Investigation of Energy Storage and Open Cycle Gas Turbine for Load Frequency Regulation

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***Abstract*- In power systems, load is continuously fluctuating and is difficult for slow generating units, such as coal-fired, nuclear and hydro power plants, to follow. Therefore, fast but expensive generation units like open cycle gas turbine (OCGT) are widely used to provide frequency regulation, maintaining system frequency within its specified limit. Owing to energy storage system (ESS)'s zero-net energy and fast response nature, one of the applications of ESS in power system is to provide frequency regulation. This paper proposes a method of sizing OCGTs and advanced lead-acid batteries to provide frequency regulation under different types of load following patterns. The rain-flow counting algorithm is used for battery lifetime modelling. The cost and savings from displacing OCGTs with ESS are calculated and discussed. It was concluded that the system load following ability is the key factor when considering whether ESS is cost effective when providing frequency regulation in a control area. The method of battery and OCGT rating presented in this paper is applicable to the situation when regulation load requirement is known or can be estimated.**

***Index Terms*—Battery sizing, energy storage, frequency regulation, life estimation, OCGT**

I. INTRODUCTION

It is difficult for generators to follow loads instantaneously and continuously because both generators and loads are constantly fluctuating. Load fluctuation results from random turning on and off of millions of individual loads [1]. Load profile also varies because of long-term variability, such as shifting weather patterns and seasonal load patterns change. On the generation side, fluctuating output power from wind generators is a key source of uncertainty as renewable energy penetration has grown rapidly in recent years.

Electric power systems in different areas are highly interconnected for security and economy reasons. Each network includes many control areas. A control area is defined as a regulated area, aiming at supplying the customer load with its own generation or electricity bought from other areas. The load from a control area can be decomposed into three components. These are base load, load following and frequency regulation [2]. Base load is the minimum constant load in the load profile. Load following is to match system generation and load by tracking the intra- and inter-hour changes in customer loads, and maintain frequency at 50 Hz during the operation of power systems. Regulation consists of the random fluctuations in load around the underlying trend [1]. Regulation is the use of generation, load with automatic generation control (AGC) to follow the moment-to-moment load fluctuations and to restore or mitigate unpredictable outages situations.

Prices for frequency regulation services are much higher than other ancillary services (i.e. spinning reserve, supplemental reserve and replacement reserve). Increasing levels of wind penetration need considerable regulation requirement due to varying wind conditions. As wind plants displace more and more conventional generation, which are often the expensive or least economic generators providing marginal power for regulation bids. This trend will increase the regulation need in power systems. AGC is used to correct the Area Control Error (ACE). ACE is the instantaneous difference between a Balancing Authority's net actual and scheduled interchange, taking into account the effects of frequency bias and correcting for meter error [3]. Slow-acting generators sometimes increase ACE when short rapid power balance direction changes occur, during which generators may increase output in the opposite direction. As a result, additional regulation actions need to be taken to counteract their negative effect.

An ideal energy storage system (ESS) can achieve a zero net energy resource with a zero net energy service. It can act as a generator at some times and act as a load at other times, varying its output around zero. Additionally, because of the capabilities of fast response and precise control, energy storage system should be a desirable choice for providing regulation services. To meet the high ramp rate and high recharge/discharge cycle requirement of frequency regulation, energy storage technologies that have high cycle life characteristics will be the most suitable candidates. Owing to the extremely fast response rate of energy storage compared with conventional generators, energy storage can achieve a more accurate and effective regulation [4]. The basic characteristics of regulation and load following are compared in Table I.

TABLE I
COMPARISON BETWEEN FREQUENCY REGULATION AND LOAD FOLLOWING CHARACTERISTICS [1]

	Regulation	Load following
Maximum swing	Small	10-20 times regulation
Ramp rate (MW/min)	5-10 times load following	Slow
Sign changes per minutes	20-50 times load flowing	Few

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Because of the fast response characteristic of ESS, it has been concluded that storage can be up to two to three times as effective as adding a combustion turbine to the system for regulation purposes, which means that a 300 MW combustion turbine is only equivalent to a 100 MW ESS dedicated to frequency regulation purpose [5]. Using conventional generators to provide regulation not only requires more MWs, but also causes indirect costs, such as additional maintenance cost, equipment wear and tear and more greenhouse gases. When the system experiences a sudden load change, systems operators can use energy storage to provide enough time, maintaining ACE whilst calling up conventional generators in an orderly manner.

Base load is nearly constant and is usually supplied by steady and most cost-effective generation units, such as nuclear power plant, Combined Cycle Gas Turbine (CCGT) and coal-fired power plant. However, load following capability in a control area varies greatly depending on the area's generation technology mix, reserves, production cost, load forecasting and frequency control mechanism. The main approach taken in this paper is to investigate and compare the cost and rating between ESS and OCTG for providing frequency regulation under different load following patterns as illustrated in Fig. 1.

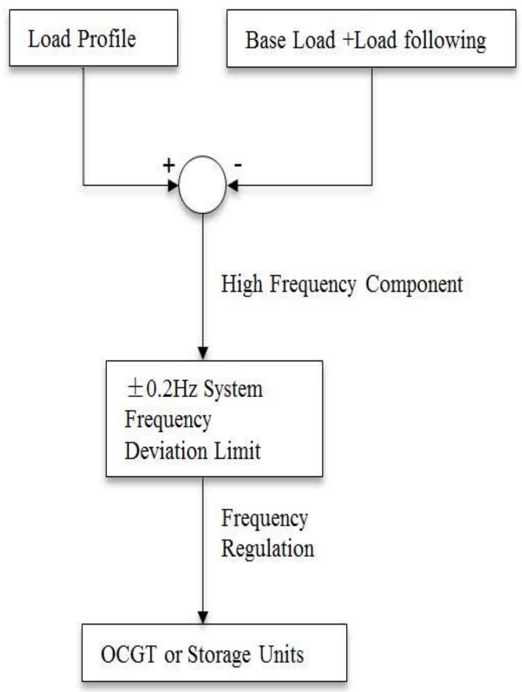

Fig. 1. Scheme to obtain system frequency regulation under ±0.2Hz frequency deviation limit.

This study uses a control area load data set from TransnetBW Grid in Germany. The data set runs for 29 consecutive days in March 2014 at a resolution of 15 minutes as shown in Fig.2.

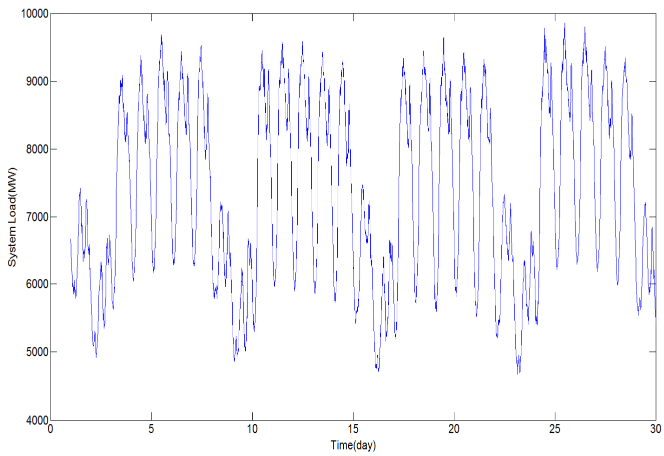

Fig. 2. Load profile in a control area for 29 days sampled every 15 minutes

II. BASE LOAD AND LOAD FOLLOWING

Four methods of deciding the sum of base load and load following are used in this study. They are 30-minute rolling average load, 60-minute rolling average load, 90-minute rolling average load and projection load.

X-minute Rolling average (also called moving average) is the un-weighted mean of consecutive values over X minutes from each data point. It is commonly used to smooth a fluctuating data set and is suitable for extracting the underlying trend of the load. The subset sizes analysed are 30 minutes, 60 minutes and 90 minutes. Projection load is the actual load forecasting obtained from power utilities. Actual load, 30-minute rolling average load and projection load in day 1 is illustrated in Fig.3.

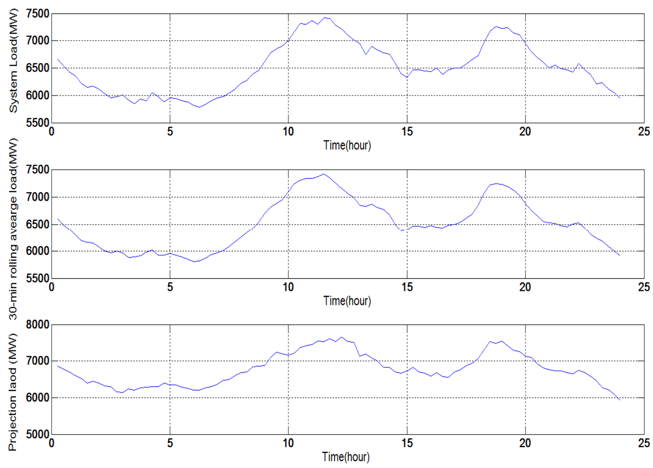

Fig. 3. Actual load, 30-minute rolling average load and projection load in day 1 (Saturday)

The high frequency component in Fig.1 is calculated by subtracting rolling average or projection load from the load profile. If the high frequency component is supplied continuously and instantaneously by fast units, system frequency is maintained at a constant 50 Hz. However, it is expensive and it is not necessary to provide such a high standard of frequency regulation. Normal operating frequency of the power system in the UK is around 50 Hz. According to the 'Electricity Supply Regulations', system frequency should not excess 1% deviation (i.e. ±0.5 Hz) in abnormal or exceptional circumstances. Normal operating limits range from 49.8 Hz to 50.2 Hz.

III. Frequency Response Modeling

This study aimed to maintain system frequency within the ±0.2 Hz deviation limit. Frequency response should be modelled to calculate the amount of frequency regulation needed in each sample point over the period of study.

The system frequency response due to imbalance depends on the system inertia and damping constant. System inertia is directly proportional to the rotating mass of synchronous generation and motor load in the system. Load damping refers to the frequency-sensitive load change when system frequency deviation arises. The general equation for calculating frequency deviation is illustrated in (1) [6].

$$\Delta fpu = -\Delta Pm\ (s)\ /(Ms + D) \tag{1}$$

where

Δfpu is the change of the frequency (pu)

ΔPm is the load and generation mismatch calculated by subtracting generation from load (pu in system load base)

M (=2H), H is the system inertia constant (seconds)

D is the power system load damping value.

In this study, M and D is equal to 10 and 1 respectively. A value of D=1 means that a 1% change in frequency would lead to a 1% change in load. For a step change in load by ΔP_m, Laplace transform of the change in load is

$$\Delta Pm\ (s) = \Delta Pm/s \tag{2}$$

Hence,

$$\Delta fpu\ (s) = -\Delta Pm/(s(Ms + D)) \tag{3}$$

Taking the inverse Laplace transform,

$$\Delta fpu\ (t) = \Delta Pm\ e^{-\frac{t}{10}} - \Delta Pm \tag{4}$$

As

$$\Delta Pm = \Delta Pactual/Pbase \tag{5}$$

$$\Delta fpu = \Delta factual/f0 \tag{6}$$

Where f_0 is the rated system frequency (50 Hz)

$\Delta factual$ is the change of the frequency (Hz)

$\Delta Pactual$ is the amount of load and generation mismatch (MW)

Pbase is system load base, $P_{base} = 10000$ MW

$$\Delta factual\ (t) = f0\frac{\Delta Pactual}{Pbase}\left(e^{-\frac{t}{10}} - 1\right)\text{Hz} \tag{7}$$

It is assumed that frequency at t=0 is 50 Hz. Without the correction of frequency regulation, system frequency exceeds ±0.5 Hz deviation limit in a short time if the load generation mismatch is high enough.

The required output of frequency regulation under ±0.2 Hz frequency deviation limit can be derived according to (7) by using MATLAB® programming. The high frequency component and frequency regulation requirement in Day 1 are compared in Fig. 4 (Based on 30-minute rolling average load). It can be observed that the frequency regulation requirement is lower than that of the high frequency component.

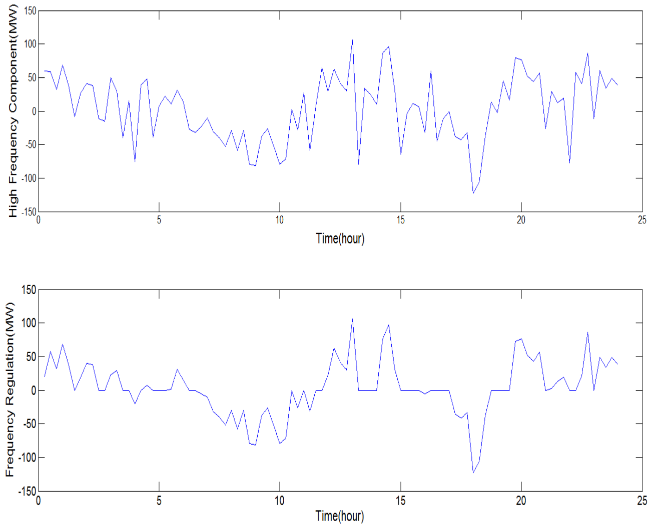

Fig. 4. High frequency component and frequency regulation output in Day 1 based on 30-minute rolling average load

IV. OCGT and ESS Rating

Once the frequency regulation requirement is obtained, the rating of fast units can be determined to meet that requirement. As the regulation service features high ramp rate and a high recharge/discharge cycle requirement, OCGT and advanced lead-acid battery are studied respectively to provide frequency regulation.

OCGT

OCGT can ramp up and down very quickly, as a result combustion turbines have mainly been used only for peaking or standby services. Without a steam cycle compared with combined cycle gas turbine, OCGT thermal efficiency is much lower.

When sizing OCGTs to provide frequency regulation, ramp rate, power capacity and initial operation state of the OCGT should be considered. In this study it is assumed that OCGTs are limited to a 5.1% per minute ramp rate. The power capacity of OCGTs should satisfy the entire frequency regulation requirement as well as the ramp rate. In other words, the power capacity of OCGTs is equal to the maximum of the power capacity determined by frequency regulation and the power capacity determined by the OCGTs ramp rate limit. The initial state of the OCGT is of great importance to make sure OCGTs operate within their output ability over the study.

Advanced lead-acid battery

Advanced lead-acid batteries are especially suitable for providing frequency regulation services because of their greatly improved cycle life compared with traditional lead-acid battery. Battery life time modelling is detailed in section V. Sizing advanced lead-acid battery is the process of determining the battery's power capacity, energy capacity and initial state of charge.

For power rating, the ramp rate of advanced lead-acid battery can be regarded as instantaneously reaching the required power demand. The power capacity should equal or exceed the peak value of frequency regulation requirement.

For energy rating, as the load data are sampled every 15 minutes, the energy required within each sample period can be obtained in (8).

$$E_N = P_N \times t \tag{8}$$

where t is the sample time, P_N is the power requirement during the nth sub-period and E_N is the corresponding energy requirement.

Energy requirement E_N as a function of N is obtained. N is the sequence number of sample points. The energy rating of advanced lead-acid battery can be determined according to (8) as illustrated in Fig. 5., assuming the initial state of battery $E_{initial}$ is high enough to recharge or discharge during the whole period of operation. The maximum and minimum residual energy are defined as E_{max}= $E_{initial}$ and E_{min}= $E_{initial}$ respectively. Then the number or the length of data points of E_N is measured as n. From N=1 to N=n, when E_N is positive, the battery needs to discharge to fast compensate the load power and when E_N is negative, battery needs to charge to absorb the surplus load power. E_R is the residual energy in the battery. Each $(-E_N)$ is added to E_R. Then E_{max} and E_{min} can be determined. The difference between E_{max} and E_{min} is the minimum requirement of energy rating of the advanced lead-acid battery. The actual initial state required can be obtained by (9).

$$\text{Actual initial state} = \mathrm{E_{initial}} - \mathrm{E_{min}} \tag{9}$$

For the presented method, the initial state of battery is of great importance to ensure that the battery is capable of coping with all the charge and discharge situations within its energy capacity. That is, if the initial state is too high, its recharge allowance is not enough to absorb surplus power. If the initial state is too low, its discharge allowance is not enough to avoid power shortage. Thus, how much energy the battery should be pre-charged and the actual energy capacity requirement is of great significance and the results of the method vary as the sample start point changes. To mitigate this disadvantage, the duration of load data used in this study should be long enough (29 days in this paper). However, the disadvantage of this method is that it is based on historic load profile. The selected rating may not suit all the situations. For security reason, it is a good way to leave enough margins in the sizing of power and energy ratings, which however inevitably increases the cost for adding addition energy capacity.

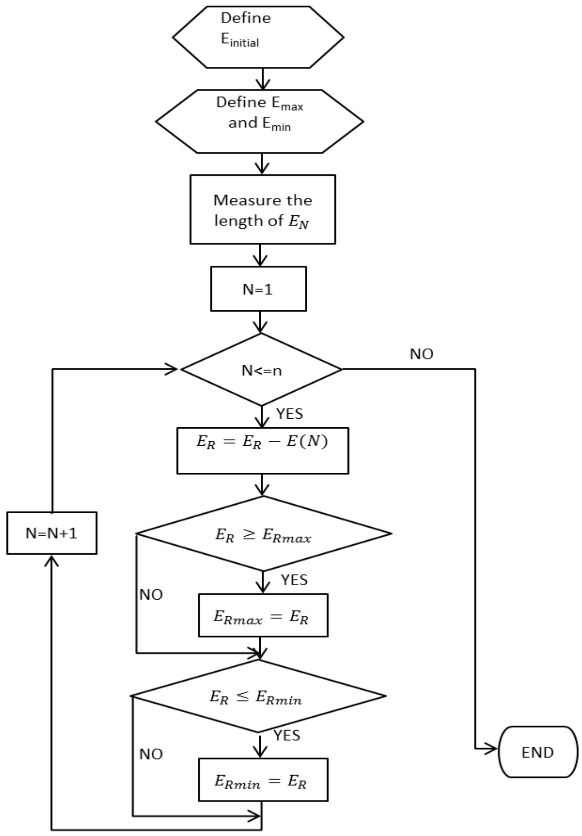

Fig. 5. Advanced lead-acid battery rating process

V. Battery Lifetime modelling

Traditional lead-acid batteries can only survive for 300 to 500 deep discharge cycles. However, some advanced lead-acid battery can withstand more than 1600 deep cycles before failure [7]. According to manufacturers' data, an extrapolated curve of cycle life of advanced lead-acid battery is illustrated in Fig. 6.

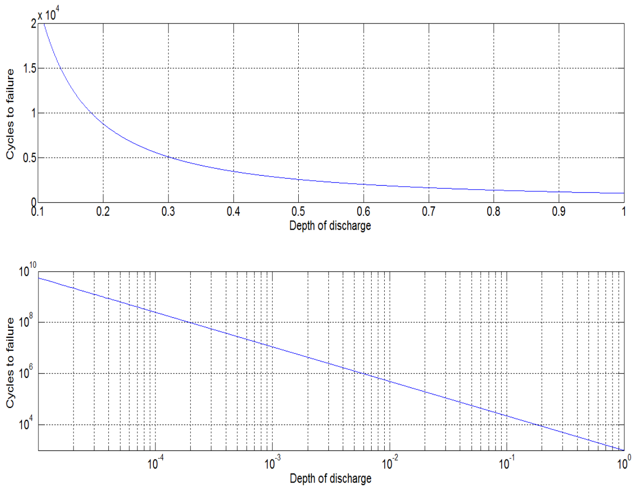

Fig. 6. Cycles-to-failure against depth of discharge for advanced lead-acid battery on a normal scale (upper curve) and on a logarithmic scale (lower curve)

The curves include the data of cycles to failures with depth of discharge less than 0.1, which is normally not contained in manufacturers' data. It is because batteries for frequency regulation often experience short-range cycles, which should be necessarily considered in battery lifetime modelling. This curve allows the effects of small cycles to be counted. The relation of cycles to failure against depth of discharge in Fig. 6 gives (10).

$$\mathrm{C(d)} = 10^{-1.349*\log10(\mathrm{d})+3} \tag{10}$$

Where d is depth of discharge, C(d) is the cycles-to-failure at depth of discharge d。

A method named as rain-flow counting is used in this paper for battery lifetime modelling. It is applied to count the number of irregular, half cycles for each charge/discharge cycle [8].

If the battery experiences a depth of discharge of d, according to (10), 1/C(d) of the battery life is consumed. If there are *i* different ranges of discharge considered and each range contains N_i cycles over the time of study, the total battery life fraction consumed X is illustrated in (11) [9]. If the study lasts Q days, the expected lifetime of advanced lead-acid battery can be evaluated in (12).

$$X = \sum_{i=i_{min}}^{i=i_{max}} N_i / C_{di} \tag{11}$$

$$Lifetime = \frac{Q}{X} \quad (day) \tag{12}$$

where Q is equal to 29 days in this study

VI. RESULTS

A. Frequency response

Fig. 7 shows the system frequency when frequency regulation services are provided by OCGTs or advanced lead-acid batteries in day 1 based on 30-minute rolling average. It can be seen that system frequency is maintained within its normal operation limit ranging from 49.8 Hz to 50.2 Hz.

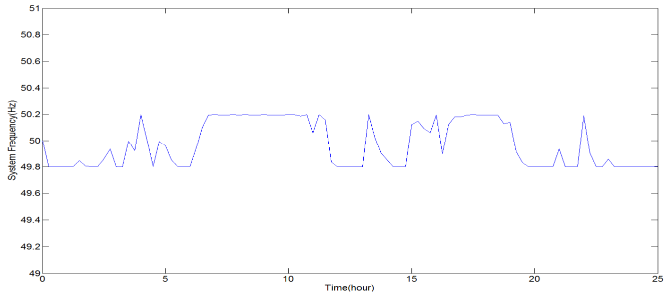

Fig. 7. System frequency with the correction of frequency regulation based on 30-minute rolling average load in day 1

B. Rating results

Table II shows the rating results of OCGT compared with advanced lead-acid battery under different types of load following. In the results, the power rating of OCGTs is determined by the frequency regulation requirement rather than the ramp rate limit of OCGTs. The size of OCGT and battery increases when the rolling average subset size rises.

However, the results for projection load looks quite large and unreasonable. It is because projection load is based on forecasting. It cannot represent the actual load trend in real time, which produces considerable error in estimating frequency regulation requirement. The process of charge or discharge often lasts a long period of time, which leads to huge power & energy capacity requirement and long lifetime estimation.

TABLE II

OCGT RATING AND BATTERY RATING WITH LIFETIME ESTIMATION

Type of load following	30-minute rolling average	60-minute rolling average	90-minute rolling average	Projection load
OCGT power capacity under ramp rate limit [MW]	262.7451	448.366	430.0654	1376.5
OCGT power capacity under regulation requirement [MW]	452	988	1379	7371
Selected OCGT Power capacity [MW]	452	988	1379	7371
Initial state of OCGT [MW]	295	652	887	3417
Battery power capacity [MW]	295	652	887	3954
Battery energy capacity[MWh]	628.5	1870.3	3088.8	170150
Initial state of battery [MWh]	239	688.75	1101	130800
Lifetime of battery (day)	1866.8	1797.4	1799.3	18887

C. *Economic assessment*

The economic savings when displacing OCGTs with advanced lead-acid battery to provide frequency regulation are composed of electricity production cost reduction and the standby cost of OCGTs. ESS can be ideally regarded as a zero net energy resource with a zero net energy service. The cost of providing energy for regulation can be saved if OCGTs is displaced by ESS. As OCGTs have to operate at an initial state to provide regulation, the cost of standby can be saved if the amount of initial state power output is supplied by cheap generation units when ESS displaces OCGTs. The levelised electricity cost of OCGT and conventional generation units are set as 180£/MWh and 120£/MWh respectively [10]. Thus, if electricity generated by OCGT is supplied by conventional generation and the frequency is maintained by ESS, 60£/MWh can be saved, excluding the savings of avoided energy for regulation service.

TABLE III

ECONOMIC COMPARISON BETWEEN OCGT AND ADVANCED LEAD-ACID BATTERY

Type of load following	30-minute rolling average	60-minute rolling average	90-minute rolling average	Projection load
Production cost savings when using battery £M	733.5	1568.7	2149	106790
Battery price £/MWh	644050	644050	644050	644050
Battery costs £M	404.78	1204.5	1989.3	109580
Balance £M	328.82	364.15	159.9	-2832.1
Required battery cost £/MWh if balance is zero	1167100	838760	695860	627610

The cost of advanced lead-acid battery system is 644050 £/MWh in this study [7]. It can be seen from Table III, except the projection load, if the system can follow load in 30-minute, 60-minute and 90-minute rolling average, it is currently cost effective to employ advanced lead-acid batteries to provide frequency regulation. Under 60-minute rolling average load following, the most savings can be obtained at £364.15M. The highest required battery cost, when balance is zero, happens at 30-minute rolling average, which means that it is cost effective to deploy ESS for frequency regulation if the battery price is under 1167100 £/MWh. If the load following ability of the system behaves as the projection load, it is currently not cost effective to displace OCGT with advanced lead-acid batteries until the battery cost decreases to 627610 £/MWh, which is slightly cheaper than that of today's cost.

The costs and savings for projection load in Table III seem to be unrealistic. Because the projection load is based on forecasting load and does not represent the actual electricity generation. In other words, the deviation between actual load and projection load is quite huge. The reason why projection load is included in this comparison is to show that systems with inadequate load following ability will need a great amount of frequency regulation capacity and cost to maintain system frequency.

VII. CONCLUSION

This study has investigated the rating of OCGTs and advanced lead-acid battery to provide frequency regulation under different types of load following patterns. By estimating the batteries' lifetime according to their charge/discharge operations, the cost and savings from displacing OCGTs with ESS are calculated and discussed. It is currently cost effective if a power system is able to provide load following service in 30-90 minute rolling average load based on the actual system load. The less the mismatch between actual load and system load following output, the less frequency services need to be provided by OCGTs or ESS (i.e. less power and energy capacity). It can be concluded that the system load following ability is the key factor when considering whether ESS is suitable for providing frequency regulation in a control area. The method of battery and OCGT rating described in this paper is applicable to the situation when regulation load requirement is known or can be estimated.

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