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Impact of cell balance on grid scale battery energy storage systems

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Abstract

With the adoption of Lithium ion battery systems for grid scale storage, a better understanding of how these systems behave is becoming necessary in order to optimise their performance. Providing different grid services results in different types of power delivery — frequency response services result in varying depth, low power cycles, whereas other services such as arbitrage result in sustained delivery, generally at a higher power. The battery systems being used consist of a large number of cells where the variation and imbalance of these can cause operational issues. Using observed data from a grid connected 2MW / 1MWh battery system these issues are presented in this paper and a hypothesis is given. The observations are recreated under lab conditions using two different types of battery module allowing analysis at cell level. The results confirm the variation in cell behaviour at upper and lower states-of-charge and methods to mitigate are proposed.

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Keywords: Battery; Grid scale storage; Cell balance; Balancing market; Energy arbitrage; Battery energy storage system

1. Introduction

Worldwide, countries are seeking to change their energy supply to renewable sources. In many cases, this means generating electricity from sources such as wind and solar, which are both intermittent, asynchronous sources. The EU Energy Roadmap 2050 suggests that one challenge with this is the need for 'flexible resources' in the power system [1], with one such solution being energy storage. In the UK, there are multiple frequency response services which consist of flexible power sources and are used to balance supply and demand of electricity on the National Grid. This is used to maintain the UK Electricity grid at the statutory 50 Hz [2]. Grid Frequency has historically been kept stable through the use of synchronous generation, providing inertia to grid, so a mismatch in supply and demand results in a longer amount of time to bring more operating units online. However, with greater penetration of wind and solar resources, the inertia is reducing, giving less time to bring on more operating units. Solutions to this include using "smart" power converters for wind turbines and solar panels to allow them to contribute to grid

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inertia [3–5]. Another solution is through the use of batteries — acting as a load on the grid during periods of high frequency and as a supply during periods of low frequency which this paper considers. The uptake of battery storage in the UK is high, with a recent report (end 2018) [6] stating that there is approximately 500 MW of battery capacity installed on the UK power grid. Of this, 201 MW is used for National Grid's newest frequency service known as Enhanced Frequency Response (EFR). It is important that these systems are well understood and therefore reliable to provide import/export when required to prevent large frequency excursions.

Aside from frequency services, battery asset owners can also generate income through energy trading such as arbitrage. Safely utilising and maximising the energy capacity within a battery asset is fundamental to maximising revenue. One aspect of grid scale batteries that may limit the amount of energy that can be stored below its theoretical maximum is cell balance. This refers to the difference between cells in the system which causes a variance in voltage across a number of cells. Newly installed battery projects in the UK have an average size of 27 MW which results in the total number of cells required being in the order of 10,000s. It is important to understand the behaviour of these cells in a grid system in order to prevent undesirable operating conditions which could cause an unexpected shutdown and to provide an insight for better design to maximise battery capacity. In this paper the observations from a grid connected battery system are presented and recreated under lab conditions for analysis.

2. Background

A battery energy storage system (BESS) connected to the grid can be subjected to different types of cycling profiles, these can generally be grouped as either frequency response or sustained delivery profiles. Frequency response demands many micro-cycles with very small depth of discharge (DOD) ($<1\%$) at c-rates of less than 0.4C. Sustained delivery requires a constant charge/discharge at a higher c-rate ($\geq$1C) and reaching a DOD of greater than 90%. This paper will focus on sustained delivery as the conditions for this lead to greater cell balance issues. One example for a grid connected battery to perform sustained delivery is through energy arbitrage — the principle of buying energy when it is cheaper and selling it when it is more expensive in order to make a profit [7]. In the UK, there are currently two main markets for this — through trading on the balancing market and triad avoidance. The balancing market is a mechanism to increase generation/reduce demand or reduce generation/increase demand on the electricity grid. Energy trades are proposed until 1 h before delivery, at which point, the system operator (National Grid in the UK) accepts offers (proposals to increase generation or reduce demand) and bids (proposals to reduce generation or increase demand) where suppliers or consumers set a price for their bid/offer, which may be accepted by the system operator to balance supply and demand in real time as illustrated in Fig. 1.

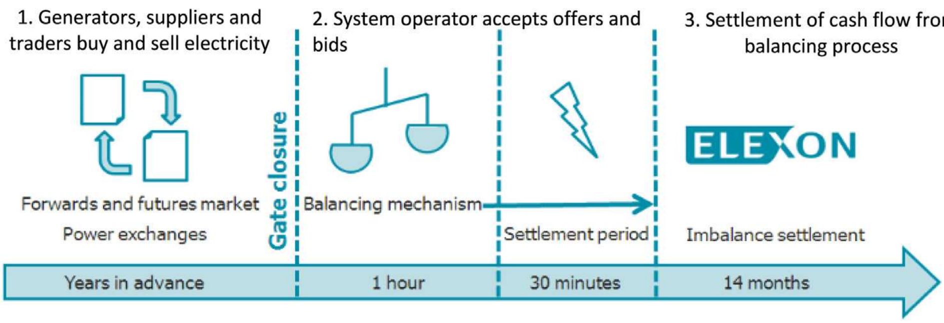

Fig. 1. Operation of the Balancing Mechanism in the UK [8,9].

During a typical 24-hour period, the imbalance volume (amount of energy required to balance the grid) can switch between positive and negative (grid requires more energy or has too much energy) around four times, as demonstrated in Fig. 2. As a grid connected battery can behave as a load (under charge) or as a generator (under discharge), it would be expected that a constant discharge would occur during one settlement period when imbalance is positive and one constant charge would occur during one settlement period when imbalance volume is negative.

The profitability of this is highly dependent on electricity markets, battery degradation rates and other operating costs. Some testing and modelling in particularly volatile markets, where prices and imbalance volumes are highly fluctuating, suggest that this is profitable [10], whereas studies in more stable markets suggest that it is not, due to the cost associated with battery degradation when performing a cycle [11,12].

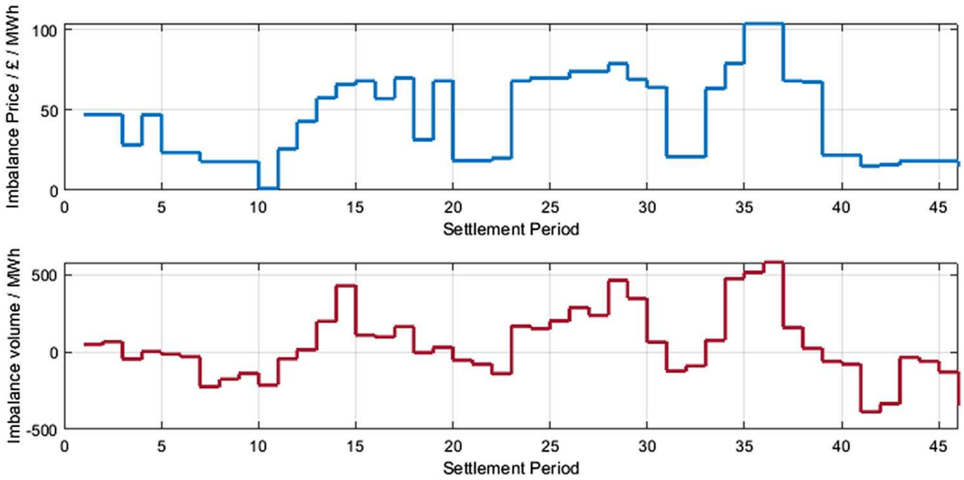

Fig. 2. Imbalance volume and price on a typical 24-hour period on the National Grid.

When performing trades in the balancing market, a battery sees a period of charge when there has been an accepted offer, followed by a rest period (awaiting a bid to be accepted), then a period of discharge once when a bid is accepted. This is significantly different to the output seen by a BESS during frequency services, where the output is constantly changing, matching the profile of the changing grid frequency.

Aside from balancing market trading, triad avoidance can also be used to generate profit using a battery, where a triad refers to the three highest demand half hourly periods on the grid, separated by 10 days. These are calculated after the triad 'season' which runs between November and February each year. Customers which are half hourly metred then face charges based upon their consumption during this period. Generators benefit during this period for exported energy. Using a battery to perform this service can greatly increase revenue, prices are location dependent but in the region of tens of thousands of £/MWh. Given that the triad periods are unknown until after the season, triads are forecast, resulting in more than three potential triad events in a season. The output of a BESS during such an event typically takes the form shown in Fig. 3. Note that the power is shown in terms of c-rate — the rate at which the BESS is discharged relative to its capacity.

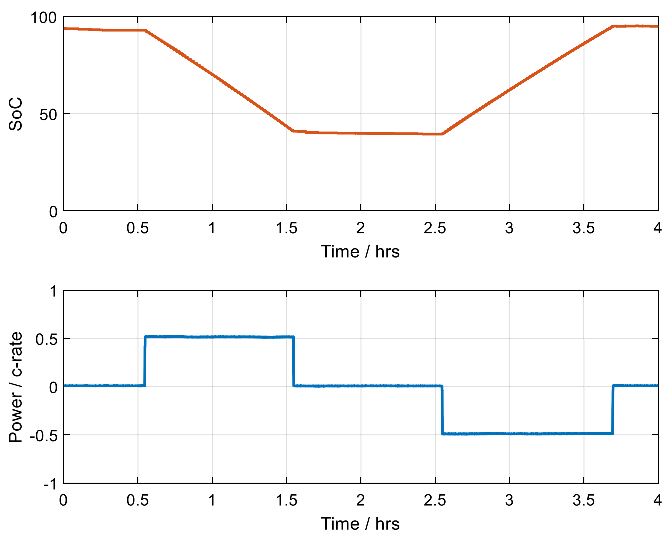

Fig. 3. Power profile and State-of-Charge (SoC) for a BESS during a Triad as recorded at the Willenhall Energy Storage System.

To compare the lab based experiments in this paper against real grid scale data, the Willenhall Energy Storage System (WESS) is being used. It is a grid connected 2 MW, 1 MWh battery and consists of 21,120 Toshiba SCiB cells which are of a Lithium-Titanate chemistry. More information about WESS can be read about in [13]. WESS has been used for grid scale experimental verification [14] of the topics explored in this paper.

3. Operational issues

Performing energy arbitrage brings issues with operating a BESS that might not be immediately obvious. This section will explore the issues faced by a BESS, giving reasons for the issues, before the following section investigates whether these issues are seen at a smaller scale. These issues have been generally observed at the WESS and are related to cell balance which are caused by cell imbalance between cells in a series string and imbalance between cells in a parallel string.

3.1. Series connected issues

When connecting cells in series strings, small variations between the cell impedance mean that some cells receive or deliver more current than other cells, or some cells have a different capacity to other cells. This means that the different cells in the string reach a different SoC or voltage when cycled. This eventually reaches a point where intervention is required in order to restore the charge in each cell to equal levels. The battery chemistry and Battery Management System (BMS) in place determine the downtime required to maintain acceptable cell balance levels. A Lead–acid BESS requires periodic ‘equalisation’ to maintain cells at equal SoC. This is achieved through overcharging the system to typically around 102% SoC. The regularity of this is anywhere from 14 days to 6 months depending upon the system [15,16].

A Lithium-ion BESS cannot be ‘equalised’ (known as balanced for Lithium-ion) through overcharge. Instead modules for BESS are typically supplied with BMS systems which perform the balancing procedure. This is achieved through the BMS selectively discharging individual cells through a load in order to bring cells at a higher voltage to the same as other cells. Other balancing methods exist which can be implemented to restore a battery system to a balanced state [17].

This generally means that no downtime is required for cell balancing as the BMS can activate balancing circuits to maintain cell balance. However, this is not always necessarily the case, for example, some BMS’s only perform balancing when the BESS is at a high SoC (>80%). This can be problematic when performing frequency services, as a BESS will not regularly reach the SoC threshold for balancing, which can then result in downtime for cell balancing. It is also common for a BMS to restrict output power of the BESS during balancing.

Lithium-ion BESS cells each have an upper and lower voltage limit. It is both dangerous and detrimental to battery health to exceed these limits. In a BESS, once a single cell reaches a voltage limit, the BESS must stop charging/discharging in order to prevent over-charge or over-discharge of the battery. However, due to imbalance, not all the cells will be at their limit and therefore there is unused capacity in the system. There are some important questions that this issue raises that are difficult to answer using a large scale BESS. Given that in a large scale BESS there can be tens of thousands of cells and upward, it is unfeasible to log the data for all of the cells. It can however be seen from a typical discharge–charge profile from WESS in Fig. 4 that near the upper limit of SoC, there is a significant difference between the highest voltage cell and the lowest (shown as “Cell Balance).

Information that would be useful in the operation of BESS is the remaining energy in the cells that have not reached the limit. This is related to the distribution of the cell voltages when a single cell reaches the limit, naturally, this reduces the amount of energy that can be utilised in the battery, thereby reducing profitability. In this paper testing of a smaller number of cells in a string is carried using a SCiB module to investigate the series connected cell balance problem.

3.2. Parallel connected issues

Through regular use of WESS, it has been noted that the balance between cells diverges during large changes in power output. WESS is capable of 4 MW power swings, from a 1 MWh battery (+2 MW to −2 MW). During these large power swings, it has been noted that the cell imbalance (difference between the cell at highest voltage and lowest voltage) increases significantly. It is most likely that there is a difference in impedance between the cells

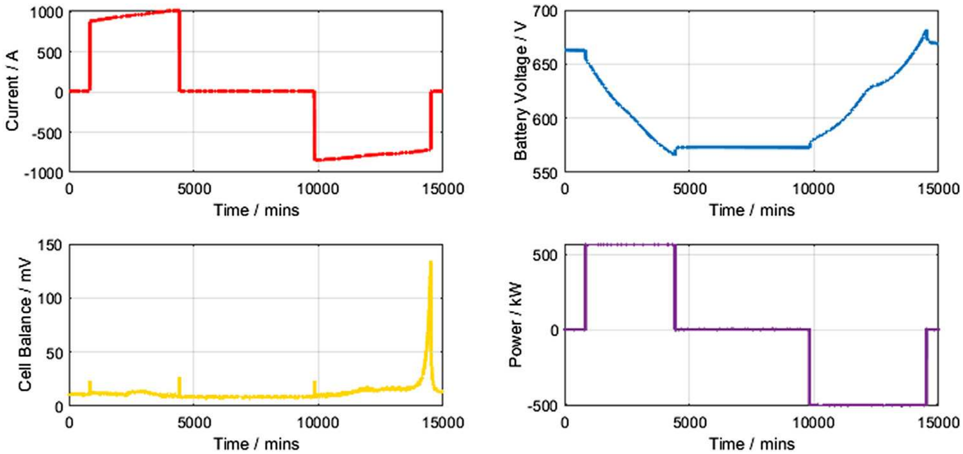

Fig. 4. A typical discharge–charge cycle from WESS.

— potentially caused through variability in manufacturing or a variation in temperature between cells. This causes the imbalance to manifest. Where the imbalance occurs in the system is less known.

One cause for the imbalance occurring is that the BMS could bring all the cells to an equal voltage during a charge phase, and on changing to discharge, the cells then exhibit a different voltage drop caused by the battery impedance, causing the voltages between the cells to diverge. This seems unlikely, as the balancing does not occur fast enough, and only for an extended period of time at low c-rates.

The other potential cause is with differences between the series strings that are combined in parallel to produce the overall battery. As the series strings are connected in parallel, they equalise voltage as current flows between them to bring them to the same charge level. When there is a significant change in current, there is a hysteresis effect, where the voltage of each series string will change due to the impedance in it. Current will then flow between the series strings until the voltage of each string is equal — a process which is not immediate as there is impedance in the connection between strings and there is a delay in sampling the cell voltages. It is fast relative to BMS balancing however — cell balance settles within 20 s of a power swing at WESS. The effect of a 1500 kW change in power at WESS on cell balance is shown in Fig. 5.

4. Module analysis

A set of experiments were designed and performed in order to better understand the observations see on the large scale BESS. These were performed on two types of modules — Toshiba SCiB 12S2P modules (identical to modules in WESS) and Yuasa LIM50EN 12S1P modules. Two modules were connected in series to give a total of 24 series cells for both the Toshiba SCiB and Yuasa LIM50EN, providing easily comparable results. The test procedure involved performing 3 cycles at 1C, 1.5C and 2C rates whilst recording the cell voltages. The data for the third cycle is then used, allowing time for the battery to reach a thermal steady state. This should demonstrate the operational issues that are seen in WESS, with the test giving a large power swing when changing from charge to discharge in a cycle and also allowing the modules to reach cell voltage limits, showing the spread of cell voltages at these points. The results for the Toshiba and Yuasa modules for 1C cycles are shown below in Figs. 6 and 7 respectively.

Little difference was observed between the different c-rates, so results for 1.5C and 2C are not shown. For the Toshiba SCiB module, there is a spread of voltages at the end of discharge and at the end of charge. However, with the Yuasa modules, there is only a spread of voltages at the end of discharge. This is more clearly shown in Fig. 8 which shows cell balance (the difference between maximum cell voltage and minimum cell voltage).

The likely reason for little change in cell balance at the high end of the voltage range for the Yuasa modules is that the high cell voltage limit specified is restricted below what it is safely capable of. This results in the voltage not reaching a high enough point where the individual cell voltages would vary to a point, where a single cell could

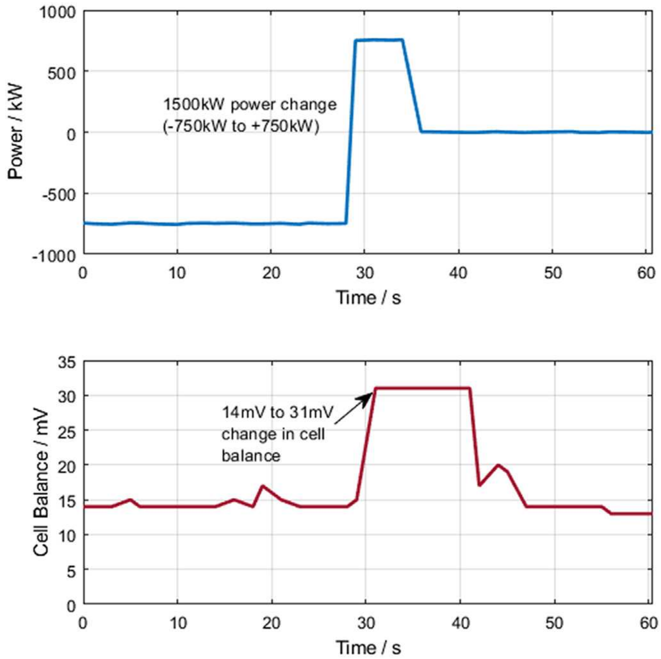

Fig. 5. Change in cell balance after a 1500 kW power swing at WESS.

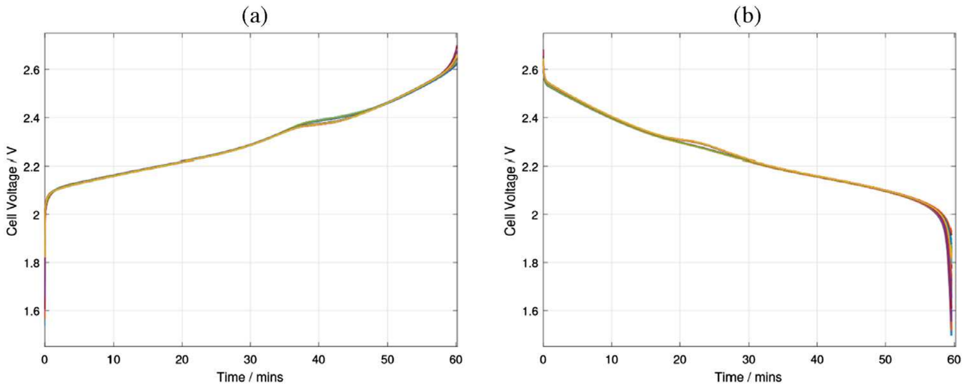

Fig. 6. 1C test of two Toshiba SCiB modules connected in series under (a) charge and (b) discharge.

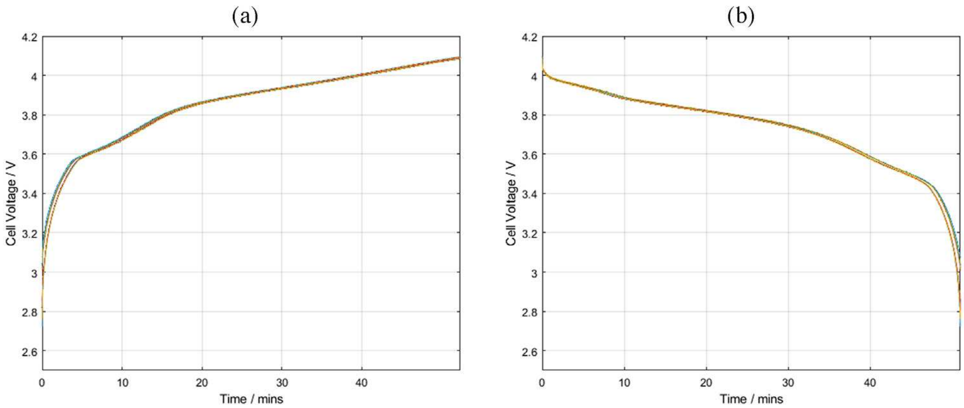

Fig. 7. 1C test of two Yuasa LIM50EN modules connected in series under (a) charge and (b) discharge.

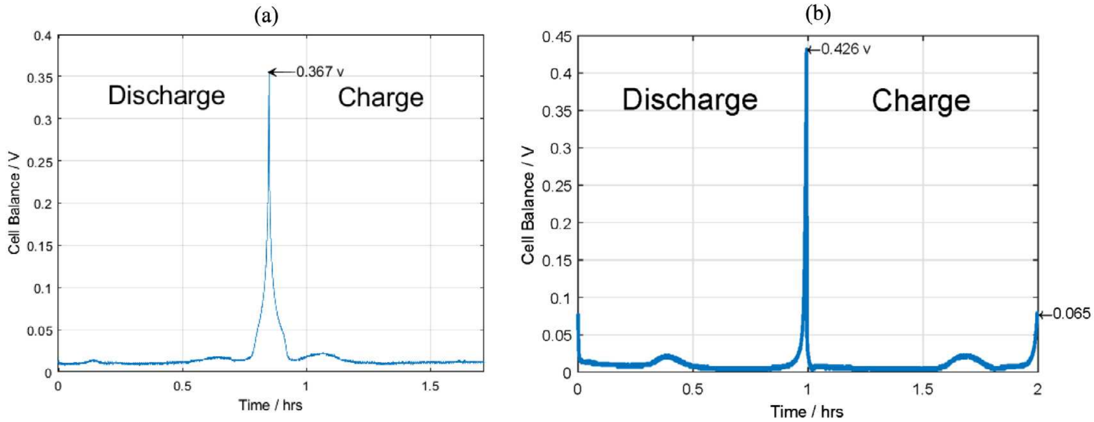

Fig. 8. Cell balance during 1C cycle of (a) two Yuasa LIM50EN modules connected in series and (b) two Toshiba SCiB modules connected in series.

reach its limit when only monitoring voltage across the entire series string. A consequence of this is that not all of the energy capacity is being used and will be discussed further in the next section.

It can be seen that both battery types experience a large difference in cell voltage at the end of discharge, confirming that the specific battery chemistry does not make a significant difference. What is not observed is a change in cell balance due to a large change in power (discharge to charge). It is likely therefore that the cell balance issues with power swings are related to batteries connected in parallel, given that only series strings are being used and no additional cell voltage imbalance is seen at the power change point.

5. Implications for grid scale storage

In order to overcome the problems with poor cell balance, the SoC range for the BESS can be reduced, in order to prevent a single cell from reaching a significantly higher or lower voltage than the others. This will prevent the cell from undergoing increased degradation caused through it reaching a higher voltage and SoC. This would then perpetuate the problem, as it will degrade faster than the other cells, thereby reaching its voltage limits even sooner. For a battery performing EFR, a restriction between 95% and 5% SoC is reasonable to ensure the cell voltage limits are not reached due to cell balance.

For example, the 10 MW, 5 MWh operated by E.ON in Sheffield performs 10 MW of EFR, and is paid £110.90/h for that [18,19]. An estimated cost for such a project is £3.5 m, using NREL's report suggesting such a system would cost 895$/kWh (∼700£/kWh) [20]. It must be able to output for 30 min at full power to meet the EFR criteria. Should it be limited to the aforementioned range, the capacity would reduce to 4.5 MWh, and therefore the battery would only be capable of performing 9 MW for one hour which would reduce the payment by 10% to £99. Over the 4-year contract, that would reduce income from £3.9 m to £3.5 m, which would only cover the capital cost. Even excluding the operational costs for the system, it can be seen that this capacity reduction is not profitable. Therefore, this should be a consideration for battery system designers when specifying a BESS. A similar calculation can be derived for energy arbitrage where a 10% reduction in capacity would reduce income by 10%.

An alternative method to overcome cell imbalance at high and low SoC would be through power curtailment. When reaching the limits of SoC, the power can be reduced in order to remove as much energy from the battery, similar to a constant voltage charge that might typically be used for a battery under non-grid conditions. This would however require careful planning from an operator to ensure that the battery does not reach a cell voltage limit whilst maximising the total energy stored or discharged from the system in a given time.

6. Conclusions

In this paper an observed cell imbalance issue from operation of a grid scale BESS is presented. Using modules in under lab conditions the observations are recreated to allow analysis at cell level of phenomenon. It can be seen from series connected module testing that cell balance is an issue when the cells approach the upper and lower limits of the SoC with an increasing spread of voltages across cells. It is possible to mitigate this by limiting the range of the SoC used or by curtailing power as cell imbalance increases, however this reduces the useable capacity at constant power and curtailing power may not be possible depending on the service being provided. From the results of the tests it is shown that power swings do not cause increased cell imbalance in series connected strings and therefore limited to parallel connected strings only which will be the focus of future work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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