Opportunities for Battery Storage and Australian Energy Storage Knowledge Bank Test System for Microgrid Applications

Nesimi Ertugrul MIEEE, Graeme Bell, Gabriel G. Haines and Qing Fang
School of Electrical and Electronic Engineering, The University of Adelaide, Adelaide, Australia, 5005

***Abstract*— Due to the availability of suitable technologies, a number of battery based energy storage solutions have already been developed, implemented and deployed around the world. However, due to the large scale of penetration of renewable energy sources and unique characteristics of Australian power network, energy storage can also present specific solutions. Although the battery technologies are developing continuously and are becoming highly competitive options, their interactions in an ever growing complexity of microgrid applications need special attention. This paper highlights the opportunities in Australia and also explains the characteristic features of the mobile test system platform and the network structure, which aims to respond the industry's needs while providing training and research facilities.**

Keywords—battery storage; battery testing; battery storage knowledge bank; microgrid.

I. INTRODUCTION

Demand on the electricity grid is unpredictable, and supply must meet demand. However, the renewable energy integration has changed the landscape of the traditional power grid and impacted of the demand pattern, which can be detrimental on the network operation since it is also unpredictable.

In addition, the network operation became highly challenging in Australia specifically in networks which are: a) weak, long and thin (such as rural farming and community loads), b) have limited import/export opportunities (such as between the states), c) have large load variations (which is likely to be associated with heat waves, or mining loads), d) have low power system inertia (due to decommissioning old power stations). However, the key requirements in a power network remain the same: to provide the power safely at acceptable power quality levels and at low cost.

It can be noted that to address a wide range of generation, transmission and distribution related problems and limitations, utility and industry scale battery storage applications can be utilized, which are summarized in Table 1.

In addition, three different application areas can be defined that suits to Australian landscape (two of which are off-grid): fringe-of-grid areas that are likely to experience reliability and power quality issues, isolated or islanded systems, and remote/very remote areas such as mining sites. It is important to note that the size of off-grid electricity market is over 7 % of the total electricity demand and a total installed capacity of about 5GW (22% from diesel fuel) [1]. Although the reduction in fuel consumption depends on load shape, renewable resource and generation profile, the battery storage can also offer significant savings in off-grid applications.

Note also that mining sites have a range of large loads that demands quality power and significantly varying dynamic reactive current both during starting and normal operation. These result both in large reactive power variations and voltage fluctuations (up to 10%) on the line [2] which needs to be addressed appropriately both for the system stability and also to address the power quality issues. Note that voltage fluctuations are the major issue in electricity networks with the integration of renewable energy (PV and wind). Furthermore, when we consider the randomness of the mining loads and their co-incident simultaneous operation, it is expected that the demand cycle of the multiple loads might have a very large short term power variation incidentally. Therefore, battery storage technologies can offer solutions and mitigate the problems in mining applications.

TABLE I. THE BATTERY STORAGE SOLUTIONS IN POWER NETWORKS

<table>
<tr><th>Generation Level</th><th>Transmission Level</th><th>Distribution Level</th></tr>
<tr><td rowspan="2">• Fast-response frequency regulation
• Black start
• Spinning reserve
• Back-up and mission critical power
• Power plant hybridization
• Ramp rate management
• Peak demand management
• Mitigating intermittency (firming)</td><td>• Dynamic line rating support
• Dynamic stability support
• Reducing interconnection cost
• Voltage support of long radial circuits</td><td>• Energy storage for utilities
• Facilitating high PV penetration embedded microgrids
• Energy arbitrage
• Ramp-Rate control of PV inputs</td></tr>
<tr><td colspan="2">• Increase asset efficiency and utilization and ancillary services
• Loss reduction
• Voltage support
• Peak-shaving, load and time shifting
• Power quality improvement
• Power reduction in curtailment events to shut down to mitigate issues associated with generator loading, export to the grid, or certain planning conditions.</td></tr>
<tr><td colspan="3">• Renewable integration (wind and solar) • Reactive power control
• Asset deferral</td></tr>
</table>

Due to the size of load, the large utility scale energy storage applications can also be classified reference to their technical characteristics, which are summarized in Table 2. Note that, from the critical load view point, it is not important whether voltage and/or frequency fluctuations come from load or generation. They still require regulation and mitigation, which can be effectively provided by energy storage such as batteries. Note that these common storage applications are also relevant to mining sites and also mining associated loads.

TABLE II. TECHNICAL CHARACTERISTICS OF UTILITY SCALE ENERGY STORAGE APPLICATIONS

	Technical Characteristics			
Common Storage Applications	**Power (MW)**	**Backup Time**	**Cycles /Year**	**Storage Response Time**
Spinning reserve	~100	hours	20-50	sec to min
Load levelling	~100	hours	250	minutes
Black start	~100	hours	seldom	<1 min
Investment deferral	~100	hours	>100	minutes
Power regulation with intermittent sources	<10	min	1000s	<1 min
Integration of non-predictable sources	~10	min	frequent	<min
Power quality	<1	min	<100	10s - 1 min
Line stability	~100	sec	100	~ cycles
Power oscillation damping	<1	sec	100	~ cycles

The variable nature of battery operation and requirements in real operating conditions means that specific functionality (and battery selection) requires special attention in any given application. In the following sections of this paper, a brief overview of battery trends will be given and the details of the Australian Energy Storage Knowledge Bank Test System (AESKB) will be provided to demonstrate its capabilities available for industrial and research purposes.

II. BATTERIES AS ENERGY STORAGE

The energy storage solutions are growing very fast to respond to some of the network related issues and limitations as mentioned earlier. It was reported in [3] that global commercial and industrial energy storage system power capacity deployments are expected to grow from 500 MW in 2016 to 9 GW in 2025. It is also envisaged that there are five major trends that drive the future of energy storage: including the rise of consumer and utility storage markets, modularity driven manufacturing, innovations from IT companies, residential storage needs, and energy storage-enabled virtual power plant concepts.

Although the key selection criteria for batteries are energy density, cycle life, calendar life, operational temperature range, and charging/discharging rate; the wide utilization of batteries will depend on primarily the cost and energy density. It is predicted that one of the most common energy storage devices, batteries, will cost five times less with five time more energy density by 2018 [4]. These clearly demonstrate the future of batteries as a form of energy storage.

The battery types Li-Ion, NaS flow, Lead-acid, Vanadium-Redox flow, NiCad and Ultra Batteries (Asymmetric ultra-Capacitor/ lead-acid) have all successfully developed and implemented energy storage applications. The year 1987 can be marked as the arrival of utility-scale battery storage technologies initially supported by Lead-acid battery, which are mostly ceased their operations in largest scale. However, the application activities have accelerated by the developments and maturity in NaS batteries by 2006 and Li-Ion batteries by 2009. Ni-Cad battery also found a unique place in cold climate operation as implemented in Alaska in 2003. Vanadium-Redox Batteries also appear to demonstrate performance suitable for utility and industry scale energy storage applications.

Note that 86 % of energy storage system (ESS) power capacity deployed worldwide in 2015 are Li-Ion types, which covered the technologies in the areas of distributed energy storage system and behind-the-meter (BTM) market segments. This is primarily due to a combination of energy density, efficiency, cycle life, warranties, and cost. In addition, Li-Ion batteries offer a range of subchemistries with different operating characteristics that are suitable for specific applications.

The yearly load utilisation or duration curves can provide us an insight to the size of battery storage, specifically on grid and off grid remote area applications (requiring long back up times, see Table 2). In the analysis of such curves it can be observed that a small percentage of the demand is always higher than the threshold value, which may be the agreed maximum demand or an optimized value limited to reduce the cost. Then the level of powers above a threshold level can be considered as the additional generation dispatch required to support load increases. This excess can be provided by a battery storage system. In those support applications where the energy storage is required for seconds or minutes battery sizing needs careful attention which needs to consider C ratings as well as the inverter sizing both during charging and discharging.

III. ENERGY STORAGE KNOWLEDGE BANK SYSTEM

Applicability of some energy storage technologies in both on-grid and off-grid systems depend on system size, reliability standards, spinning reserve as well as generation technology, which may include a number of different energy storage technologies, from batteries and capacitors to mechanical storage such as fly wheels.

Therefore, the main aim of the test system described in this paper is to provide both an advanced testing, training and research platform for the components of battery storage systems in real applications that usually contain multiple generation and load options.

Australian Energy Storage Knowledge Bank (AESKB) mobile test system is built in a custom built container aiming to address the utilisation of energy storage technologies specifically in real environments that can be deployed around Australia. The project is funded by ARENA (Australian Renewable Energy Agency) currently under contruction and it has been planned to perform the first grid connected tests by the end of 2016.

A. *Hardware Specifications:*

The major components of the test system are illustrated in Fig 2. The test system has following main charactersitic features:

An LG Chem type battery bank with a total of 273kWh energy capacity (expendible to 354kWh), a 350kVA isolating transformer, a 270 kW bi-directional ABB inverter (expandible to 360kW) and suitable switchgear and bus bar configurations. In addition, 200kW dynamic load bank will be available via an external connection.

B. *Data Acqusition System*

The data acquisition system will use 35 voltage and current transducers to measure the voltage, current and power at 9 different locations in the test system. These quantities will be continuously acquired every second. Measurements will include RMS, peak, fundamental and THD values. When a power quality event is detected, high bandwidth waveforms are also recorded for each transducer for the duration of the power quality event.

Note that the majority of the electrical quantities are recorded with a bandwidth of between 10kHz to 50kHz, and up to 250kHz for the inverter electrical quantities. Precision RTD sensors (resistance temperature detectors) are used to measure temperatures at 8 locations each in the inverter and battery compartments (16 total, expandable if required). A weather station and associated data will also be recorded to link to the operating condition of the system and system components under real environmental conditions.

C. *Mobile and Stationary Test Platforms*

The containerised component of the AESKB platform will be transportable and able to be relocated as required to deliver its functionality in any location. In addition there will be 500kVA diesel generator and 6x120kW induction motor loads are also available on a university site to perform primarily off-grid tests and performance tests of various components.

D. *Duration of Tests or Trials*

The duration of tests conducted away from the stationary test facility (field trials) will range in duration from month(s) to year(s).

E. *Battery Tests*

All test programs for a given battery will begin and conclude with standard full charge / full discharge capacity tests to determine Ah/kWh capacity of the bank at commencement and on completion of the test program.

The primary focus remains on testing how batteries perform in various real-life battery applications. Therefore, the test system will not be carrying out the range of specific tests normally associated with cell tests such as type testing, safety compliance testing, or standards testing. Total kWh throughput/cycled will be monitored for all batteries tested. Progression of cumulative kWh throughput will be periodically time-stamped so that other cell performance attributes can be linked to this measure of service life. In addition, cell level data (including temperatures and voltages) will also be available via the BMS and/or using additional sensors if test involves a specific battery performance test.

F. *Network Structure*

The test system includes standard termination arrangements for interconnecting cables from a compatible third party battery (if used). An open source software coding platform has been used to facilitatedevelopment of custom interface at the BMS where required. The system also deploys an “Internet of Things” controller architecture. The AESKB network structure is illustrated in Fig.1.

The data logging system will be composed of two National Instruments CompactDAQ systems that acquire the sensor data, and the logging PCs that process and store the data. Historical data is archived on the Network Attached Storage (NAS). Real time summarised data are encrypted and sent over the 4G network to the knowledge bank server. The 4G link also provides remote monitoring and management of the logging system. The ‘Knowledge Bank’ server stores the detailed historical data, and provides access to this data for web based users. The web users will be able to access a range of information from real test data of the system and its components to knowledge based research outputs as well as links to the other energy storage sites.

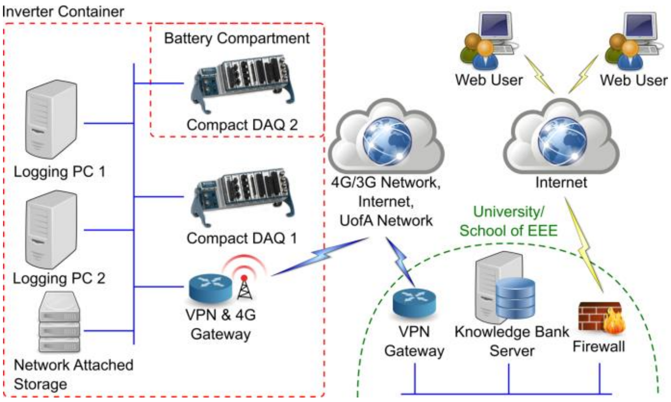

Fig. 1. AESKB Network Structure

IV. CHARACTERISTICS AND MODES OF THE TEST SYSTEM

A grid battery is usually the result of a design process involving a carefully customised or tailored pairing of a bi-directional inverter and a battery system. For example, the operating voltage range of the battery bank between minimum and maximum levels must suit the allowable input voltage range of the chosen inverter. Maximum inverter power levels (during charging/discharging) should not cause current levels in the battery that exceed allowable levels applicable at any given state of charge.

In addition, inverter controller platforms at the battery and inverter interfaces must use communication protocols that are compatible with the Battery Management System (BMS) and embedded inverter controller. Moreover, further signal conditioning circuits also need to be interfaced the inverter/ application controller as well as the inverter and battery system.

The ‘Plug and Play’ functionality of the AESKB mobile and stationary test platform are designed within the confines of the reality that boundary conditions at the interface are

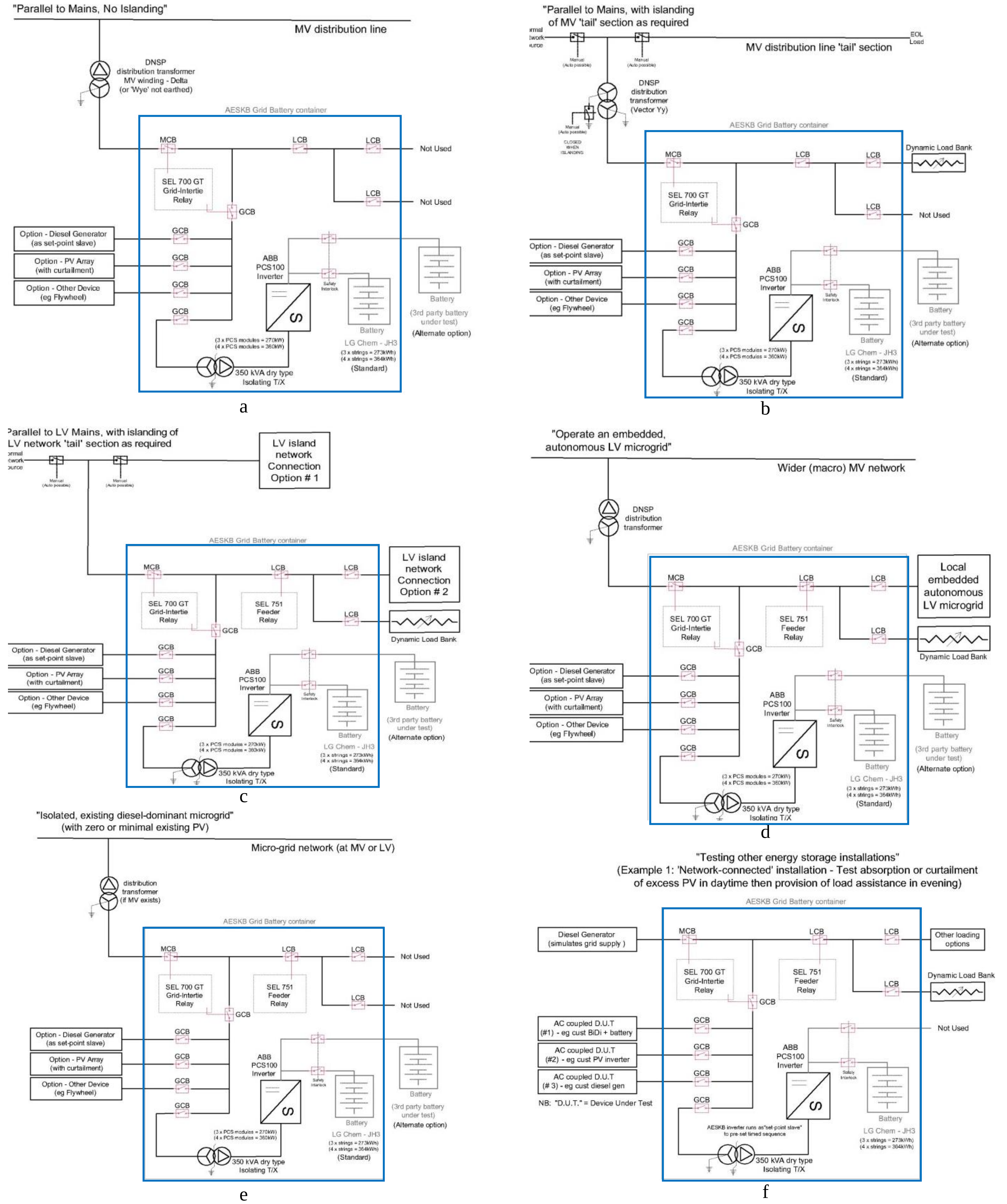

Fig. 2. The principle connection diagrams of AESKB test system illustrating operational modes for specific tests in microgrid applications: a) Parallel to mains only, No islanding, b) Parallel to mains with islanding of an MV feeder 'tail' section, c) Parallel to LV network mains only and carrying an LV 'tail' section only, d) Parallel to mains with an embedded LV microgrid load, e) Parallel to Mains with embedded LV microgrid plus PV array and/or Diesel Generator, f) Parallel to isolated microgrid.

TABLE III. THE PRINCIPAL OPERATING MODES AND CORRESPONDING POTENTIAL TESTS

MODES	**POTENTIAL TESTS**
1. Parallel to mains only, No islanding	• Peak shaving above a set point; reactive power support capabilities; demonstrating arbitrage; and showing stability at maximum continuous charge / discharge rates.
2. Parallel to mains with islanding of an MV feeder 'tail' section	• Off-line demonstrations of inverter grid-forming and maximum step load capability; inverter behaviour at top of charge with excess microgrid generation; confirmation and test of realistic "induced fault" scenarios to test adequacy of protection schemes applied to the "normal parallel to mains" and "MV island" scenarios. • On-line demonstration to form an island (MV microgrid) supply from standstill; ability to maintain stable supply to MV microgrid.
3. Parallel to LV network mains only and carrying an LV 'tail' section only (Future)	• Off-line demonstrations of inverter grid-forming and maximum step load capabilities; demonstration of inverter behaviour at top of charge with excess microgrid generation; confirmation and test of protection relay set-points relevant to the "normal parallel to mains" and "LV island" scenarios. • On-line confirmation of ability to form an island (LV microgrid) supply from 'standstill' and ability to maintain stable supply to MV microgrid. Demonstrate seamless segregation and bump-less reintegration with network.
4. Parallel to mains with an embedded LV microgrid load (connected directly to the grid battery)	• Off-line demonstration of inverter's grid-forming capability, maximum step load capability and forming microgrid supply following loss of normal supply • Demonstrate seamless segregation and bump-less reintegration with network, with the battery supplying the embedded LV load during disconnection with network. • Demonstrate adequacy of protection arrangements through simulated faults.
5. Parallel to Mains with embedded LV microgrid plus PV array and/or Diesel Generator (or other generation sources) connected directly to the grid battery (and controlled by the grid battery) "Future"	• Seamlessly disconnect from the network supply following failure of that supply (voltage levels or supply frequency out-of-bounds) • Demonstrate inverter capability to "form" a grid supply (to the embedded LV network), follow the microgrid load using a frequency droop response, operate a connected diesel generator as a set point slave, and curtail any controllable PV connected either directly at the grid battery, or distributed around the microgrid. • Demonstrate grid battery ability to carry out "bump-less reintegration" once stable network supply becomes available again. • Whilst connected to the network, demonstrate the ability of the grid battery to buffer the network from the potentially disruptive effects of a "high penetration level PV array" connected directly to the grid battery and forming a part of the embedded LV microgrid. • Demonstrate optimal deployment of PV energy in terms of an imposed "hierarchy" or priority.
6. Parallel to isolated microgrid. (Similar to 'PTM', but the network is a microgrid.)	• Synchronise grid battery to an existing microgrid supply at LV when the voltage and frequency of that supply is within bounds • Safely disconnect from the microgrid supply following failure of that supply (voltage levels or supply frequency out-of-bounds) • Read a remote power meter indicating total load values (P, Q, PF, etc.) as would apply at the existing DG power station; to curtail PV inverter output to a (moving) target; to maintain total load on an in-service DG to be just less than a pre-set critical threshold level, while connected load on the microgrid is increasing beyond that level. Maintain this balance by discharging from the battery and / or running the small DG connected to the grid battery. • Demonstrate ability to reduce magnitudes of step loads applied to an existing diesel generation station • Demonstrate ability to impose ramp rate controls for loads on an existing microgrid.

accommodated. The AESKB project has addressed this by making the choices during the design and specification stages and the operational modes are illustrated in Fig. 1. Table 3 has also been given to summarise basic tests corresponding to each mode of operation. Note that the operational modes marked as “Future” will be made functional once the specifications of the tests are fully available. Note that various other operating modes can also be created to accommodate other operating scenarios, including fault scenarios. The work required to accommodate any other operating modes primarily depends on the development of the controller source code.

Note that the test system incorporates a flexible three phase low voltage switchboard / switchgear arrangement that allows it to be configured and operated in different modes, which can simply be classified under three main groups: grid-connected, fully isolated island, stand-alone ‘load or generation’ slave operating to a sequence of set-points intended to test the functionality of a third party energy storage device.

In all arrangements, connection to the network (and / or microgrid) occurs at LV and where the network that being supported operates at MV then an interconnecting step up transformer is required.

If the grid battery is only providing ‘Parallel to Mains’ support (no MV islanding) then a standard winding distribution transformer, delta HV/wye LV, is adequate. However, where the grid battery is required to carry a section of MV feeder as an island then a ‘wye/wye winding arrangement will be required and the HV star point earthed only after normal network MV supply has been lost (or removed) and before the islanded MV supply from the grid battery is formed.

When connected to a network, the network supply needs have the standard earthed neutral arrangement, capable of driving unbalanced single phase loads because the auxiliary supplies within the grid battery are single phase loads.

V. Conclusions

The battery storage technology in grid, utility and industrial applications is emerging significantly within the last decade. It is clear that energy storage in grid asset optimisation, T/D deferral and renewable integration will emerge strongly as anticipated and will increase exponentially.

It is envisaged that, in Australia, the integration of energy storage systems will also occur at the existing wind turbines. This will significantly increase the percentage of wind energy penetration, will improve intermittency and hence will alter the network operation while improving quality, stability and wind power’s efficiency.

In mining applications, to improve reliability of the existing electricity network and to increase access to electricity services battery storage can be used together with renewable energy solutions as well. Note that even few hours discharge durations via batteries may be a technically viable way to defer potential transmission and distribution upgrades in critical loads such as mining. Battery storage systems can also offer effective solution for critical contingency frequency control.

In addition, the problems associated with the high PV penetration on distribution systems can be rectified by the localized battery storage system and even operate in a forced-islanding mode (in a street or suburb level) with suitable inverter and high speed communication technologies.

Although some desirable battery types are not available and economical yet in utility and industry scale applications to provide sufficient energy or power density and often do not live up to cycle life expectations, there are a number of batteries which can still offer acceptable and reliable solutions as it was demonstrated in real applications. A screening study [5] has also reported and assessed batteries and rated them against a number of criteria, to identify emerging electricity storage technologies that are anticipated to be available within the next few years. Although there are still some shortcomings, Li-Ion batteries have emerged as one of the leading technologies. In addition, Na-S batteries improve cycle life and dynamic discharge profiles for large scale stationary energy storage applications.

Finally, to understand battery and inverter performances, power quality issues and complex interactions in on-grid and off-grid operations a mobile battery storage test system has been described in detail. The detailed measurements obtained from the test system can provide critical load profile data to understand the interactions between the battery and other supplies, loads and the network. In addition, the test system can be used for training and research purposes to provide the unique skills required in Australia. Furthermore, data can be used to develop a local area computer model to understand the dynamic behaviour of the network under potential fault scenarios at specific sites and at the point of common connection.

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