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Battery energy management strategies for UK firm frequency response services and energy arbitrage

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Abstract: Due to the increasing renewable penetration, there is potential for larger and faster grid frequency fluctuations increasing the risk of system instability. The National Grid Electricity Transmission, primary electricity transmission network operator in the UK, has introduced various frequency response services that are developed to provide a real-time response to deviations in the grid frequency. A battery energy storage system is a suitable choice for delivering such services. Here, a control algorithm is presented which generates a charge/discharge power output with respect to deviations in the grid frequency and the required specifications. Using the real UK electricity prices, an arbitrage control algorithm has been also developed to deliver different types of grid balancing services, while scheduling throughout the day for energy arbitrage. Simulation results show that the proposed algorithm delivers both dynamic and non-dynamic firm frequency response and also enhanced frequency response to specifications, while generating arbitrage revenue in the balancing market. Simulation results on a 1 MW/1 MWh lithium-titanate BESS are provided to verify the proposed algorithm based on the control of an experimentally validated battery model.

1 Introduction

Due to the shift towards increased utilisation of renewable energy sources (RESs) in the form of wind and solar, the power grid is increasingly required to manage intermittent sources with variable output. Energy storage systems (ESSs) are being integrated with RESs that are linked to the power grid to maintain a safe grid operation and to balance demand and supply [1–3]. The ESSs can meet the requirement for increasing reserves to manage the renewable generation uncertainty and varying output. ESSs have a great potential in modern grids, performing the essential task of storing excess generated power and making it available during suboptimal generating conditions or peak demand [3]. Improvements in energy storage technologies and power electronics, coupled with these changes in the electricity market, lead to an increasing reliance on ESSs as a cost-effective energy resource [3]. Energy storage can provide numerous benefits to the generation, transmission, and distribution systems through the provision of ancillary services [4]. Among ESSs, battery energy storage system (BESS) is one of the most suitable candidates for grid-scale applications [5] as BESSs offer rapid active power response, being suitable to compensate for the fluctuations generated by RESs [6] and demand usage.

Balancing the demand and generation to maintain the system frequency closer to a nominal frequency (e.g 50 Hz for the UK) is a critical issue in power system operation and control. Since the high penetration of renewable generation not only leads to power fluctuation on the generation side, but also reduces the system inertia, the frequency stability issues become inevitable [7]. To overcome this issue, National Grid Electricity Transmission (NGET), the primary electricity transmission network operator in the UK, introduced grid frequency balancing services such as firm frequency response (FFR), including primary, secondary, and high response, and a new enhanced frequency response (EFR) service, to assist with maintaining the grid frequency. For delivering such services to the grid, BESS is a suitable candidate due to its capability of import/export and fast response. In 2013, the UK's first grid-connected lithium-titanate BESS, the Willenhall ESS (WESS), was commissioned by the University of Sheffield to enable large-scale batteries and to create a platform for research into grid ancillary services [1, 2].

The aim of this paper is to investigate two applications for BESS; grid frequency regulation and energy arbitrage in day-ahead spot markets. The electricity price tends to follow a daily pattern of a low price during off-peak night-time hours and a high price during on-peak day-time hours. If the BESS stores energy at off-peak times with the lower price and then resells at on-peak times with higher price, it can make profit from the price difference, this is referred to as arbitrage [1]. There are several papers in literature that investigate energy arbitrage. The reference study [8] presented an economic analysis on the potential of energy arbitrage utilising a residential energy storage system in typical California homes. In [9], a building-to-grid (B2G) model was developed to evaluate energy arbitrage value of smart thermal ESS devices in residential building across Ireland. Reference [10] presents an energy arbitrage scheduling algorithm for electric vehicles (EVs) under a real-time pricing scheme with uncertainty and evaluates also the battery degradation. Reference [11] investigates arbitrage operation of an energy storage facility in Alberta electricity market. In contrast to other recent works in the field, this paper considers layering grid balancing services; including FFR (dynamic and non-dynamic) and EFR in the UK, while scheduling throughout the day for energy arbitrage in order to maximise the system's availability and profitability.

This study presents new UK FFR control algorithms that enable BESSs to deliver a bi-directional power in response to changes in the grid frequency. An arbitrage control strategy is also developed to achieve maximum arbitrage revenues that can be generated from the grid balancing services by layering FFR and EFR services throughout the day. Here, the obtained arbitrage revenue generated by different UK grid balancing services is also compared with that of a previous study [1] which investigates a forecasting SOC management strategy to deliver only EFR service, while scheduling throughout the day energy arbitrage opportunities.

2 FFR design control algorithm

In order to manage the grid system frequency within the normal operating range 49.5 Hz to 50.5 Hz, National Grid (NG) relies on balancing service providers to adjust their active power output or consumption in order to minimise the imbalance between demand and generation on the system. The extent of the required

$$\mathrm{SOC_{out}} = \mathrm{SOC_{init}} + \frac{\int_0^t P_{\mathrm{batt}} dt}{3600 \cdot Q} \quad (1)$$

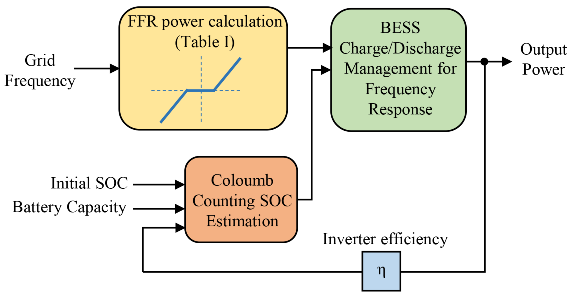

Fig. 1 *Blok diagram of the proposed dynamic firm frequency response implemented in the BESS model*

Table 1 NGET required DFFR power & frequency setpoints and calculation in the control algorithm [13]

Freq., Hz	Contracted power, kW	DFFR Power setpoint (CPower), kW
A = 49.5	a = 1025	CPower = a
B = 49.6	b = 820	$\mathrm{CPower} = \left[\left(\frac{B-f}{B-A}\right)x(a-b)\right] + b$
C = 49.7	c = 615	$\mathrm{CPower} = \left[\left(\frac{C-f}{C-B}\right)x(b-c)\right] + c$
D = 49.8	d = 410	$\mathrm{CPower} = \left[\left(\frac{D-f}{D-C}\right)x(c-d)\right] + d$
E = 49.9	e = 205	$\mathrm{CPower} = \left[\left(\frac{E-f}{E-D}\right)x(d-e)\right] + e$
F = 49.984	f = 33	$\mathrm{CPower} = \left[\left(\frac{F-f}{F-E}\right)x(e-f)\right] + f$
G = 49.985	g = 0	CPower = g = 0
H = 50	h = 0	CPower = h = 0
J = 50.015	j = 0	CPower = j = 0
K = 50.016	k = −33	$\mathrm{CPower} = \left[\left(\frac{K-f}{K-J}\right)x(j-k)\right] + k$
L = 50.1	l = −205	$\mathrm{CPower} = \left[\left(\frac{L-f}{L-K}\right)x(k-l)\right] + l$
M = 50.2	m = −410	$\mathrm{CPower} = \left[\left(\frac{M-f}{M-L}\right)x(l-m)\right] + m$
N = 50.3	n = −615	$\mathrm{CPower} = \left[\left(\frac{N-f}{N-M}\right)x(m-n)\right] + n$
P = 50.4	p = −820	$\mathrm{CPower} = \left[\left(\frac{P-f}{P-N}\right)x(n-p)\right] + p$
R = 50.5	r = −1025	$\mathrm{CPower} = \left[\left(\frac{R-f}{R-P}\right)x(p-r)\right] + r$

adjustment is determined by the system frequency deviation from 50 Hz [12]. Therefore, NG purchases balancing services to manage the grid frequency; FFR is a frequency response service for grid balancing service that can supply a minimum of 1 MW active power within a frequency deviation. FFR is open to all parties that can prequalify against the service requirements. This service is a proportional or continuous modulation of demand and generation; so FFR service can be either dynamic or static. In dynamic FFR (DFFR), power changes proportional to system frequency and in static FFR (SFFR), a set power level is delivered at a defined frequency and remains at the set level for an agreed period [13].

2.1 Dynamic firm frequency response (DFFR) control

A BESS model is developed in MATLAB/Simulink and verified against experimental operation of the WESS. A new DFFR control algorithm is then implemented in the model to deliver a grid frequency response service to the NGET specification (Fig. 1). Fig. 1 shows the proposed DFFR control scheme implemented in the BESS model, where the inputs are real-time grid frequency (F) and battery SOC, with the output being the requested import/export power to deliver a frequency response according to the service specification. The algorithm starts by detecting the position of the measured frequency with respect to the zones bounded by frequency values ‘A’ to ‘R’ in Table 1 (left column). This is achieved by the ‘FFR Power Calculation’ block, where the required DFFR response envelope is calculated as a function of the limits given with their values in Table 1 (left and middle column). The calculation method of the proposed DFFR power envelope is described in the final column of Table 1. The required DFFR power is zero within the DB. In this work, battery SOC is calculated using (1) [2] where $\mathrm{SOC_{init}}$, Q and P_{batt} represent initial SOC, Watt-hour capacity and instantaneous battery power, respectively.

$$\mathrm{SOC_{out}} = \mathrm{SOC_{init}} + \frac{\int_0^t P_{\mathrm{batt}} \mathrm{d}t}{3600.Q} \quad (1)$$

DFFR is a continuously delivered service used to control the normal second-by-second grid frequency changes. Energy storage providers must respond to changes in nominal grid frequency by decreasing or increasing their import/export power. A deadband (DB) is defined where there is no requirement to import/export power to the grid but there is also no opportunity to charge/discharge battery to manage its state-of-charge (SOC). Providers must deliver continuous import/export power as detailed in the DFFR service envelope in Table 1. The power level must remain at this required envelope at all times; power provided outside the envelope will decrease the service performance measurement (SPM) and hence the income revenue [12].

Operation principle of the proposed BESS charge/discharge management for delivering DFFR service (Fig. 1, green block) is described in Fig. 2. According to the logic of the DFFR control algorithm in Fig. 2, BESS can only import/export power with respect to the required DFFR power envelope described in Table 1 to respond to grid frequency changes outside of DB (±0.015 Hz).

2.2 Static firm frequency response (SFFR) control

SFFR delivers a non-dynamic service where an agreed amount of power is delivered if the grid frequency reaches a certain trigger point (e.g 49.7 Hz or 50.3 Hz). The service providers monitor the grid frequency and adjust their generation or consumption power when the frequency goes below the specified frequency trigger. There are two modes of SFFR response, including high-frequency response (SFFRhigh) and low-frequency response (SFFRlow). Figs. 3 and 4 show the logic of the low and high SFFR services, which have to maintain their power output for 30 min. NG specifies a high reset frequency (50.3 Hz) and low reset frequency (49.7 Hz). The aim of the resets is to discontinue the frequency response if the grid frequency changes sharply for the period of the service.

According to the proposed BESS management for SFFRlow shown in Fig. 3, when the frequency drops below the low trigger frequency (Flow), the BESS starts to deliver a maximum power response (SPower>0) until the grid frequency goes back above the specified high trigger frequency (Fhigh); the response continuation must not be interrupted until it reaches the trigger reset or 30 min. The logic is reversed for SFFRhigh. According to the proposed BESS management for SFFRhigh, when the frequency goes above the high trigger frequency (Fhigh), the BESS starts to import a maximum power response (SPower<0) until the grid frequency goes back below the specified low trigger frequency (Fhigh); the response continuation must not be interrupted until it reaches the trigger reset or 30 min.

3 Simulation results

All the FFR control algorithms are simulated in MATLAB/Simulink using real frequency data set obtained from the NG [14]. The simulation results presented here are all based on a 1MWh BESS model, which has been experimentally validated on the WESS plant in the UK [15] with a maximum FFR power of ± 1 MW. The parameters used in the control algorithms are shown in

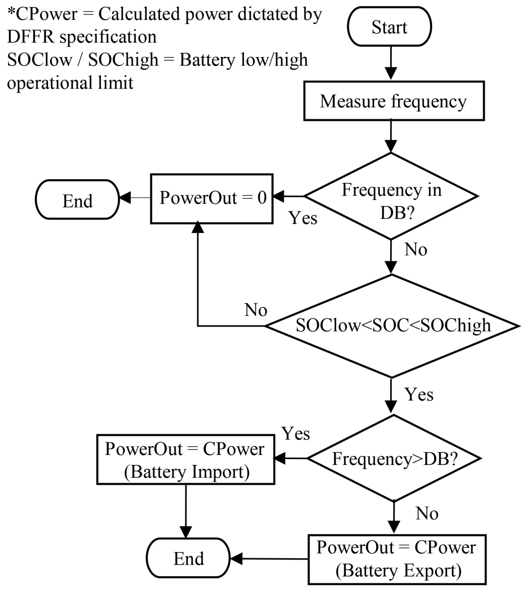

Fig. 2 *Flow chart of the proposed battery energy management strategy for DFFR service*

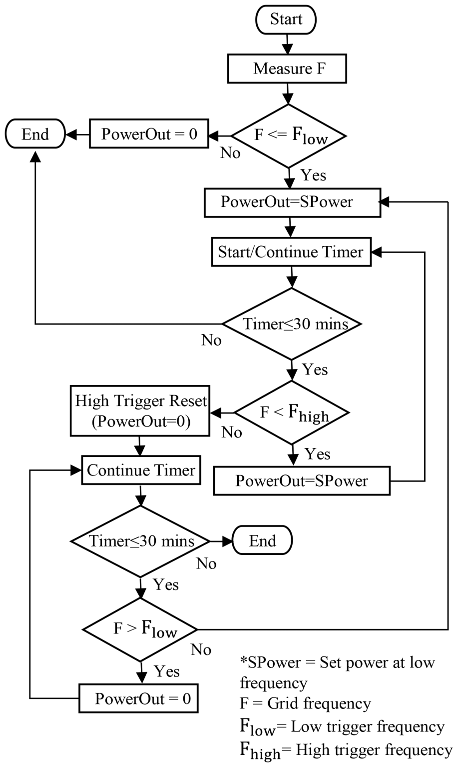

Fig. 3 *Flow chart of the proposed battery energy management strategy for SFFR low frequency response service*

Table 2. In order to show the performance of the reported FFR algorithms in Section 2, the real-frequency data for the 11 November 2015 (first 3 h data) [14] is used herein, as this particular day is known to have both a low- and high-frequency event. Fig. 4 shows the simulation results of the DFFR control algorithm. On the frequency plot, the DB (±0.015 Hz) is shown by the green lines. It is clear from Fig. 4*a*, the BESS continuously imports/exports power within the specified power envelope described in Table 1. Fig. 4*b* illustrates the power response versus grid frequency plot of DFFR control algorithm for 11 November 2015 (first 3 h). The red line represents the NGET required DFFR power line described in Table 1. It is clear that the DFFR power (blue circles) does remain within the required envelope, meaning that the BESS achieved 100% availability and met the service requirements.

Figs. 5 and 6 show the simulation results for 11 November 2015 of the SFFR low- and high-frequency response control algorithms, respectively. On the frequency plot, the high and low trigger reset frequency set points are shown by the dotted green lines. Over the 3-h profile, the algorithms deliver to the SFFRlow and SFFRhigh specification [16] with no power being delivered until a frequency event occurs at −0.3 Hz. It can be seen that when the grid frequency returns above the trigger frequency, the export power continues until it reaches the trigger reset or 30 min. The aim of the resets in the SFFR control algorithms is to discontinue the frequency response if the grid frequency changes sharply for the period of the service

4 Energy arbitrage

This section provides an arbitrage control strategy to achieve maximum arbitrage revenues that can be generated from the grid balancing services by scheduling FFR and EFR services throughout the day. This study examines the potential arbitrage revenues, while delivering DFFR, SFFRlow, SFFRhigh and EFR service for all settlement periods in a day. For the EFR service, this is achieved by manipulating the battery SOC target in the proposed frequency response control algorithms; decreasing the SOC target band when electricity prices are high, and increasing the SOC band when the prices are low; effectively shaping the BESS energy delivery profile to export at high prices and import at low prices. Using UK historical electricity pricing data, the proposed SOC management strategy selects the appropriate battery SOC profile to maximise the arbitrage revenue, while delivering the EFR service. More explanation about the new EFR service design control algorithm and its NGET requirements can be found in [1]. For the DFFR and SFFR services, considering the electricity price discrepancy during the day, the proposed arbitrage control algorithm selects the appropriate frequency balancing services considering the grid frequency conditions of the day and the time to maximise arbitrage revenue, while delivering different type of frequency response services during a day. It should be noted that here, the obtained arbitrage revenue through providing different UK balancing services will also be compared with that of a previous study [1] which investigates a battery SOC management for delivering only EFR service.

Stored energy in the BESS can be calculated as in (2),where η_D is battery discharge efficiency, η_C is battery charge efficiency, E_t is energy stored in the BESS at hour t, if $P_t > 0$ BESS delivers power at hour t, if $P_t < 0$ BESS absorbs power at hour t. The cost of the BESS charge/discharge and the total arbitrage revenue can be calculated using (3) [1], where C_{DC} is cost of BESS discharging, C_C is cost of BESS charging, A_t is system real electricity price in £/MWh at hour t.

$$\begin{aligned} &\text{Discharging}: P_t > 0 E_t = \int_0^t \frac{P_t}{\eta_D} \times \mathrm{d}t \\ &\text{Charging}: P_t < 0 E_t = \int_0^t P_t, \eta_C, \mathrm{d}t \end{aligned} \tag{2}$$

$$C_C = \sum_{t=1}^{24} E_t \times A_t \,\text{if}\, P_t < 0 \tag{3}$$

$$C_{DC} = \sum_{t=1}^{24} E_t \times A_t \,\text{if}\, P_t > 0 \tag{4}$$

$$\text{Max}(CA_t) = C_{DC} - C_C \tag{5}$$

The charge/discharge energy output of BESS can be calculated for charging cost and discharging cost as given in (3) and (4), respectively. The total arbitrage revenue (CA_t) can then be calculated by using (3) and (4) as given in (5).

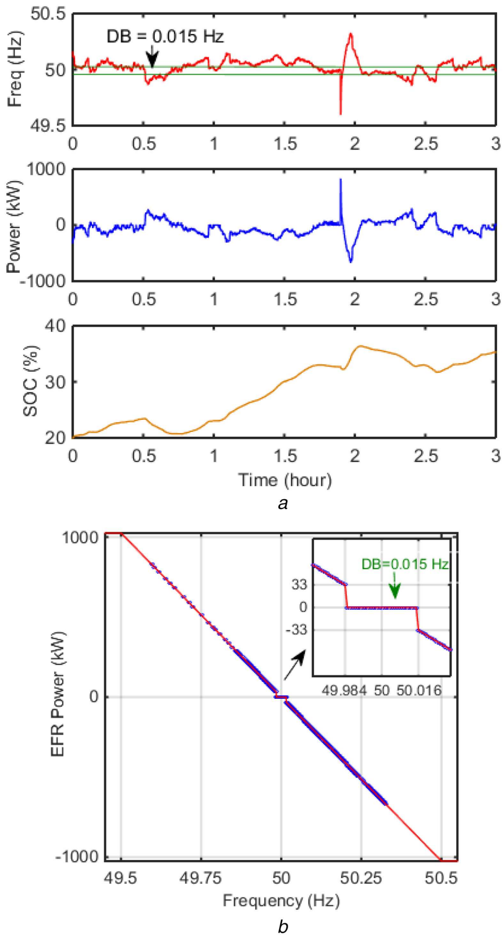

Fig. 4 *Simulation results of*
(a) The BESS for DFFR service for 11th Nov 2015 (first 3 h), ***(b)*** Power vs frequency response

Table 2 Parameters used in the BESS model [13]

Parameter	Value
nominal frequency	50 Hz
low/high DB	± 0.015 Hz (for DFFR)
high/low trigger frequency	± 0.3 Hz (for SFFR)
max/min FFR power limit	± 1 MW
battery rated power/capacity	1 MW/1 MWh
battery initial SOC (SOCinit)	20%

4.1 Simulation results of the arbitrage control algorithm

The aim of the proposed arbitrage control algorithm is to generate potential arbitrage revenues, while layering different UK frequency response services, including DFFR, SFFRlow, SFFRhigh, and EFR, for all settlement periods in a day by importing at low electricity prices and exporting at high prices. The arbitrage algorithm is developed in MATLAB/Simulink and its simulation results are all based on the experimentally validated 1MW/1MWh BESS model. The frequency data of 14th April 2014 [14], containing high-frequency events, are simulated here to compare the arbitrage revenue obtained from this study with those from the comparative study found in [1] that considers only EFR service for energy arbitrage. Based on recorded UK system sell/buy electricity price [17], the arbitrage algorithm has been analysed for nine scenarios in order to achieve a maximum arbitrage revenue. The findings of the proposed arbitrage control algorithm for 14 April 2014 are shown in Table 3. The arbitrage revenue for the day period was summed over the year to attain annual values on a £/kWhr.yr basis. According to the scenario 2 (S2) shown in Fig. 7, the first service selected is DFFR with the DB of ± 0.015 Hz to deliver dynamic power until 2am with relatively low electricity price and then SFFRhigh service is selected until 6am in order to

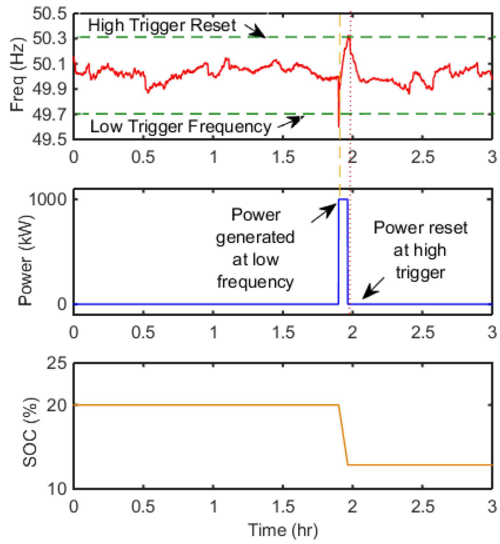

Fig. 5 *Simulation results of the BESS for SFFRlow service for 11th Nov 2015 (first 3 h)*

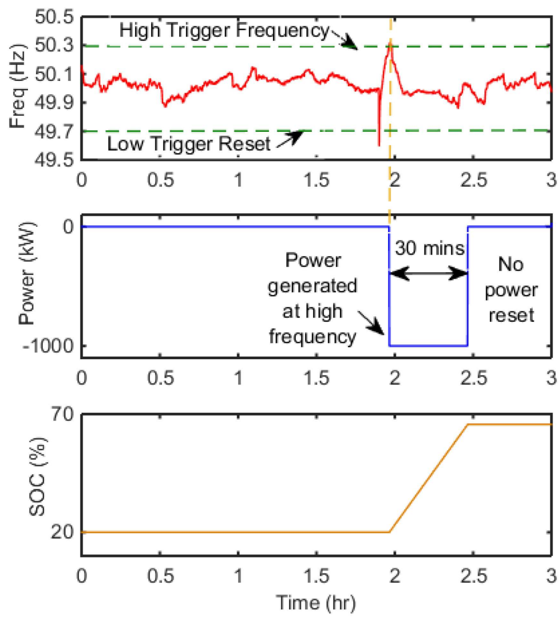

Fig. 6 *Simulation results of the BESS for SFFRhigh service for 11th Nov 2015 (first 3 h)*

absorb a maximum constant power (−1 MW) from the grid at a high trigger frequency of 50.3 Hz. The third service selected is EFR with a SOC band of 90–95% to charge the battery until 8pm during low costs and then its SOC band is decreased to 15–20% in order to supply power to the grid at peak time where the electricity price is high (Table 3). According to the scenario 9 (S9) shown in Fig. 8, the first frequency response service selected is DFFR to deliver a continuous dynamic power until 4am with low electricity price and then SFFRlow service is selected until 6am in order to deliver a constant 1 MW power to the grid at low trigger frequency of 49.7 Hz. The third service selected is EFR with a high SOC band of 90–95% to charge the battery until 8pm with low price and then its SOC band is decreased to 15–20% in order to export power to the grid selling at a high price.

However, S6* is selected as the best scenario in the comparative study [5], with £3.21/kWh.yr arbitrage revenue, this paper achieves 25% higher (£4/kWh.yr) revenue with scenario 1 (S1), by scheduling different types of frequency response service throughout the day.

Using frequency response service payments (for EFR = £10/hr, DFFR = £11/hr and SFFR off-peak = £4/hr and on-peak = 6/hr), the daily frequency response service benefits obtained from each scenario in Table 3 are shown in Table 4.

Table 3 Findings of the arbitrage algorithm for 14th April 2014

Time, hr	Selected service	SOC band, %	Energy output, kWh/ day		APR, £/kW h.yr	S
			Imp.	Exp.		
12am–2am	EFR	90–95	1528	1287	4.004	1
2am–6am	SFFRhigh	–				
6am–8pm	EFR	90–95				
8pm–12am	EFR	15–20				
12am–2am	DFFR	–	1530	1289	3.805	2
2am–6am	SFFRhigh	–				
6am–8pm	EFR	90–95				
8pm–12am	EFR	15–20				
12am–6am	SFFRhigh	–	1429	1205	3.644	3
6am–8pm	EFR	90–95				
8pm–12am	EFR	15–20				
12am–2am	DFFR	–	1545	1307	2.922	4
2am–6am	SFFRhigh	–				
6am–5pm	EFR	90–95				
5pm–12am	EFR	15–20				
12am–2am	DFFR	–	1397	1056	1.466	5
2am–6am	SFFRhigh	–				
6am–12am	DFFR	–				
12am–8pm	EFR	90–95	1516	1277	3.21	6*
8pm–12am	EFR	15–20				
12am–4am	EFR	90–95	1412	1190	2.998	7
4am–6am	SFFRlow	–				
6am–8pm	EFR	90–95				
8pm–12am	EFR	15–20				
12am–4am	DFFR	–	898	852	1.648	8
4am–6am	SFFRlow	–				
6am–12pm	DFFR	–				
12am–4am	DFFR	–	1412	1190	2.107	9
4am–6am	SFFRlow	–				
6am–8pm	EFR	90–95				
8pm–12am	EFR	15–20				

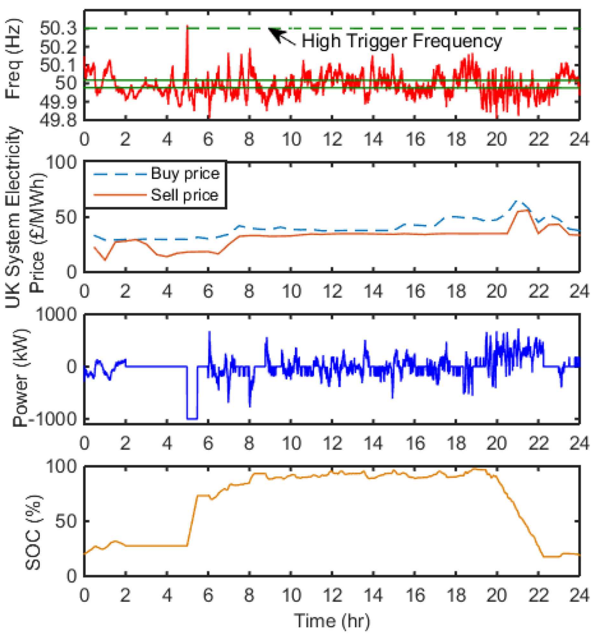

Fig. 7 *Simulation results of the arbitrage control algorithm for 14th April 2014 for scenario 2 (S2)*

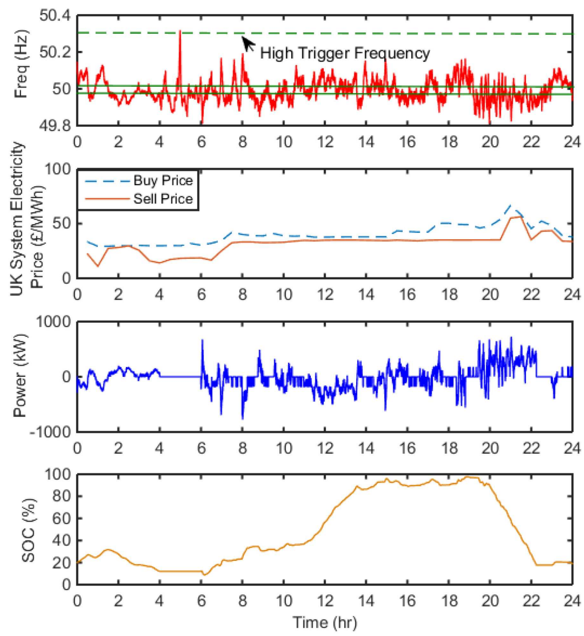

Fig. 8 *Simulation results of the arbitrage control algorithm for 14th April 2014 for scenario 9 (S9)*

5 Conclusion

A dynamic and a static high and low FFR control algorithm based on a model of a 1 MW/1 MWh BESS have been developed to meet the NGET published service requirements. In addition, a method for arbitrage has been presented that uses layering and scheduling of grid balancing services (FFR and EFR) throughout the day. Simulation results of the control algorithms were carried out using NGET frequency data for 11 November 2015, which is includes both over and under frequency events, and 14 April 2014, which

Table 4 Frequency response service profit obtained from each scenario in Table 2 for 14th April 2014

Scenario	DFFR, £/day	SFFR, £/day	EFR, £/day	Total service revenue, £/day
S1	—	16	240	216
S2	22	16	180	218
S3	—	24	180	204
S4	22	16	180	218
S5	220	16	—	236
S6	—	—	240	240
S7	—	8	220	228
S8	242	8	—	250
S9	44	8	180	232

contains an over frequency event and used as a comparison with another study. The simulation results based on an experimentally validated model show that arbitrage profits can be made and that by layering different services throughout the day the revenue generated by a BESS can be maximised.

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