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Battery SOC Management Strategy for Enhanced Frequency Response and Day-Ahead Energy Scheduling of BESS for Energy Arbitrage

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Abstract—**The electricity system has to balance demand and supply every second, a task that is becoming evermore challenging due to the increased penetration of renewable energy sources and subsequent inertial levels. In the UK, a number of grid frequency support services are available, which are developed to provide a real-time response to changes in the grid frequency. The National Grid Electricity Transmission (NGET) – the primary electricity transmission network operator in the UK – has introduced a new faster frequency response service, called the Enhanced Frequency Response (EFR), which requires a response time of under one second. Battery energy storage systems (BESSs) are ideal choice for delivering such a service. In this paper a control algorithm is presented which supplies a charge/discharge power output with respect to deviations in the grid frequency and the ramp-rate limits imposed by NGET, whilst managing the state-of-charge (SOC) of the BESS to maximise the utilisation of the available energy capacity. Using the real UK market clearing prices, a forecasted battery state of charge (SOC) management strategy has been also developed to deliver EFR service whilst scheduling throughout the day for energy arbitrage. Simulation results demonstrate that the proposed algorithm delivers an EFR service within the specification whilst generating arbitrage revenue. A comparative study is also presented to compare the yearly arbitrage revenue obtained from the model of the Willenhall and an experimental Leighton Buzzard battery storage system. Simulation results on a 2MW/1MWh lithium-titanate BESS are provided to verify the proposed algorithm based on the control of an experimentally validated battery model.**

Keywords—Battery energy storage, day-ahead market, energy arbitrage, enhanced frequency response, grid support, Lithium-Titanate.

I. INTRODUCTION

Global electricity demand is forecasted to increase by 3.1% annually from 2010 to 2050 [1-2]. The UK electricity consumption in 2015 was 303 TWh [3]. Conventional approaches such as installing more fossil-fuel power plants to meet the increased electricity demand are environmentally unfriendly and costly. Renewable energy sources such as wind, solar are considered a promising solution to improve energy efficiency and relief system overloading [2]. However, intermittent renewable energy causes significant issues on power system operations such as demand-generation balance, voltage/frequency stability and operational planning in electricity markets [2, 4-6]. Energy Storage Systems (ESSs) can play a significant role in mitigating the issues highlighted above, and improve the dynamic response of the system [7, 8]. Furthermore, ESS can increase power quality and reliability, meeting demand during peak hours, facilitating control of energy imbalance charges and reducing losses [7]. There are numerous ESS technologies such as fuel cells, compressed air, pumped hydro, hydrogen, flywheel, cryogenic, and superconducting magnetic storage technologies [1, 5, 9]. Development of improved battery technologies and decreasing costs make the application of Battery ESS (BESS) a favourable solution for grid application. Large scale BESS can provide numerous market benefits such as frequency regulation, electricity arbitrage, ancillary services and reserve services [10, 11, 15]. BESSs having different battery chemistries have been installed around the world for power grid support [1].

The motivation of this paper is to investigate two applications for battery energy storage; frequency regulation and energy arbitrage in day-ahead spot markets. The electricity price tends to follow a daily pattern of a high price during on-peak daytime hours and a lower price during off-peak night time hours. If the BESS stores energy at the lower price (off-peak) and resells at the higher price (on-peak), it can benefit from the electricity price discrepancy, this is referred to as arbitrage [11, 14, 16, 17]. In power distribution networks, the system frequency changes continuously due to the imbalance between total generation and demand; if demand surpasses generation, a decrease in the grid frequency will occur and vice versa [1, 12]. Maintaining the grid at a nominal frequency (i.e. 50 Hz for the UK) requires the management of many disparate generation sources against varying loads. This is becoming increasingly challenging due to the penetration of renewable energy sources and loss of traditional generation that provide inertia to the system. To overcome this issue, National Grid Electricity Transmission (NGET), the primary electricity transmission network operator in the UK, is introducing a new faster frequency response service, called Enhanced Frequency Response (EFR), to assist with maintaining the grid frequency [1,13]. A BESS is an ideal candidate for providing such service to the power system due to its capability to import/export and its rapid response rates. In 2013, the UK's first grid-connected lithium-titanate BESS, the Willenhall Energy Storage System (WESS), was commissioned by the University of Sheffield to enable research on large scale batteries and to create a platform for research into grid ancillary services [1].

In this paper, a new Enhanced Frequency Response (EFR) service model is developed to evaluate control strategies for providing a real-time response to deviations in the grid frequency as defined by NGET specifications [13]. Simulation results based on the 2MW/1MWh WESS plant verify the proposed control strategy's transient performance. Finally, using real-time UK market clearing prices [21], a forecasted battery management strategy has been developed to deliver the EFR service whilst scheduling throughout the day for energy arbitrage.

II. Enhanced Frequency Response Service

EFR is introduced as a new fast response service for grid balancing service that can supply 100% active power within one second of registering a grid frequency deviation. NGET provided an EFR specification to facilitate a tender competition for 200MW amongst potential energy storage providers in late 2016. According to the specification, storage systems must supply power to the grid to respond to frequency changes outside of a dead-band (DB) set around the nominal 50Hz. Within the DB, there is no statutory requirement to supply power to the grid [13] but there is an opportunity to charge/discharge the battery, within power limits, in order to achieve a desired SOC range. Systems must deliver continuous power to the grid as described in one of the two EFR service envelopes (Service-1 and Service-2) as detailed in Fig. 1, Table I, Table II [13]. The power level must remain within the lower and upper envelopes at all times; power delivered outside the envelope will decrease the service performance measurement (SPM) and therefore the income revenue [13].

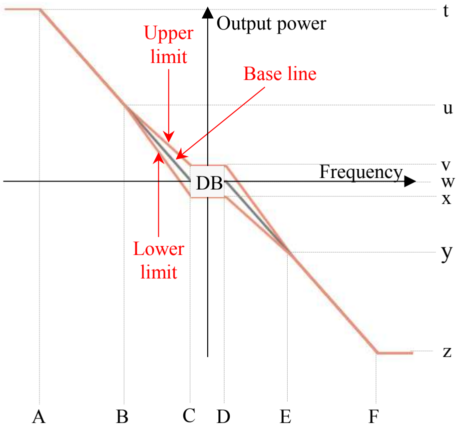

Fig. 1 EFR envelope [13].

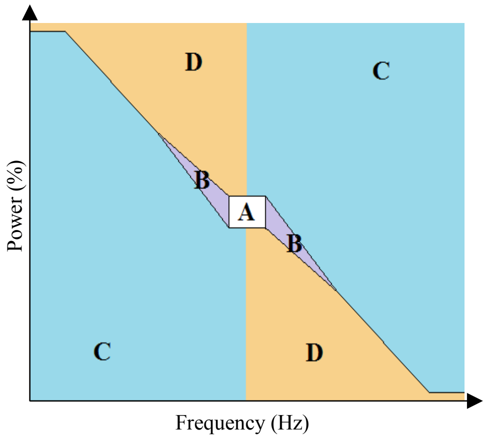

Fig. 2 EFR power zones [13].

The BESS can be operated freely in DB, however the maximum power must not exceed 9% of the maximum EFR power [13]. Systems may operate anywhere within the upper and lower envelopes to deliver a continuous service to the power system, but must adhere to the specified limitations on ramp rates as given in Fig. 2, Table III and Table IV [13]. For a BESS, this effectively provides some control over the state-of-charge (SOC) of the battery. For the zones A, C, D in Fig. 2, the ramp rate must obey the specified values in Table III. Operation in C and D will lead to penalties to the availability payment. Therefore, in such cases, EFR power output has to return to the specified envelope with respect to the ramp-rate proportions (see Table III).

TABLE I
EFR Envelope Frequency Boundaries [13]

Ref. Point	Service-1 (Hz)	Service-2 (Hz)
A	49.5	49.5
B	49.75	49.75
C	49.95	49.985
D	50.05	50.015
E	50.25	50.25
F	50.5	50.5

TABLE II
EFR Envelope Power Boundaries [13]

Ref. Point	Service-1 (%)	Service-2 (%)
t	100	100
u	44.44444	48.45361
v	9	9
w	0	0
x	-9	-9
y	-44.44444	-48.45361
z	-100	-100

TABLE III
Ramp Rate as a Precentage of Operational Capacity for Power Zones A, C and D [13]

Area	Max Ramp Rate (MW/s)	Min Ramp Rate (MW/s)
A	1%	0%
C	200%	0%
D	10%	0%

TABLE IV
Ramp Rate as a Precentage of Operational Capacity for Power Zone B [13]

EFR Service	Max Ramp Rate (MW/s)	Min Ramp Rate (MW/s)
1 (wide)	$\left(-\frac{1}{0.45}\frac{df}{dt}+0.01\right)\times 100$	$\left(-\frac{1}{0.45}\frac{df}{dt}-0.01\right)\times 100$
2 (narrow)	$\left(-\frac{1}{0.485}\frac{df}{dt}+0.01\right)\times 100$	$\left(-\frac{1}{0.485}\frac{df}{dt}+0.01\right)\times 100$

Ramp-rate zone B is described as being the area between the upper and lower envelopes, excluding the DB, and extends to reach the full EFR power capability at ±0.5 Hz [13]. The allowable ramp rates within zone B depend on the rate of change of frequency. For EFR Service-1 and Service-2, the ramp rate limitation at all frequencies in zone B are given in Table IV. With these ramp limits, output EFR power changes proportionally to changes in frequency, whilst allowing the storage providers some flexibility to manage the battery SOC [13].

III. DESIGN CONTROL ALGORTHM

A BESS model is developed in MATLAB/Simulink and verified against experimental operation of the WESS. A novel EFR control algorithm is then implemented in the model to provide a grid frequency response service to the NGET specification (see Fig. 3) [1]. Fig. 3 illustrates the control scheme implemented in the EFR Model, where the inputs are real-time grid frequency (f) and battery SOC, and the output is the required EFR power. The algorithm starts by detecting the position of the measured grid frequency with respect to the zones bounded by vertical lines 'A' to 'F' in Fig. 1. This is achieved by the 'EFR Power Calculation' block, where the required EFR response envelopes are calculated. In the 2MW BESS model, the frequency and power bounds are calculated as a function of the limits denoted in Fig. 1 EFR envelope [13]., with their values declared in Table I and Table II. The EFR power output is restricted to ±180 kW (9%) within the DB and both services include an upper, reference and lower power line denoted U, Z and L, respectively. The next block in the sequence selects the required power line with the decision being based on the measured battery SOC. For example, if the SOC is currently below a predefined limit, the demanded power is calculated using the equations derived for the lower line (L). This has the effect of either importing energy to charge the battery or minimising the exported energy to maintain a desired SOC range. The 'Zone Assignment' block is responsible for identifying the current operating zone (see Fig. 3) for the calculation of the power-output levels. Finally, the change in power output per time step (1 second) for each zone is determined using the given ramp-rate limits in Table III and Table IV [1]. In this work, battery SOC is calculated using (1),

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

where $\mathrm{SOC_{init}}$, Q and P_{batt} represent initial SOC, Watt-hour capacity and instantaneous battery power, respectively.

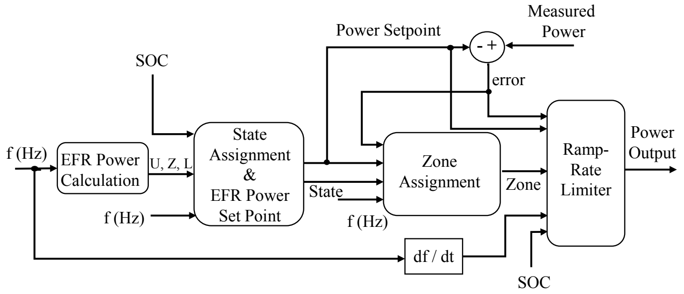

Fig. 3. Enhanced frequency response model control scheme [1].

The EFR specification defines grid frequency outside DB for longer than 15 minutes as an extended event whereby, after the 15 minutes it is optional to supply power for up to 30 minutes post the system frequency returning to DB. In order to improve the availability of the BESS for EFR delivery by avoiding SOC limits, an extended 15-minute frequency event control algorithm is implemented as shown in Fig. 4. The algorithm introduces a timed control block which measures the length of time that the grid frequency is continuously outside of the DB. If this block measures a value higher than 15 minutes, then the BESS's output power is set to zero. The BESS remains in this state until the grid frequency returns within DB, at which point a second timer starts timing for 30 minutes. The algorithm allows the BESS to manage its SOC during the 30-minute rest period by charging/discharging the battery within the ±9% EFR power limit [1].

TABLE V
PARAMETERS USED IN EFR MODELS [1], [13]

Parameter	Value
High/Low DB	±0.015 Hz (Service 2)
Min/max EFR power limit	±2 MW
Battery rated power/capacity	2 MW/1 MWh
Initial SOC @ 00:00hrs ($\mathrm{SOC_{init}}$)	20%
Inverter efficiency (η_{inv})	97%
Battery charge/discharge efficiency (η)	94%

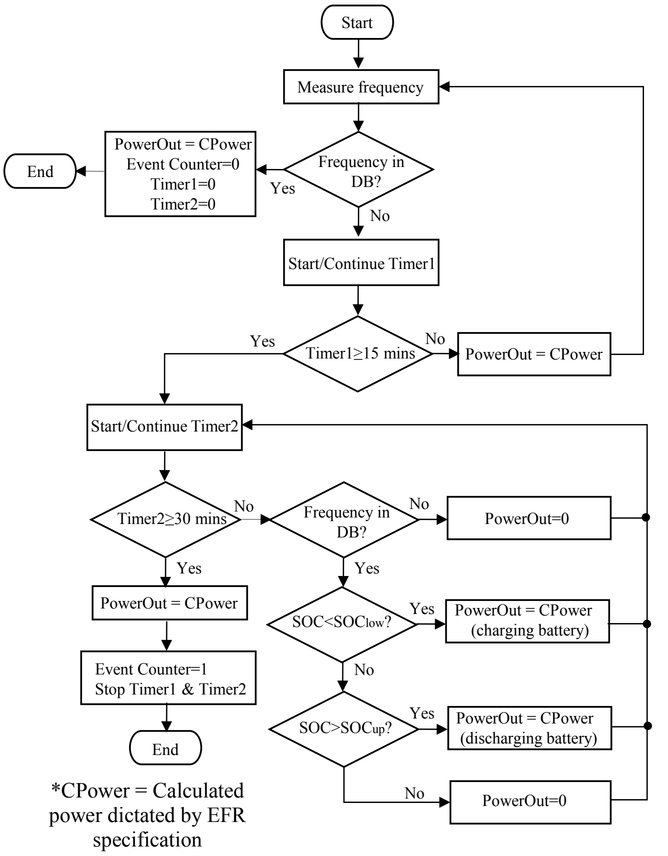

Fig. 4. Flow chart presenting the structure of the proposed battery energy management strategies for enhanced frequency response in the UK.

IV. ENERGY ARBITRAGE

Past studies have examined the potential of ESS for arbitrage revenue though not whilst simultaneously providing other services. These studies have focused on a week or two-week time period, or whole year analysis using both day-ahead market prices with and without foresight, using historical data [10-11, 14, 18-19, 22]. This study investigates the potential arbitrage revenues whilst delivering EFR for all settlement periods in a day by manipulating the SOC target in the EFR algorithm. This is achieved by increasing the SOC target when prices are low and decreasing the SOC target when prices are high; effectively shaping the energy delivery profile to import at low prices and export at high prices. Using UK historical pricing data, the proposed strategy selects the appropriate battery SOC profile to maximise the income revenue for arbitrage whilst delivering the EFR service. Stored energy in the BESS is expressed in (2) [11, 18-20].

$$
\begin{aligned}
&Discharging: \; P_t > 0 \quad E_t = \int_0^t \frac{P_t}{\eta_D}.dt \\
&Charging: \quad P_t < 0 \quad E_t = \int_0^t P_t.\eta_C.dt
\end{aligned}
\qquad (2)
$$

where η_D is battery discharging efficiency, η_C is battery charging efficiency, E_t is energy stored in the BESS at hour *t*, if $P_t > 0$ BESS injects 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 simply calculated using the following [11, 18-20, 24]:

$$C_C = \sum_{t=1}^{24} E_t \,.A_t \quad \text{if} \quad P_t < 0 \qquad (3)$$

$$C_{DC} = \sum_{t=1}^{24} E_t.A_t \quad \text{if} \quad P_t > 0 \qquad (4)$$

where C_{DC} is cost of BESS discharging, C_C is cost of BESS charging, A_t is system electricity price in £/MWh at hour *t*.

$$Max\,(CA_t) = C_{DC} - C_C \qquad (5)$$

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

V. SIMULATION RESULTS OF ENERGY ARBITRAGE MODEL

The EFR model is simulated in MATLAB/Simulink using real frequency data obtained from NGET [13]. The simulation results provided in this paper are all based on a 1MWh BESS model, which has been experimentally validated on the WESS in the UK, with a maximum EFR power of ±2 MW. The parameters used in the models are shown in Table V. Using the real-time UK system electricity price data [21], the model is simulated to analyse the effects of a selected number of SOC target profiles to maximise arbitrage revenue. Two days of frequency data are simulated which both represent significant EFR delivery but differing in the balance of EFR energy consumed for import against export.

A. Simulation Results of the Arbitrage Model for 14th April 2014

In order to demonstrate the performance of the reported EFR algorithm in Section III, the real grid frequency data for the 14th April 2014 is used herein, as this particular day is known to have a large period of over frequency.

TABLE VI

FINDINGS OF EFR SERVICE SCHEDULING THROUGHOUT 14TH APRIL 2014 FOR ARBITRAGE

Time (hr)	**SOC band (%)**	**Energy Output (kWh/ day)**		**APR (£/kWh.yr)**	**S**
		Imp.	**Exp.**		
12am - 8pm	90-95	1516	1277	3.21	1
8pm - 12am	15-20				
12am - 1am	90-95	1516	1277	3.21	2
1am - 3am	50-55				
3am - 8pm	90-95				
8pm – 12pm	15-20				
12am - 3pm	90-95	1547	1308	3.03	3
3pm - 8pm	70-75				
8pm - 12am	15-20				
12am - 1am	90-95	1537	1300	3.14	4
1am - 3am	20-25				
3am - 8am	90-95				
8am - 8pm	70-75				
8pm - 12am	15-20				
12am - 3pm	90-95	1531	1295	2.34	5
3pm - 12am	15-20				

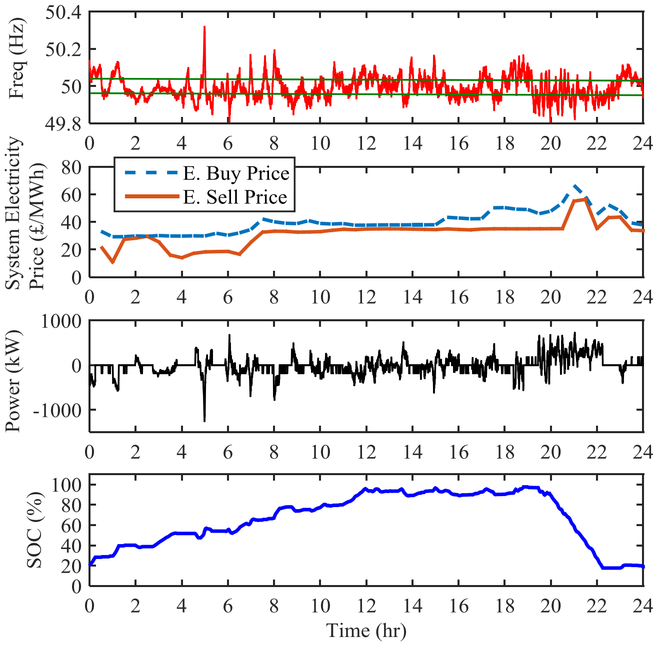

Fig. 5. Simulation results of Arbitrage Model for 14th April 2014 (S1) [21].

Fig. 5 shows the model simulation results for a ‘Service-2’ EFR with energy arbitrage; the green lines on the frequency plot show the DB, whilst Fig. 6 shows the power plotted against frequency. Based on the UK system sell/buy electricity price, the EFR model has been analyzed for five different SOC management scenarios in order to maximize the arbitrage revenue. The findings of the EFR service scheduling throughout the 14th April 2014 for arbitrage are given in Table VI. The revenue of arbitrage for the day period was summed over the year to achieve annual values on a £/kWh.yr basis.

According to scenario 1 (S1), the battery SOC band is selected at 90-95% to charge the battery until 8pm with relatively low electricity and then the SOC band is decreased to 15-20% in order to deliver power to the grid at peak time where the electricity is high. Scenario 5 (S5) demonstrates the worst case where the battery charges for 3 hours at night, but discharges over a long time period, hence unable to maximise revenue by delivering power to the grid during on-peak time (8pm – 10pm).

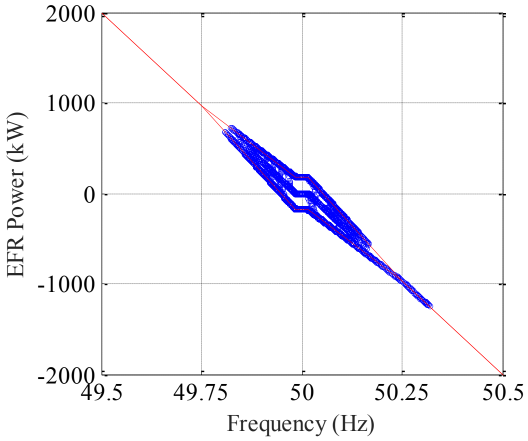

Fig. 6. EFR power against grid frequency of Arbitrage Model for 14th April 2014 (S1).

Fig. 5 shows the simulation results of the arbitrage model based on the UK real-time system sell/buy electricity price. Despite the high-frequency event occurring at 5am on 14th April 2014, a favorable battery SOC management has been achieved with S1, achieving 100% EFR service delivery in combination with a significant arbitrage potential revenue (APR). The APR findings from the simulation are comparable with the optimized yearly arbitrage profit obtained from the 6MW/10MWh Leighton Buzzard battery system in [23]. Comparing both values in year base, the arbitrage profit earned from the experimental battery in [23] is higher (£5.91/kWh.yr) because only arbitrage is considered, no other services are delivered simultaneously, therefore taking full advantage of the capacity of battery. Using the NGET specifications [13], the EFR cost benefit with S1 can be calculated as: The BESS delivering 2 MW of EFR for 24 hours per day would have 48 half-hourly settlement periods each with an availability factor of 100%. Using the specified availability price of £5/MW/h [13], the payment equates to £240 per day or £43.8/kWh.yr. The results from this simulation show that it is possible to increase revenue by 7.5% through arbitrage based on the conditions on this day. Finally, the BESS is 100% available for delivering EFR power through energy arbitrage according to the EFR specification as seen in Fig. 6.

B. Simulation Results of the Arbitrage Model for 21st Oct 2015

For comparison the actual grid frequency data for the 21st Oct 2015 is used herein, as this particular day is known to have a large period of under frequency.

TABLE VII

FINDINGS OF EFR SERVICE SCHEDULING THROUGHOUT 21ST OCT 2015 FOR ARBITRAGE

Time (hr)	**SOC band (%)**	**Energy Output (kWh/day)**		**APR (£/kWh.yr)**	**S**
		Imp.	**Exp.**		
12am - 5pm	80-85	1674	1348	1.72	1
5pm - 12am	15-20				
12am - 6am	80-85	1622	1305	1.74	2
6am – 4pm	60-65				
4pm - 8pm	15-20				
8pm - 12am	20-25				
12am – 6am	80-85	1606	1326	1.97	3
6am - 4pm	60-65				
4pm - 12am	15-20				
12am - 6am	80-85	1611	1341	2.12	4
6am – 4pm	50-55				
4pm – 12pm	15-20				
12am - 5pm	80-90	1683	1318	1.42	5
5pm - 12am	15-25				

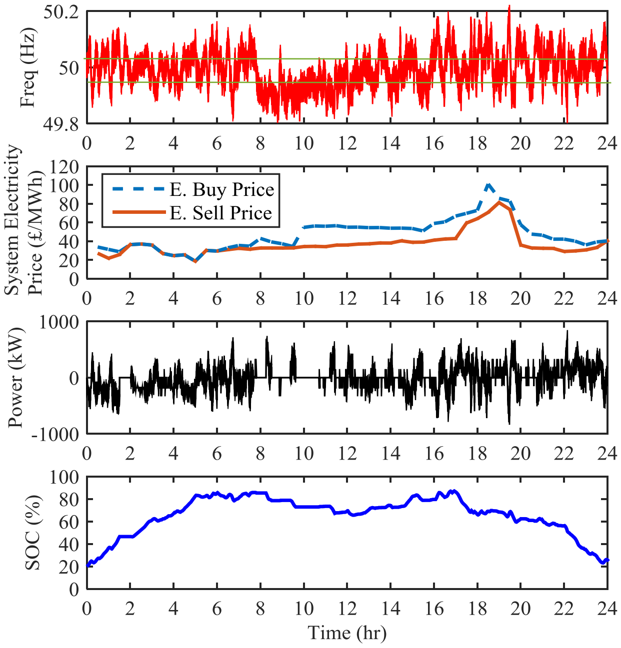

Fig. 7. Simulation results of Arbitrage Model for 21st Oct 2015 (S1) [21].

Fig. 7 shows the model simulation results for a 'Service-2' EFR with energy arbitrage, with the SOC scenarios presented in Table VII. It can be seen that S3 and S4 provide the highest amount of arbitrage revenue, however these are very specific profiles, perhaps only possible with foresight knowledge of pricing. To compare with the previous 14th April 2014 simulation results, the SOC management scenario for S1 are provided in Fig. 7. The SOC target band is 80-85% from 12am until 5pm in order to charge the battery with the lowest electricity price. As can be seen from Fig. 7 the battery actually discharges between 8am to 1pm because of extended low grid frequency events, and the increased export power for the EFR service required. The results for the two days show that the ability to import/export energy for arbitrage through SOC management varies with EFR demand.

VI. CONCLUSION

A new EFR control algorithm based on a model of a 2MW/1MWh BESS has been developed to meet the NGET published requirements and a forecasting battery SOC management strategy has been also developed to deliver the EFR service whilst scheduling throughout the day for energy arbitrage. When there is a frequency deviation on the grid, the BESS supplies a power response according to a specified EFR envelope. The algorithm exploits both the EFR power delivery envelope and extended frequency event windows, managing the SOC of the BESS according to a defined target band. To generate arbitrage revenue the target SOC band is periodically moved according to the electricity pricing profile for the day. Setting the SOC band high has the effect of importing energy and setting the SOC band low exports energy. Simulations of the control algorithms were carried out using NGET frequency data for 14th April 2014 and 21st Oct 2015, which are representative of two over frequency and under frequency days. The simulation results demonstrate that the EFR algorithms meet the UK's NGET EFR requirements and can successfully manage the SOC of battery, and by tracking the real-time UK electricity prices, maximize energy arbitrage revenue without EFR service penalties. Whilst in this paper the value of arbitrage is evaluated using exact foresight of electricity pricing, the methodology can be applied in conjunction with existing electricity pricing forecasting algorithms.

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