also meeting the downstream feeder load. Charging while maintaining minimum feeder load uses two setpoints, the maximum and minimum upstream feeder load. The Microgrid Plus control system continually compares the upstream network load to the two setpoints. When charging, the system absorbs power equal to the difference between the minimum power setpoint and the current upstream feeder demand, so long as the upstream feeder demand is less than the maximum setpoint. When the upstream feeder demand is greater than the maximum setpoint the GESS performs peak lopping as described above.

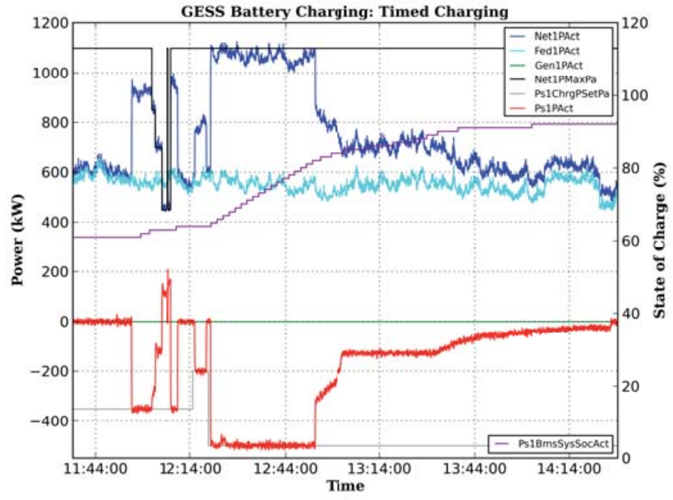
Figure 18 shows the GESS performing a timed charge. As with charging while maintaining minimum feeder load, the maximum upstream feeder load is used to ensure that the system does not overload the upstream feeder. However, in timed charging the power used to charge the batteries is also able to be set, and this parameter determines the power used to charge the batteries. The time period during which to charge the batteries is set through a start time parameter and an end time parameter. The ability to set both the power and time of the charge, coupled with the known size of the battery, enables the charging period to be set to ensure the batteries are fully charged, while limiting upstream feeder loading. Timed charging can also be used to charge the batteries during times of low energy cost, allowing the system to discharge at time of high energy cost when price differences are present.

17



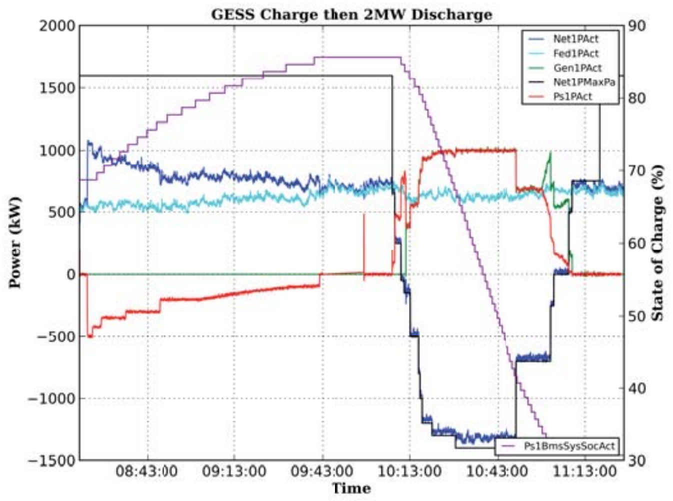
17 GESS Battery Charging: Minimum Feeder Load. Upstream feeder power (Net1PAct), maximum power setpoint (Net1PMaxPa) and minimum power setpoint (Net1PMinPa), downstream feeder power (Fed1PAct), generator power (Gen1PAct), PowerStore power (Ps1PAct) and battery system state-of-charge (Ps1BmsSysSocAct) during charging while maintaining minimum feeder load

18



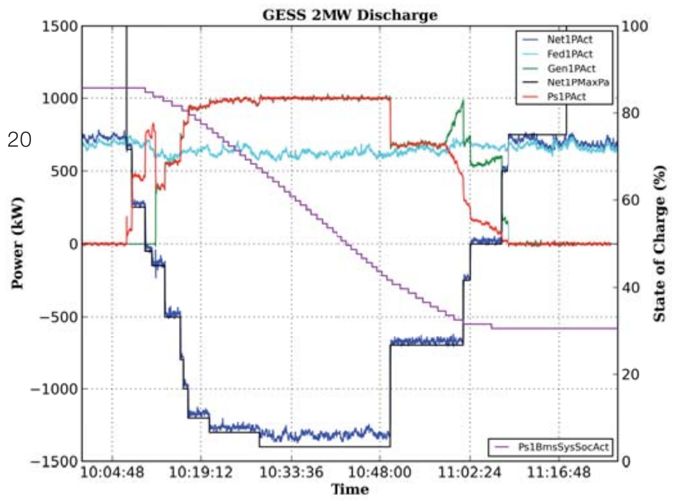
18 GESS Battery Charging: Timed Charging. Upstream feeder power (Net1PAct) and maximum power setpoint (Net1PMaxPa), downstream feeder power (Fed1PAct), generator power (Gen1PAct), PowerStore power (Ps1PAct) and PowerStore maximum charging power (Ps1ChrgPSetPa) and battery system state-of-charge (Ps1BmsSysSocAct) during timed charging

19



19 GESS charging then 2MW discharge. Upstream feeder power (Net1PAct) and maximum power setpoint (Net1PMaxPa), downstream feeder power (Fed1PAct), Generator power (Gen1PAct), PowerStore power (Ps1PAct) and battery system state-of-charge (Ps1BmsSysSocAct) during charge then full power 2MW discharge

20



20 GESS 2MW discharge. Upstream feeder power (Net1PAct) and maximum power setpoint (Net1PMaxPa), downstream feeder power (Fed1PAct), Generator power (Gen1PAct), PowerStore power (Ps1PAct) and battery system state-of-charge (Ps1BmsSysSocAct) during full power 2 MW discharge.

Additionally, Figure 18 shows the GESS battery management system limiting the charging power as the lithium batteries' state-of-charge increases and the charging methodology changes from constant current charging to constant voltage charging. Communication between the Microgrid Plus control system and the Samsung SDI battery management system ensures that the lithium-ion batteries are charged in such a way that maintains system performance and lifetime.

The capability of the GESS to both transition between charging and discharging and to act as a 'traditional' generation source can be seen in Figure 19 and Figure 20. After charging the batteries (using timed charging and demonstrating the power limiting seen in constant voltage charging) the GESS undertakes a full power discharge with both the PowerStore and the backup generator outputting 1 MW, resulting in the downstream feeder load being met and the GESS exporting additional power upstream. Figure 20 again demonstrates the GESS battery management scheme as when the state of charge of the batteries reaches a setpoint (here set at 35%), the load-sharing algorithm increases the proportion of the load that is taken by the generator.

System Outcomes

The results presented show encouraging possibilities for the use of urban systems such as the GESS to defer network investment by providing network support during peak demand. With islanding capabilities and a compact portable design allowing it to be positioned near to customers, the GESS will strengthen the power grid while enabling power system upgrades to be postponed or eliminated. Energy Storage systems such as the GESS also present an effective method of managing temporary feeder disconnection in times of need (line maintenance, bushfire prevention), because the system can support the connected microgrid for time periods sufficient to allow the system interruption to be dealt with.

Future works and Applications

While the GESS is currently under a two-year trial and investigation period, the capabilities of the system as demonstrated show promise for future microgrid applications.

Historically, the PowerStore has used a flywheel-based energy storage system with a capacity of 5 kWh in microgrid applications. The increased and customizable energy storage capacity of the Samsung lithium-ion battery-based system compared to flywheel-based systems shows promise for increasing the contribution of renewable energy sources by over-sizing the renewable resource with respect to the microgrid load to charge the batteries during times of renewable generation, for discharge during times of intermittent/no generation (e.g. using solar generation stored in battery based systems for night time supply). This increased contribution would result in increased diesel savings and reduced emissions in such applications, with the possibility of eliminating the need for backup diesel generation.

Battery-based energy storage systems also show promise for increasing the penetration and contribution of solar generation into larger traditional Macrogrids. The longer duration of intermittencies caused by solar generation compared with wind generation necessitates a support system with a larger energy capacity suited to battery-based storage systems such as the GESS. With such support systems, larger distributed sources of solar generation could be integrated into Macrogrids as their intermittency would be smoothed by a GESS or similar system. Support provided by systems such as the GESS would not be limited to solar generation as any distributed sources of generation could be supported, given the power system supply and stability capabilities of the GESS.

The islanding capabilities of the system also show promise for reducing the severity and duration of outages in larger macro-grids as serious faults can be isolated and rectified, while the supply to interrupted areas is maintained by a GESS. Given the prevalence of bushfires in Victoria, the islanding and 'bumpless' reconnection capabilities of systems similar to the GESS may be used to mitigate the effect of such fires on the supply to remote and rural areas. In such cases, a feeder would be de-energized just prior to a bushfire passing through the area with any disconnected communities supplied by the GESS. Once the fire had passed through and the feeder checked for damage, the line would be re-energized before the GESS would perform a 'bumpless' transition, and the area could then be supplied by the feeder.

The dual functionality of systems with respect to both network supply and stability such as a GESS also show promise in reducing the CAPEX required to integrate high penetration levels of renewable generation into grids. As the one system functions in the same way as both an energy storage device and a STATCOM, the supply and stability issues associated with renewable intermittency (e.g. voltage and frequency variations caused by renewable intermittency) can be mitigated at a reduced CAPEX level in comparison to investing in a stand-alone energy storage component and a standalone STATCOM system component. This is especially important for microgrids, as the smaller power rating of such grids (and economics resulting from related power purchase agreements) usually results in a smaller CAPEX and higher targeted penetration, making effective integration of the renewable resource vital to the success of such projects.

Advances in lithium-ion battery technology with respect to charge and discharge ratings (the 'C' rating) are currently 4C pulsed (whereby a 250 kWh system would be able to discharge at 1 MW for 5 minutes). This opens exciting possibilities for energy storage systems in microgrid applications as the smaller footprint of such systems without a degradation in power rating make them attractive for smaller, remote systems. Increasing ratings also are attractive in larger grid connected systems for local intense peak load support, such as that needed to support arc furnaces, large cranes and hoists and other large, intermittent industrial loads.

> "ABB and Samsung SDI plan to continue to develop modular and scalable energy storage systems for use in microgrids and other applications, and will continue to explore the possibilities that such technologies will enable our customers to reduce their environmental impact and increase stable and sustainable renewable penetration and contributions to their grids."

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