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Battery energy storage systems for the electricity grid: UK research facilities

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Abstract

Grid-connected battery energy storage systems with fast acting control are a key technology for improving power network stability and increasing the penetration of renewable generation. This paper describes two battery energy storage research facilities connected to the UK electricity grid. Their performance is detailed, along with hardware results, and a number of grid support services are demonstrated, again with results presented. The facility operated by The University of Manchester is rated at 236kVA, 180kWh, and connected to the 400V campus power network, The University of Sheffield operates a 2MVA, 1MWh facility connected to an 11kV distribution network.

1 Introduction

Power balance in the electricity grid has traditionally been achieved by ramping generation to match demand [1]. This is detrimental to both plant efficiency and life [2], and is insufficient when high levels of non-controllable 'renewable' generation exist. Grid connected energy storage overcomes these limitations by providing a power buffer, which decouples the load from the generation capacity [3], to maximise efficiency and optimise the carbon intensity of the power network.

Battery energy storage systems (BESSs) are becoming economically viable for grid connected energy storage [4]. Electrochemical energy storage in battery modules can be both modular and scalable, while offering high round trip efficiency, long cycle life, and with low maintenance requirements [2]. BESSs can perform a wide range of grid support services which improve network efficiency and stability [5], thus increasing profitability [4]. Crucially battery systems are also able to provide the fast response rate required to achieve many of the high value benefits from grid connected energy storage [6].

BESSs with a fast control response are a key technology in facilitating the increased uptake of renewable generation systems [1]. Renewably generated electrical energy can be stored when its output exceeds network capacity and supplied when load demand is high [7] thus ensuring that dispatch commitments are met. For example research, [8], has suggested that energy storage with a 10 minute capacity can allow 10% more wind energy to be absorbed without network reinforcement. Furthermore, an inability to store energy contributes to short term volatility in the energy market [9] which in turn may deter investment, particularly in renewable generation sources.

The modern power network requires energy storage in order to improve its efficiency and use of renewable generation, however, BESSs are costly and so the local power system operator may incentivise their installation by regulation, direct finance, or indirectly by paying for the services they provide. To really drive the installation of network storage capacity the BESS must offer a good financial return to investors, with income outstripping the devaluing, or aging, of the main asset, the battery. The business case for energy storage requires value to be accrued from multiple grid services [10]. Therefore the challenge is to optimise the BESS control to provide multiple services while minimising battery aging.

1.1 Existing battery energy storage systems

This section provides an overview of BESS installations throughout the world detailed in academic literature, with a particular focus on UK-based systems with lithium batteries. Initial findings have been published from a 200kW, 200kWh BESS connected to the 11kV distribution network near Great Yarmouth, UK [11]. However, results show a response time frame of minutes, not fully utilising the capability of the technology. Table 1 lists lithium-based BESS and their usage.

Table 1: Installed grid-connected lithium-ion BESS

Rating	Location	Usage / comment
10MW, 10.8MWh	Feldheim, Germany	Grid load and frequency support
6MW, 10MWh	Leighton Buzzard, UK	For upgrade deferral, peak shaving, arbitrage [12]
200kW, 200kWh	Great Yarmouth, UK	For research, 11kV connection, [11]
250kW, 100kWh	Quebec, Canada	Lithium-ion, for research [13]

Globally there are a large number of BESSs in commercial operation, with the majority of them used to smooth the output from renewable generation. BESS technology is most commonly used in Japan [14] [15] [6] and the USA [16] [17] [18] [6]. The number of commercial installations demonstrates a positive outlook on the economic viability of BESSs.

This paper considers fast acting control of BESS with practical results from active hardware. The two hardware systems are installed for research purposes meaning that full control of their operation is afforded to academic use.

2 Grid services offered by energy storage

Energy storage is typically installed with the aim of providing a single function to the grid or local user; this ensures a straightforward economic assessment for installation and operation. Alongside these primary services, the storage can also be tasked to provide ancillary services for the grid, which may be paid, but the exact mechanism varies according to the local power system operator.

Primary services include: **Upgrade deferral** for transmission and distribution systems by easing network congestion [16], this is particularly required where high levels of renewable generation exist [19]. **Capacity firming** by providing a power buffer to ensure economic despatch [20], allowing generators to avoid financial penalties on despatch bids [21]. **Price arbitrage** to take advantage of price difference in the free energy market [18], **backup power** for emergency or selective islanding [10], and the time shifting of energy which may be used for **peak shaving**.

Ancillary services contribute to the stability and health of the overall power network, and are best characterised according to the time scale on which they operate [18]. Primary and ancillary services provided by BESS are shown with their time scale and approximate value in Figure 1.

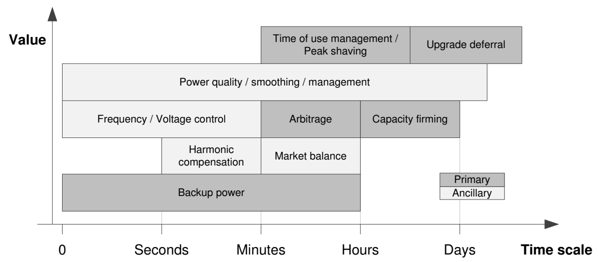

Figure 1: BESS grid services with time scale

To ensure stability, the power network requires frequency control and power quality support at a rapid ramp rate, this is often referred to as spinning reserve [21], and also acts to stabilise the energy market [18]. Power management may take place over a broad time scale to support the network in relation to specific assets and conditions, and as such has a high value. Frequency regulation and power smoothing are also required over a longer time frame [18]. Harmonic compensation and voltage control, by power factor correction are also achievable. Power flow management may be used to correct for short duration faults, to longer term weather and seasonal variations in load and generation [10].

3 System descriptions and performance

This section provides detailed descriptions of both the hardware and control schemes for the BESSs at the University of Manchester and The University of Sheffield. Performance data is also provided including: round-trip efficiency, ramp rate, and control bandwidth.

3.1 University of Manchester

The University of Manchester has recently commissioned a 236kVA, 180kWh, BESS which is connected to the 400V campus power network within the Manchester city centre. The energy store consists of four banks of fourteen series connected 48V lithium-ion polymer battery UPB4860 modules, supplied by LG Chem. Each of the banks has their own Battery Management System (BMS) which monitors the cell voltage and temperature, and reports SOC and SOH. The battery banks are arranged in two pairs each connected to a 118kVA inverter; the inverters are paralleled on the AC side. The power hardware is designed and built by Siemens and marketed under the name SieStorage. The electrical power connections as well as the control structure are shown in Figure 2; a photograph of the facility is shown in Figure 4.

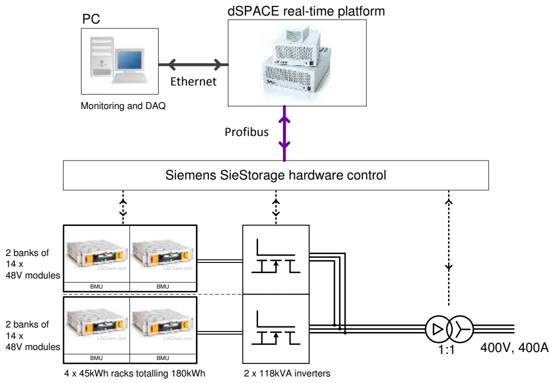

Figure 2: Schematic-180kWh BESS with real-time controller

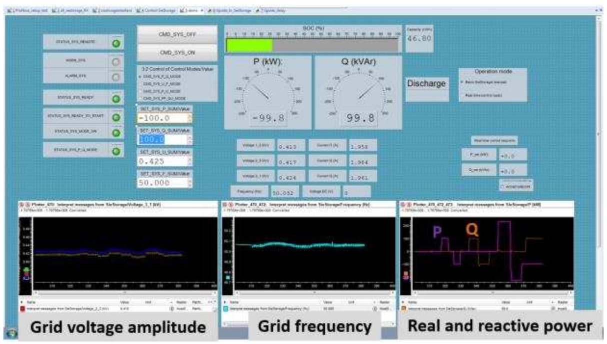

Figure 3: Real-time controller HMI screenshot

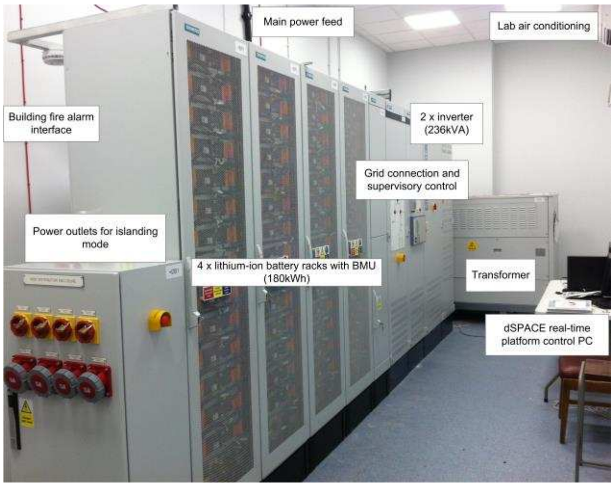

Figure 4: Photograph-BESS facility

The SieStorage system has a dedicated hardware controller which monitors signals from the battery racks, inverters, transformer and network connection, and commands the inverter set-points. The hardware control ensures the safe operation of the BESS and can perform several operational and service functions. A bespoke control interface, using a dSPACE real-time controller has been developed, which can access all the measurements made by the hardware controller and controls the power flow delivered by the inverters. The BESS with real-time control has a control bandwidth of approximately 0.5Hz. A HMI, shown in Figure 3, allows real-time control of the BESS and can be used to implement control algorithms, and record measurements over long durations.

Performance data (University of Manchester)

The rapid response of the BESS to a full power (230kW) discharge to a full power (230kW) charge is shown in Figure 5.

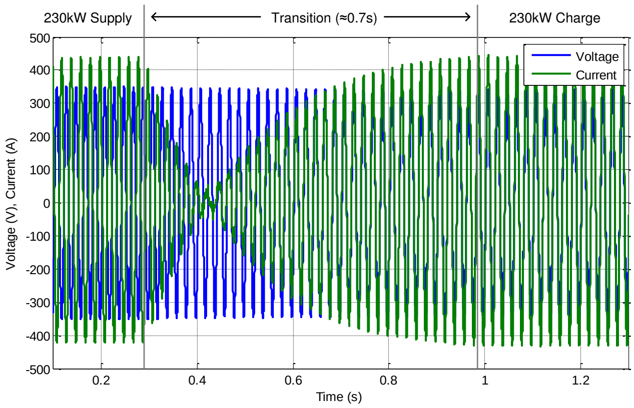

Figure 5: Voltage and current for transition from supply to charge at rated power

Initially the phase voltage and current are 180° out of phase representing unity power factor operation while the battery is being discharged. The reversal of the power output is requested at approximately 0.3s in Figure 5. In response to this change in power set-point, the RMS current falls rapidly to zero in a little over 0.1s, before being ramped up over approximately 0.6s until the current equals the nominal value and is in phase with the voltage; during this region the battery is being charged. The full transition takes approximately 0.7s and represents a power swing of nearly 0.5MW. Although the fast dynamics of the inverters offer the potential for a more rapid transition the ramp rate of the current is limited in order to protect the battery. A low harmonic distortion in the waveforms can also be observed, which has a THD of 2.8% at nominal power, which is comparable to the measured THD of 3.0% with the BESS power breakers open.

The round trip efficiency of the BESS is calculated from measurements of SOC and power when the battery is fully charged and discharged at rated power; such waveforms are shown in Figure 6.

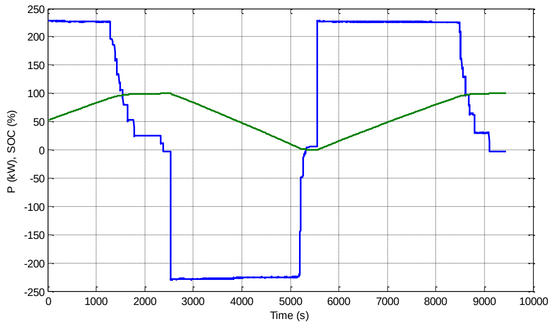

Figure 6: P and SOC for a full charge and discharge cycle

The initial SOC in Figure 6 is just above 50% and rises to full charge as rated power is applied. When SOC reaches 100% the power is reversed until SOC falls to 0% before again charging to 100%. SOC rises and falls linearly, but as it approaches 0% or 100% the hardware controller reduces the power level to limit battery current.

A full charge of the battery, at rated power, uses 194.4kWh, while the full discharge of the battery, at rated power, delivers 169.9kWh. This represents a round trip efficiency of 86.6%, this figure include the power consumption of the control platforms, the BMS system, self-discharge of the batteries, and transformer losses but excludes air conditioning.

3.2 The University of Sheffield

The University of Sheffield (TUoS) has built a bespoke 2MVA, 1MWh BESS based on a Toshiba Lithium Titanate battery and a 2MVA ABB inverter. The interface and communication between the two parts of the system is done by a bespoke control system built by the University of Sheffield. An overview schematic of the system is shown in Figure 7.

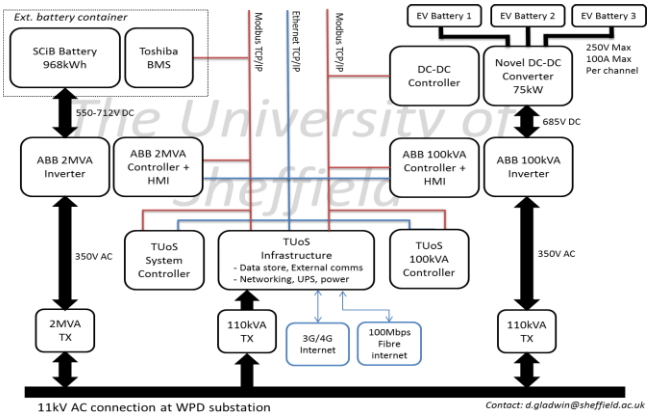

Figure 7: TUoS BESS schematic

In addition to the BESS, a flexible DC / DC and 100kVA inverter based system is installed for interfacing 'second life' EV batteries to the utility supply for grid support applications. The systems are grid connected to the 11kV utility supply at the WPD Willenhall substation in the West Midlands. To facilitate operation, the whole system can be controlled remotely over a dedicated VPN connection, over 'fibre' or a 3G network. Data from the system is available via an SQL database, updated on a 1s timescale, and can allow access to voltage, current and temperature of any of the >21,000 cells in the system. The bespoke nature of the system allows flexible control and rapid response from the hardware.

The TUoS system is capable of power transients from 2MW charging to 2MW discharging within 2 cycles of the utility supply. An example of the transient capability is shown in Figure 8, which shows the 3 phase currents on the 350V side of the 350:11kV transformer, when a discharge transient from 0 to 2MW is requested from the system.

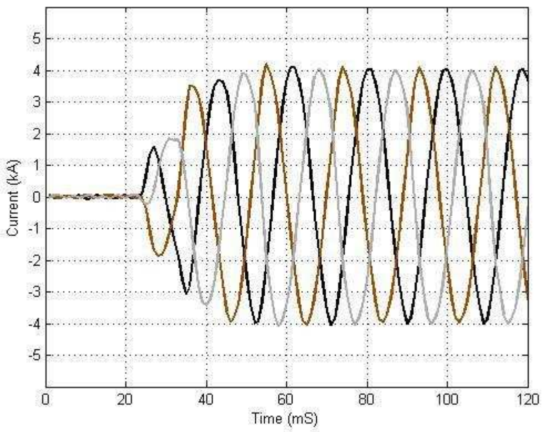

Figure 8: TUoS Output phase current transient

Both the BESS and the second life systems are capable of being fully controlled remotely, or switched to local control where the inbuilt controller can perform programmed tasks, for example frequency response following the National Grid EFR tender regime, as shown in Figure 9.

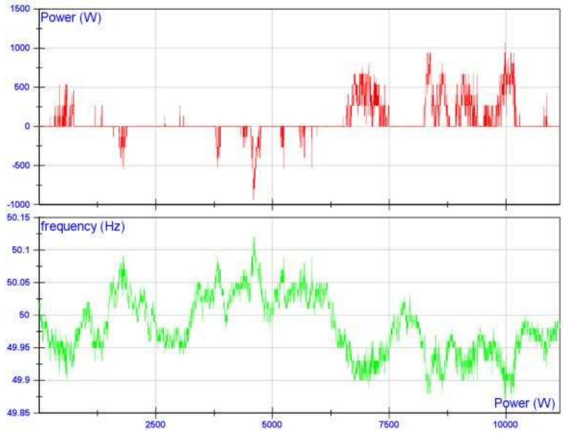

Figure 9: EFR frequency response, frequency (green) and output power (red) against time (seconds)

4 Demonstration of grid support services

The majority of grid services are implemented by injecting or absorbing real (P) or reactive power (Q), in response to grid conditions. Figure 10 shows the output real and reactive power in the bottom plot, together with the measured grid frequency and average line voltage over a 3 minute period for The University of Manchester BESS. At 43s the BESS is charged at 227kW for 15s, before being returned to zero, at 74s it is discharged at -227kW for 17s before being returned to zero. At 110s, 100kVA is absorbed for 16s and at 143s, 100kVA is injected for 18s, at all other times Q is zero.

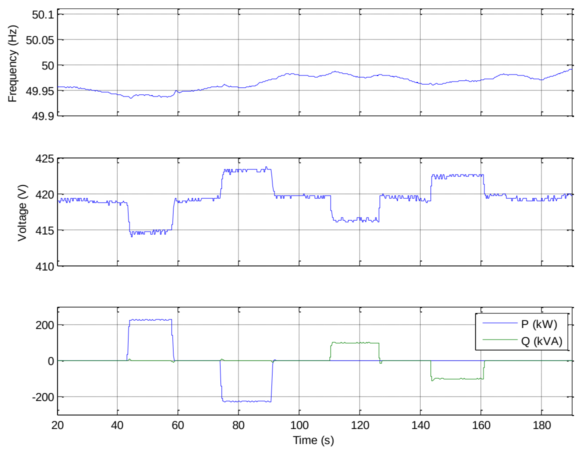

Figure 10: Influence of P and Q on LV power network

Grid frequency in Figure 10 varies between approximately 49.95Hz and 50Hz within the normal expected range. Average grid line voltage is approximately 419V.

Neither P or Q have an impact on grid frequency (beyond transient measurement noise) as it is too stiff. The real power decreases the grid voltage by 4.5V and increases it by 5.2V, while the reactive power decreases voltage by 2.7V and increases it by 3.4V. This demonstrates that the BESS has sufficient rating to influence the local power network and can support it with both P and Q.

4.1 Frequency and voltage control

Real and reactive power support for the local power network is achieved using the simplified control scheme shown in Figure 11. All of the set-points, minimum and maximum values shown in Figure 11 can be modified to adjust the level of grid support or best utilise available storage capacity. When frequency or voltage exceeds the deadband zones (F_{min} to F_{max} and V_{min} to V_{max}) power is delivered/absorbed according to the set-point gains.

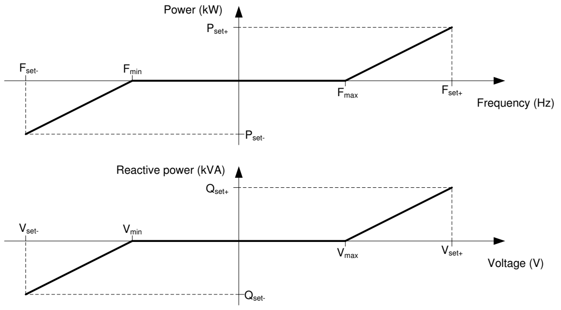

Figure 11: P(frequency) and Q(voltage) profiles

During prolonged operation the frequency, voltage, P and Q, and SOC are recorded, data from a two hour period is shown in Figure 12 from The University of Manchester BESS. The deadbands and gains tested are F_{min}=49.99Hz, F_{max}=50.01Hz, V_{min}=420V, V_{max}=430V, P_{set}/F_{set}=±200kW/Hz Q_{set}/V_{set}=+12kVA/V, -3.4kVA/V.

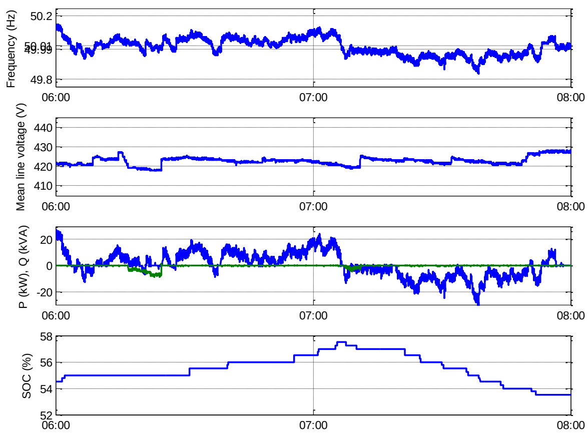

Figure 12: Measurements of P(f)/Q(V) support 13.01.2015

P and Q are seen to be controlled when grid frequency and voltage exceed the deadband zones, at these low gain levels the SOC varies by only 5% over the 2 hour period.

4.2 Peak load shaving

Power measurements points are distributed throughout the campus at The University of Manchester. Figure 13 shows daily usage profiles over a 4 week period for a multi-use university building which contains high-power research labs, offices and lecture theatres. The data shows a consistent base load of 190kW, with a peak demand of approximately 325kW appearing only on working days

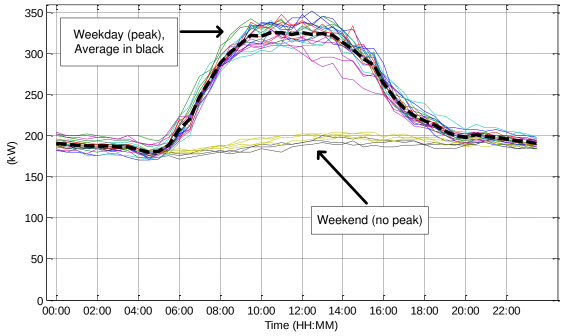

Figure 13: Building daily power demand (06.07 to 02.08.2015)

The consistency of load means that usage can be predicted with some accuracy. The average weekday usage is calculated and processed to create a power profile which is converted to a lookup table for the BESS to follow. This provides a peak shaving capability where the daytime peak load is reduced and the BESS is recharged overnight when the building demand is lowest. Power set points are taken from the lookup table. The BESS power profile and SOC are shown in Figure 14.

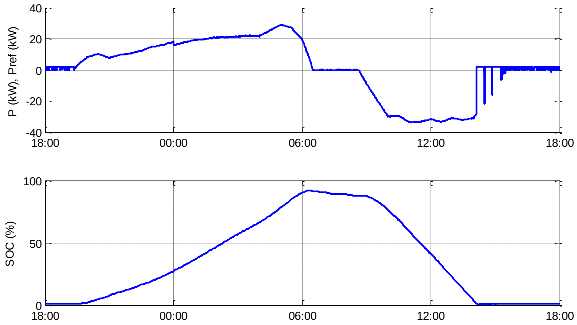

Figure 14: Peak shaving using power profile (28.08.2015)

The battery is charged slowly during the night, with the real power level peaking at 29kW when demand is lowest at 05:00. During peak demand, the profile power injects power to reduce peak load by 30kW. SOC is depleted to 0% by approximately 14:00, slightly sooner than expected as the profile was designed without consideration of round trip efficiency.

5 Conclusions

Two high performance BESSs connected to the UK electricity network are described in this paper. Initial performance results have shown ramp rates as low as 40ms for a full 2MW power reversal, and round trip efficiency of 86.6% from the 236kVA system. Further results have demonstrated their ability to support the network voltage and frequency and a control scheme is used to automate this showing only a 5% variation in SOC during a 2 hour period for mild voltage and frequency support. Test data is also provided for the design and implementation of a peak load shifting control scheme functioning on a commercial building.

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