Study of Enhanced Frequency Support for the UK Electrical Network

Study of Enhanced Frequency Support for the UK Electrical Network

BY

Laolu Obafemi Shobayo, BEng.

A Thesis Submitted to the School of Graduate Studies in Partial Fulfilment of the Requirements for the Degree of Master of Philosophy

University of Huddersfield

January 2020

The University of Huddersfield MASTERS OF PHILOSOPHY (Computing and Engineering) Huddersfield, West Yorkshire, UK, 2017.

TITLE:	Study of Enhanced Frequency Support for the UK Electrical Power Networks
AUTHOR:	Laolu Obafemi Shobayo BEng (University of Huddersfield)
SUPERVISOR:	Professor Nigel Schofield Professor Pavlos Lazaridis
NUMBER OF PAGES:	

Abstract

The transition from hydrocarbon-based energy to a cleaner alternative in the form of solar, wind and tidal energy. These cleaner alternatives are regarded as Renewable Energy Sources (RES). The high penetration of RES is causing a shift in grid infrastructure, a need for decentralized ancillary services in the form of Energy Storage Systems (ESS) is required to assist the modern grid which would have a high penetration of RES. Energy management schemes (EMS) model the power exchange between the grid and ESS for frequency control. This thesis is focused on design of EMS to operate the ESS required for frequency control. Two management schemes are deployed and tested using real time frequency data from the NGET (National Grid Electricity Transmission). The management scheme aims to give insight into ESS sizing based on different time audits such as monthly, weekly and daily. The EMS is designed in Matlab/Simulink environment and aimed at improving ESS state of charge (SOC), availability and ESS longevity.

The BESS modelled in this thesis is developed for EFR specification only, the EFR protocol requires the BESS to respond to frequency perturbation on the utility network. The BESS model has not been technically specified for Ancillary services on the utility network such as Black Start, Voltage control and Back-Up, which will require longer sustained output from the BESS.

Acknowledgements

I give thanks to Almighty God who guided me through the years, I would also use this opportunity to thank and appreciate Bruce Meek, Professor Steve Donnelly and Richard Dockery and special thanks to Nigel Schofield for all the support.

Contents

List of Figures

Table of Tables

Table of Abbreviations

RES-Renewable Energy Sources

SO-System Operator

SOC-State of Charge

Rate of Change of Frequency ROCOF

NGET- National Grid Electricity Transmission

EFR-Enhanced Frequency Response

FFR-Fast Frequency Response

MFR-Mandatory Frequency Response

SC-Supercapacitor

SMES-Super Magnetic Energy Storage

FESS-Flywheel Energy Storage System

BESS-Battery Energy Storage System

ESS-Energy Storage System

DB-Dead Band

VDS-Variable Deadband Scheme

CDS-Constant Dead Band Scheme

EMS-Energy Management System

PV-Photovoltaic

WT-Wind Turbine

Declaration of Academic Achievement

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other place of learning.

Chapter 1

Introduction

1.1 Energy Mix in the UK

The demand for electrical energy is increasing worldwide in both developed, and developing countries as electricity have become a basic need for humanity. There is a unidirectional relationship between electrical energy demand and economic growth. Developed countries are focused on developing and maintaining an electrical grid with cleaner and more sustainable energy by using Renewable Energy Sources (RES) rather than Carbon-Based Generation to generate electrical energy. Wind, Solar, Hydro, Biomass, and Tidal energy are examples of (RES), which are utilised globally [1].

Solar, wind and Hydro are the most common RES utilised globally, and statically have grown in the last decade in the UK, according to Drax-Insight. Programs such as Vison 2050, which promotes the increase of RES technologies to replace the penetration of carbon-based generation on the Electrical Grid of the UK.

Solar and wind energy are intermittent as such are dependent on natural phenomena, namely solar irradiance (W/m^2), wind speed (m/s). Due to change in season, solar energy is not as available during the year as wind, as wind is readily available in the UK compared to solar.

The Utilization of RES is increasing yearly in Fig (1.1) shows an increase of RES penetration on the Utility Grid from 2016 -2019 on average. Wind, Solar, and Biomass increased on average from 2016-2019 [3], while energy resources such as Coal and Nuclear and gas reduced, due to the increased penetration of RES.

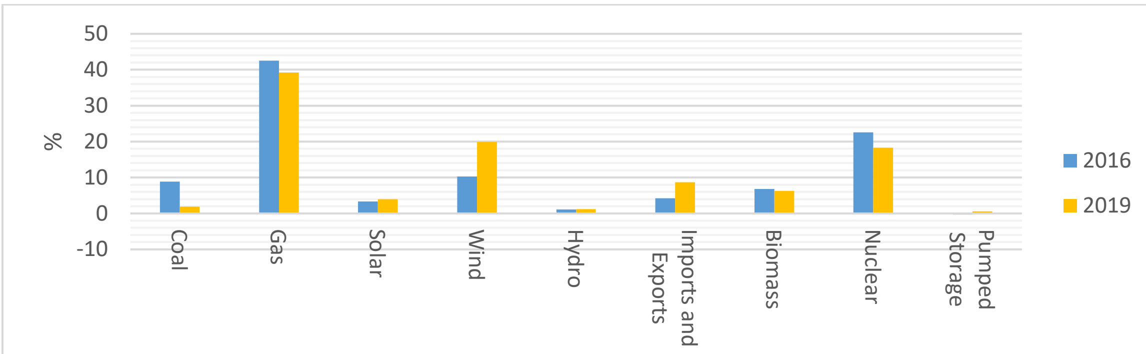

Figure 1.1 Energy Mix in the UK

Intermittence Generation is associated with technical issues such as voltage instability and grid instability. Additionally, RES cannot directly contribute to system inertia without an altercation to RES controllers [4]. Network frequency is a function of demand and supply. The power imbalance within the electrical grid is caused by the difference between mechanical supply and electrical demand [5]. Network frequency is a function of demand and supply.

Intermittence Generation is associated with technical issues such as voltage instability and grid instability. Additionally, RES cannot directly contribute to system inertia without an altercation to RES controllers [4].

Inertial response is a conventional attribute generator (Synchronous Generators) possesses to arrest the power imbalance between supply and demand. The introduction of RES is causing a shift from Carbon Based Generation to RES generation, this shift in the generation is causing a reduction in system inertia which affects the Rate of Change of Frequency (ROCOF). System Operators (SO) have a more daunting task of managing system frequency with lower system inertia [4].

The SO's have the responsibility of maintaining grid frequency between 50Hz ± 0.5Hz [5]. The variation of system frequency outside is dependent on the magnitude of the power imbalance which occurs on the network. In the event of a power imbalance between 300MW-1000MW network, frequency should not deviate more than 0.5 Hz. Subsequently, in the event of a power imbalance between 1000MW-1800MW network frequency should not vary beyond 0.8Hz [6]. Services such as frequency control and voltage control are implemented on the utility grid to support generation, transmission, and distribution. Frequency control and Voltage control are ancillary services because these services support the transmission of electrical energy from the seller to purchaser.

NGET introduced Enhanced Frequency Response (EFR) in late 2016 as the new fast frequency response service in the UK. The EFR aims to maintain grid frequency closer to 50Hz. The EFR exchanges active power with the electrical grid during power imbalances, the source of the EFR powers is from ESS such as Battery Energy Storage System (BESS), Super Capacitor (SC), and Super Magnetic Energy Storage (SMES). The EFR tender received 68 submissions from a wide variety of parties with a total capacity submitted more than 1.3GW, 888MW of that being from BESS projects [7].

1.2 Research Objectives

The main target of this research is to design Energy Management Philosophies for EFR systems based on NGET design criterion. Additionally, the study analyses EFR energy consumption as a means to estimate the size of ESS for EFR operations based on monthly, weekly and daily analysis. Two Energy Management Philosophies are used to analyses the frequency response data. The scope of this thesis is centred around the sizing of the BESS in regards to **Energy and Power.** The following steps are merged to complete the research aims:

- Model the exchange of power between BESS to Electrical Grid (Discharging) and Electrical Grid to BESS (Charging).

- To develop the EMS to calculate the amount of cumulative energy dissipated during EFR operations.
- Analyse frequency data on a timed base audit to give an estimation of ESS in regards to energy and power specifications.
- Compare Proposed ESS size to ongoing EFR projects.

1.3 Outline of the Thesis

This thesis is composed of four chapters, Chapter two expands on the literature surrounding the impact of RES on inertia and discusses frequency control in power systems. Chapter 3 gives an overview and comparison of ESS for EFR operations. Chapter 4 explains how the Energy Management Philosophies are designed and provides a comprehensive comparison between both philosophies. Finally, 5 presents the final conclusions to the thesis, while including further work and papers published.

Chapter 2

Introduction to Frequency Control

2.1 System Inertia

Traditional, power system operates on the assumption that electrical generation, in the form of thermal plants and fossil fuels, is fully controllable and dispatchable via stored kinetic energy within the rotating parts of the synchronous generator. The energy stored within the rotating parts of a generator is inertia. Inertial Response is an attribute synchronous generator possess to curtail the immediate balance between demand and supply of electrical power [8]

Large capacity synchronous generators provide approximately 70% of the UK inertia, and smaller synchronous generators supply the remainder. The capacity of inertia derived from synchronous generators capacity is expected to reduce to about 30%-40% because synchronous generators are expensive to run and produce large amounts of greenhouse emission.

The required capacity for FFR (Fast Frequency Response) services in the summer is higher than in other seasons due to low demand. Consequently, fewer synchronous generators are required to meet the demand during the summer season [8].

The contribution of inertia from synchronous generations is an essential feature of any power system. Synchronous generators are designed with electromagnetic; coupled rotating masses that release kinetic energy to the grid or absorbs kinetic energy from the grid in the event of under frequency events and over frequency events respectively [8].

2.1.1 Droop Speed Control for Synchronous Generators

Droop Speed control is a control method deployed on the utility grid to control the power output of a generator for frequency control. The technique is the speed control mode for the governor of a prime mover driving a synchronous generator connected to an AC electrical gird. Droop speed control operates by regulating the power produced concerning network frequency [9].

In the event of maximum frequency, the prime mover power is set to 0%, and in the event of the minimum operating frequency, the prime mover power is set to 100%. The droop control characteristics are similar to the equation of a straight line. In the event of an over frequency event, the prime movers will absorb the excess energy within the AC electrical grid and in the event of an under-frequency event the prime movers will increase power output. Droop Control enables grid operators to rebalance the system to evade minor speed changes resulting in small variations of frequency within the allowable tolerance [10].

In most generator applications, the load is supplied by more than one generator operating in parallel to supply power to various loads; the North American Grid is an example where multiple generators are connected in parallel. Fig (2.1) shows a line diagram of generators operating in parallel.

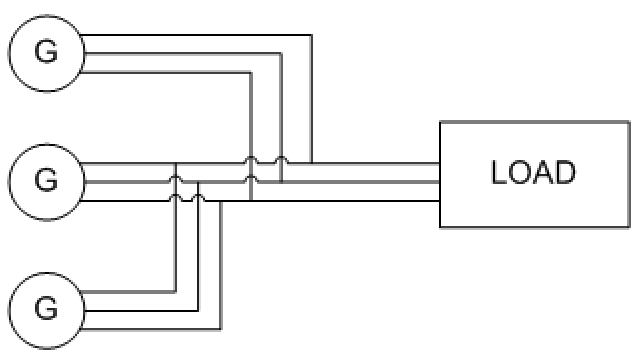

Figure 2.1 Generators Operating in Parallel [11].

Parallel operation of generators has various benefits such as [11]:

- System Reliability increases when generators operate in parallel as multiple generators can serve one load, in the event of generator failure or maintenance, other generators are available to absorb the load.

2.2 The Swing Equation

The equation for kinetic energy is shown in Equation (2.1); there are two variables in the Equation.

$$W = \frac{1}{2} J\omega^2 \qquad 2.1$$

Where *J* is *Kg.m*^{2} and *Speed* is (ω) measured in *Rad/s.*

In relation to power system, the shift from carbon-based generation to RES is causing a gradual decline in system inertia. System inertia can be supplied artificially from ESS.

The Swing Equation models the power exchange between the mechanical rotor and the electrical grid. Power Systems consists of numerous synchronous machines operating synchronously under all operating conditions. The synchronous machines under normal operating conditions have the position of the rotor axis and resultant magnetic field axis fixed. The angle between the rotor axis and the resultant magnetic field is known as the power angle. The rotor decelerates or accelerates during power disturbances, creating relative motion.

Three-phase synchronous generators are equipped with prime movers; Newton's second law determines the rotor motion of the prime mover. The Equation of the rotor motion detailed in Equation (2.2).

T_m and T_e are positive for generators operating in steady-state. T_m equals T_e thus accelerating torque *Ta* is zero, and from Equation (2.2); rotor acceleration is zero resulting in a constant rotor velocity called synchronous speed [12].

During under frequency events, T_e is more significant than Tm, as such Ta is positive and is therefore positive resulting in an increase in rotor speed, alternatively in over frequency events when Tm is less than T_e. T_a is Negative and the rotor speed decreases.

$$J\alpha_m(t) = T_m(t) - T_e(t) = T_a(t) \quad 2.2$$

Where J is the Moment of inertia of a rotating mass measured in Kgm^{-2}. α_m is the angular position of the rotor in rads/s^2, T is the time in seconds (s). T_m is the mechanical torque supplied by the prime mover minus the retarding torque due to mechanical losses measured in Nm. T_e is the electrical torque that accounts for the total three-phase electrical power output of the generator, plus electrical losses measure in Nm, and T_a is the net accelerating torque measured in Nm. The rotor angular acceleration is given in Equations (2.3) and (2.4) [12]:

$$\alpha_m(t) = \frac{dw_m(t)}{dt} = \frac{d^2\theta_m(t)}{dt^2} \quad (2.3)$$

$$\omega_m(t) = \frac{d\theta_m(t)}{dt} \quad (2.4)$$

Where ω_m is rotor angular velocity measured in rad/s and θ_m is rotor angular position with respect to a stationary axis measure in Rad. The rotor angular position is measured with respect to a synchronously rotating reference, this is shown in Equation (2.5) [12]:

$$\theta_t = \omega_{msyn}t + \delta_m(t) \quad (2.5)$$

Where ω_{msyn} is the synchronous angular velocity of the rotor and δ_m is the rotor angular position with respect to a synchronously rotating reference measured in Rad/s.

Using Equations (2.3), (2.4) and (2.5) defines Equation (2.6) [12]:

$$J\frac{d^2\theta_m(t)}{dt^2} = J\frac{d^2\delta_m(t)}{dt^2} = T_m(t) - T_e(t) = T_a(t) \quad (2.6)$$

Power systems ratings are denoted in VA as such to convert torque to power, Equation (2.6) is multiplied by $\omega_m(t)$ and divided by S_{rated}, the three-phase volt-amperes rating of the generator is denoted in Equation (2.6) [12].

$$\frac{J\omega_m(t)d^2\delta_m(t)}{S_{Rated}\,dt^2} = \frac{\omega_m(t)T_m(t) - \omega_m(t)T_e(t)}{S_{Rated}} = \frac{P_m(t) - P_e(t)}{S_{Rated}} \qquad (2.7)$$

Where $P_m(t)$ is mechanical power supplied by the prime mover minus mechanical losses and $P_e(t)$ is the electrical output of the generator plus electrical losses per unit. $P_m(t)$ is regarded as mechanical supply and $P_e(t)$ is regarded as demand. S Rated is the total machine rating of all interconnected synchronous generators measured in VA

The inertia constant is denoted as H and defined in Equation (2.8) [12], H is measured in MVA

$$H = \frac{Stored\ Kinetic\ Energy\ in\ Megajoules\ at\ Synchronous\ Speed}{Machine\ Rating\ in\ MVA} = \frac{J\omega_{msyn}^2}{2S_{Rated}} \qquad (2.8)$$

2.3 Impact of Low System Inertia

However, RES such as Wind Turbines (WT) is used to provide synthetic inertia if the turbines controllers can be modified for this purpose. The increasing penetration of RES is problematic to system inertia since RES do not possess rotational mass to provide system inertia. The assumption that grid inertia will vary slightly over time will not be valid for power systems with high penetration of RES [13]. Fig (2.2) shows the frequency drop and the required frequency response capacity of a simulated Great Britain power system employed by the National Grid.

Fig (2.1) depicts the reaction of frequency drops and simulated response required to the frequency variation. The frequency decreases will prompt the system operator to inject active power to balance demand and supply and vice versa. The simulation conditions are 20GW demand and 600MW generation loss; different values of inertia are tested in this study. As system inertia decreases, frequency response services are used to maintain system frequency between statutory limits [14].

The system requires more active power to bridge the power imbalance with lower system inertia. However, with higher system inertia, the system requires less active power to bridge the power imbalance, these are the observations from Table (2.1), which highlights frequency response requirements from constant generation loss but different inertia constants. In Fig (2.1) the active power response is higher with inertia constant of 100GVA, but less active power is required to balance the system with higher inertia. Moreover, the system oscillates more with lower inertia constant but oscillates less with higher inertia constant [14].

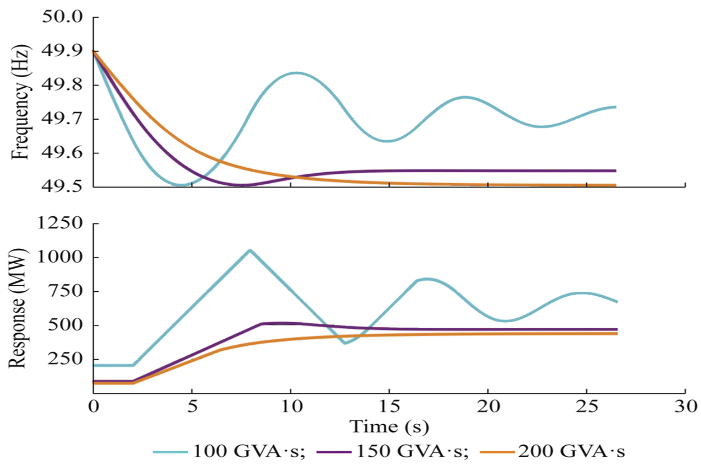

Figure 2.2 Frequency Simulation of 600MW generation Loss showing the impact of inertia loss [14].

Table 2.1 Frequency Response to Different Inertia Constants [14].

System Inertia (GVA.s)	Response Requirements (MW)	
	500MW	600MW
100	590	1285
150	365	575
200	365	365

The impact of low system inertia caused by the increases of RES will result in a reduction of inertia which leads to faster frequency dynamics, more significant frequency deviations and higher transient power exchanges for frequency control [13]. The ancillary service responsible for mitigating these frequency deviations should provide fast and stable frequency response. NGET proposed the solution to this problem by introducing EFR as a means to regulate network frequency by using ESS to breach the active power difference between mechanical supply and electrical demand.

2.4 Frequency Control in Power Systems

Network frequency can deviate between the operational and statutory limits. The operational limits allow frequency deviation between 50±0.2Hz and statutory between 50±0.5Hz [15]. Table (2.2) gives insight into the UK frequency containment policy for power systems.

Table 2.2 Frequency Containment Policy of the UK.

Frequency Limits (Hz)	Containment Policy
±0.2	The maximum frequency deviation of a power imbalance of ±300MW is 50±0.2 Hz
±0.5	The maximum frequency deviation of a power imbalance between ±300MW and less than or equal to ±1320MW.

Innovations such as frequency response services, system security services, and reserve services are aimed towards maintaining the frequency within acceptable limits. These services include the control of both generation and demand. According to National Grid, there are three types of frequency response services that are utilised in the UK [15].

2.4.1 Firm Frequency response (FFR)

FFR provides a dynamic or non-dynamic response to changes in network frequency. The service is required from generators except for generators that participate in Mandatory Frequency Response (MFR) [16].

2.4.2 Mandatory Frequency Response (MFR)

MFR refers to the automatic change in active power output in response to frequency variations. This service keeps the frequency between statutory and operational limits. Large capacity generators i.e(>100MW) are connected to the transmission system in the UK for this purpose. These generators work under 80% load and are required to provide a primary response, secondary response, and high-frequency response. Table (2.3) classifies the size of generators with regards to MFR services [17].

Table 2.3 Sizing of Generators based on NG criterion [17].

Generator Size	Generator Rating (MW)
Small	<50
Medium	50 -100
Large	>100

2.4.2.1 Primary Response

The primary frequency response automatically increases generator output by 10% in response to a frequency drop within 10 seconds and can be sustained for another 20 seconds [17].

2.4.2.2 Secondary Response

Secondary frequency response automatically increasing generator output by 10% in response to a frequency drop within 30 seconds and can be sustained for another 30 minutes [17].

2.4.2.3 High-Frequency Response

High-frequency response reduces generators' output within 10 seconds of frequency rise and is sustained indefinably [17].

2.4.3 Enhanced Frequency Response

In 2016, NGET prepared a tender which included technical requirements for the design of EFR systems. EFR is an ancillary service where active power changes proportionally to changes in system frequency. The service aims to maintain system frequency closer to 50Hz. The EFR response is dependent on the frequency change [18].

2.4.4 Technical Requirements

EFR units must deliver active power as a proportional response to a change in system frequency outside the Dead-Band (DB). This means an increase or decrease in frequency from 50Hz will prompt the ESS to decrease or increase active power respectively. The BESS should respond to deviations in frequency within less than one second. This delay is inclusive of detection time [18].

2.4.4.1 Delivery Envelopes

The assets should deliver continuous active power as represented in one of the two service envelopes listed in Table (2.4). The service envelopes are highlighted in Fig (2.4) and Table (2.4). The service envelopes have been developed to narrowest range frequencies which occurs post fault. The available services are wide and narrow. The EFR unit must ensure their outputs are always within the upper and lower limits (shown on Fig.2.4). The DB is the only region on the delivery envelops (Labelled C-D) where the active power assets do not have to respond proportionally to system frequency. The input and output from the DB should not exceed ±9%. The DB is used to manage the state of charge of the BESS during EFR operations [18].

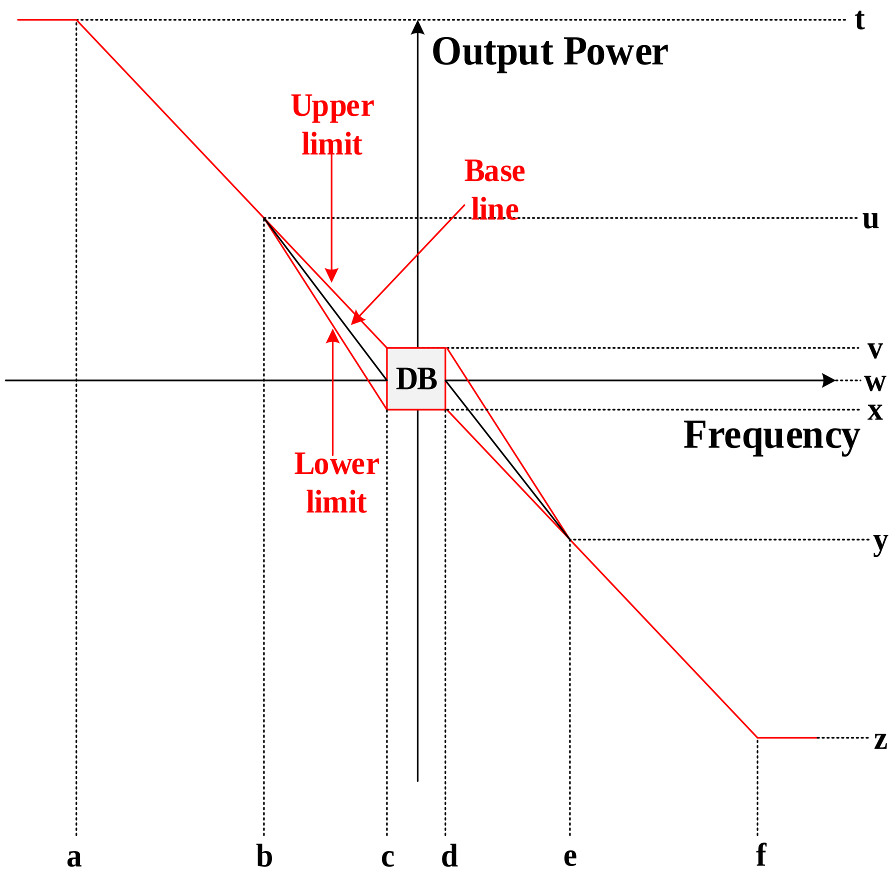

Figure 2.3 Delivery Envelopes for EFR [18]

Table 2.4 ESS Output Specification [18]

Frequency (Hz)			**Power (%)**		
Ref. Point	**Service-1**	**Service-2**	**Ref. Point**	**Service-1 (Wide)**	**Service-2 (Narrow)**
a	49.5	49.5	t	100	100
			u	44.44444	48.4536
b	49.75	49.75	v	9	9
c	49.95	49.985	w	0	0
d	50.05	50.015	x	-9	-9
e	50.25	50.25	y	-44.4444	-48.4536
f	50.5	50.5	z	-100	-100

2.4.4.2 Ramp-Rates

Assets may act within the upper and lower envelopes to provide continuous service in the future (e.g. for a BESS by managing the state of charge), subject to the limitations on ramp rates. In Fig. (2.4), the shaded areas A, C and D must comply with ramp rate limits highlighted in Table (2.5). The allowable ramp rates within the regions marked B on Fig (2.5) depend on the ROCOF. Table (2.6) explains the ramp rate limitation mathematically in region B. The service envelopes will take precedence over ramp rates. Ramp Rate limits ensure the output changes in power are proportional to frequency while giving EFR operators flexibility [18].

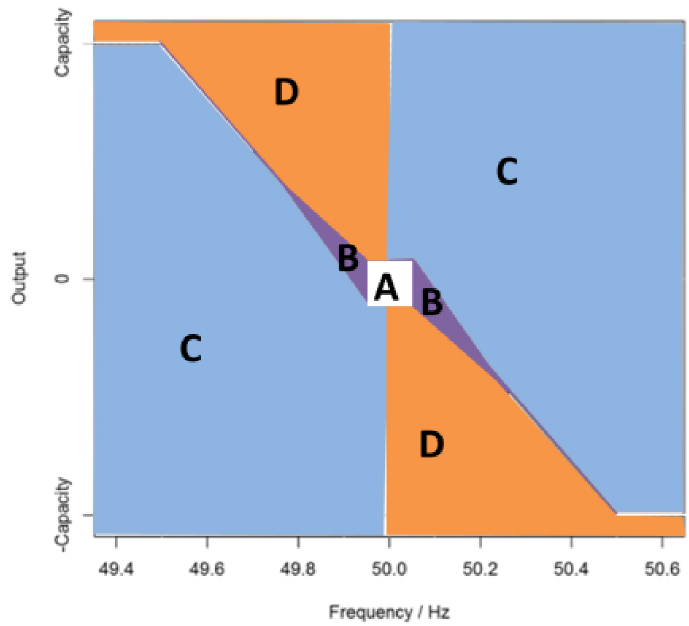

Figure 2.4 Ramp Rate Limits for EFR [18]

Table 2.5 EFR Ramp Rate Limits [18]

Area	Maximum Ramp Rate as a Percentage of Operational Capacity (MW/s)	Minimum Ramp Rate as a Percentage of Operational Capacity (MW/s)
A	1%	0%
C	200%	0%
D	10%	0%

Table 2.6 Ramp Rates for Zone B [18]

Ramp Rate Zone B	Maximum Ramp Rate as a Percentage of Operational Capacity	Minimum Ramp Rate as a Percentage of Operational Capacity
Service 1 (Wide)	$\left(-\frac{1}{0.45}\left(\frac{df}{dt}\right)+0.01\right)\cdot 100$	$\left(-\frac{1}{0.45}\left(\frac{df}{dt}\right)-0.01\right)\cdot 100$
Service 2 (Narrow)	$\left(-\frac{1}{0.485}\left(\frac{df}{dt}\right)+0.01\right)\cdot 100$	$\left(-\frac{1}{0.45}\left(\frac{df}{dt}\right)-0.01\right)\cdot 100$

2.5 Overview of Existing EFR systems

NGET introduced EFR in late 2016 as the new fast frequency response service in the UK. There has been limited literature about the EFR project since the services have only been online for a short period.

Alexander Cooke el al proposed a novel method for providing frequency support to avoid holding excess Fast Reserves in form of BESS. This study proposed a novel responds curve to manage network frequency in the event of loss of generation. This study gave priority to control design of a PI controller as a means to reduce frequency perturbations caused by loss of generation [19].

D. M. Greenwood el tal compares the performance of both the wide and narrow service envelopes. The study concludes that the narrow service envelopes require four times the storage of the wide service envelope [20]. The method does not consider the 15 min frequency event control, which would enhance BESS availability, specifically for the narrow DB. The study designs a novel control algorithm using DC-DC converters to fulfil EFR service requirements [20].

Although EFR control is achieved using the BESS energy management system rather than energy storage converters control. The algorithm manages the SOC efficiently by limiting the SOC between 49%-51%. The improved SOC management aids to reduce BESS degradation and improved BESS life cycle [20].

In [21], the authors asses the performance of a BESS for EFR operations, by simulating BESS response to grid frequency following EFR requirements and evaluating the exchange of energy between the gird and BESS. The study assumes the BESS is connected to the UK and continental Europe synchronous area. The study did not, however, consider ramp-rate limits in the EFR service requirements and the 15 min frequency event control to improve BESS availability was not considered.

B. Gundogu el tal proposed a BESS energy management strategy for EFR service to avoid triad avoidance for the maximization of EFR availability and profitability [22]. Triad is referring to the three and a half –hour settlement period between November and February with the highest demand, each period must be separated by ten days. The approach varied the delayed required for the EFR to respond to frequencies that are outside the DB. The EFR will check if the frequency is within the DB every 15mins and 30mins. The conclusion from the studies shows a 15min time frame ensures better ESS SOC availability than a 30min window for EFR operations. [22].

2.6 Conclusion

The main contribution of this thesis is comparing two energy management philosophies based on NGET standards. Furthermore, the study compares the energy required for EFR response for 2014 and 2018 based on a monthly, weekly and daily time audit. The EFR tender produced in 2016 did not consider the amount of energy needed to perform EFR operations but accounted for power. The previous studies mentioned did not consider the amount of energy required from the BESS technology. An investigation into EFR sizing would benefit both EFR operators and investors, as oversizing or under-sizing of assets is bound to occur without knowledge from in-depth frequency response analysis and historical data. The work presented in this thesis is an extension of the work done in [23] and is based on a 1MWh BESS. Although the study in [20], used DC-DC converters to improve BESS SOC, this study is primarily focused on the use of DB to improve BESS management schemes rather than converter controls.

Chapter 3

Review of Energy Storage Technology

3.1 Introduction

This chapter explores different ESS technologies suitable for EFR operations. Energy Storage (ES) is a process of converting energy from one form to the other. Energy occurs in different forms, such as chemical, electrical, mechanical, electromechanical, and thermal. These types of energy can be stored and later converted to electrical energy. The SOC of an ESS is referred to as the capacity that is currently available as a function of rated capacity (kWh), alternative the SOC is the cumulative sum of daily charge and discharge conditions for the ESS, when the battery SOC is at 100% the ESS contains the as maximum capacity battery capacity [24].

3.1.1 Super-Capacitors (SC)

Super-capacitors are double-layered capacitors that contain two electrodes, an electrolyte and a permeable membrane for ions to move between the two electrodes, namely anode and cathode. The anode is the positive terminal and the cathode the negative terminal of the capacitor. Energy stored in a supercapacitor is stored in the electric fields between two the two electrodes. Super-Capacitors operate on the same principle of capacitors expect the insulating material is replaced with electrotype conductor for ions to move in the electrode with higher surface area resulting in higher energy density. The energy stored within the

dielectric plates of a supercapacitor is proportional to the square of the voltage between the electrodes of the electrochemical cell, while the capacity is proportional to the electrode surface area and inversely proportional to the distance between the electrodes [25].
The Equation for the energy stored (W) in a supercapacitor is shown in Equation (3.1) while Equation (3.2) shows the equation of power for a capacitor.

$$W = \frac{1}{2}CV^2 \tag{3.1}$$

$$P = \frac{V^2}{4R} \tag{3.2}$$

where C is capacitance, V-voltage, and R is resistance

The difference between a capacitor and a supercapacitor is mainly the addition of porous electrodes with the higher surface area, resulting in higher energy density. Electrolytes and electrodes materials are the only factors that affect the energy stored and power capacity of supercapacitors [25]. Long cycling times, high cycle efficiency, and high specific power and energy density are the advantages of a supercapacitor. These attributes are well suited for short-term storage applications with short charge and discharge cycles but not for long-term and large-scale energy storage because of the high discharge rate.

3.1.2 Superconducting Magnetic Energy Storage (SMES)

The SMES is coupled together using four main components namely vacuum system, refrigeration, superconducting coil and power conditioning subsystem. The SMES stores energy in the magnetic field created by a Direct Flow (DC) in a superconducting coil.
The schematic diagram from a SMES is shown in Fig. (3.1).
Materials such as mercury and vanadium under very low temperature (-270C) will have nearly zero resistance which will allow maximum current to flow, ultimately leading to zero losses during energy storage. The amount of energy stored is dependent on the self-inductance of the coil and current flowing through the coil [24]. The mathematical representation of energy stored (W) is shown in Equation (3.3). High power density, rapid response time, quick discharge time and high cycling efficiency, these features make the

SMES useful in suitable for short-term storage in power systems, also expected to play an essential role in reducing the interment nature of renewable energy. The major drawback of the system is the high discharge rate [26].

$$W = \frac{1}{2}LI^2 \tag{3.3}$$

where L is the inductance and I is current through the coil

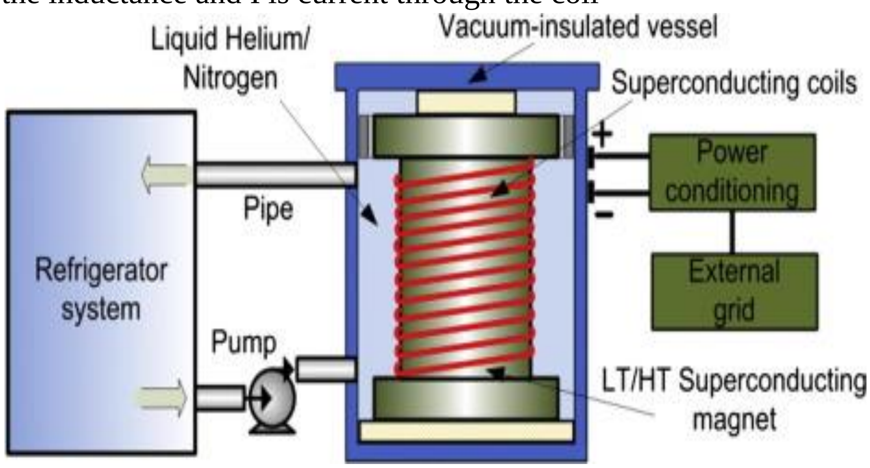

Figure 3.1 Schematic of SMES[27].

3.1.3 Flywheel Energy Storage System (FESS)

FES has two different states of operation during charging and discharging. The ESS device operates as a generator and motor, respectively. The standard flywheel has a reversible motor/generator, power electronics unit, vacuum chamber, and a group of bearings. The energy stored in the system is dependent on factors such as the size of the rotor, the speed of the rotor, and the power rating of the motor/generator [27]. The energy is stored in the form of kinetic energy and releases the energy stores by accelerating a rotor to high speeds.

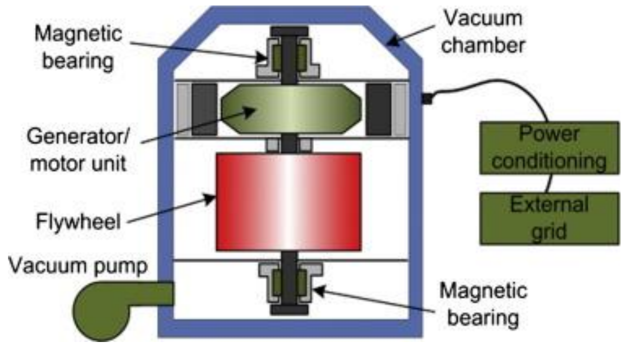

Figure 3.2 FES Schematic [28].

Fig (3.2) describes the operation of a typical flywheel that spins at high velocity to gain maximum kinetic energy. The Equations (3.4) depict the energy stored in a flywheel. A vacuum is utilised to minimize windage losses and protect the motor from external factors. The bearing assembly provides a support mechanism for the flywheel rotor and control system for monitoring the operation of the flywheel to store or produce energy. The Energy Stored in a FES device is given by [27]:

$$W = \frac{1}{2}mr^2\omega^2 \tag{4.4}$$

where *m* is the system rotating mass, *ω* the rotational speed and *r* the radius.

FES can be classed into two groups, namely the Low-speed FES and the High-Speed FES. The low-speed FES use steel as the rotating material while the high-speed FES use carbon fibre. Low-speed FES is used usually for short-term and high-power applications, whereas the high-speed FES is used mainly for high voltage applications and ride through power services in traction [27].

FES has features such as high efficiency, long cycling life, high power, and density, on the other hand, high self-discharge rate and losses due to air resistance and bearing losses make the FES not adequate for long-term energy storage.

3.1.4 BESS (Battery Energy Storage System)

The BESS consists of electrochemical cells arranged in series to increase voltage or parallel to increase the current capacity from the process of electrolysis.

Electrochemical cells have two electrodes (anode and cathode) coupled with an electrolyte. The electrolytes ensure the exchange of ions between electrodes. The BESS converts chemical energy into electrical energy through the process of electrolysis. During discharging electrochemical reactions occur at the anode and cathode, electrons are provided at the anode and collected at the cathode, while charging electrons are collected at the cathode and moved to anode [29]. The Fig. (3.3) describes the schematic of a BESS

.

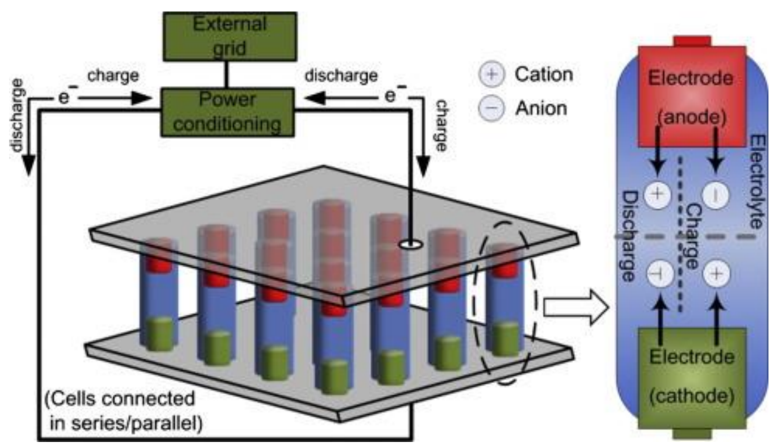

Figure 3.3 Schematic of BESS [29].

3.1.4.1 Battery Electrolyte Comparisons

BESS features such as power density, energy density, cycle life and efficiency are discussed in this subsection. Table (3.1) gives a brief overview of battery electrolytes in comparisons to the attributes mentioned above. BESS technology is dependent on the electrolytes; different electrolytes will have benefits and drawbacks. BESS technology is used for improving power quality, energy management systems, ride-through power, and frequency control. BESS electrolytes such as Sodium Nickel Chloride and Sodium Cadmium BESS have a high discharge rate and low cycling efficiency as such cannot be utilized for short term energy storage. The lithium-Ion electrolyte has a high energy density, low self-discharge, and high cycling efficiency these qualities make the lithium-ion suitable for short term energy storage [30].

Table 3.1 Comparison of Battery Technologies [30].

Type	LA (Lead Acid)	NiMH (Nickel Metal Hydride)	Li-ion (Lithium Ion	NaS (Sodium Sulphate	VRB (Vanadium Redox Battery)
Energy Density	25-50	60-120	75-120	150-240	10-30
Power Density	75-300	250-1000	500-2000	150-230	80-150
Cycle Life	200-1000	180-2000	1000-10,000	2500-4000	>12,000
Round Trip Efficiency	75-85	65-87	85-97	75-90	75-90
Self-Discharge	Low	High	Medium	-	Negligible

3.2 ESS suitable for EFR operations

EFR operations require short term energy storage as the ESS is constantly either charging or discharging power to and from the utility grid's technology such as flywheels, super-capacitors, batteries, and SMES can be utilized for short term energy storage. The role of the ESS in EFR operations is primary to breach the power imbalanced caused by the difference between electricity demand and mechanical supply on the utility grid.

3.2.1 Comparison of ESS Technologies

Table 3.2 Comparison of ESS Technology [28]

Technology	Energy Density (Wh/L)	Power Density (W/L)	Cycling Times (Cycles)	Response Time	Daily Self-Discharge (%)	Round Trip Efficiency (%)
Lithium Ion	75-120	500-2000	1000-10,000	Milliseconds	0.1-0.5	85-97
SC	10-30	100,000	100,000	Milliseconds	10-20	95
FESS	20-80	1000-2000	20,000+	Seconds	<20	90-93
SMES	0.2-0.5	1000-4000	20,000-100,000	Milliseconds	10-15	95

3.2.1.1 The criterion for EFR Technology

Due to the nature of this application, the appropriate ESS technology would have attributes such as high cycling efficiency, low discharge rate and Fast Response time. The criterion for ESS more short-term energy storage is listed below based on literature.

3.2.1.2 High Cycling Efficiency (Round Trip Efficiency)

Round Trip Efficiency is the ratio of electrical output to electrical input. Fig (3.4) presents a vivid comparison of round-trip efficiencies of various energy storage technologies.

SMES, supercapacitors, PHS, Flywheels, and batteries typically have medium to high cycling efficiency.

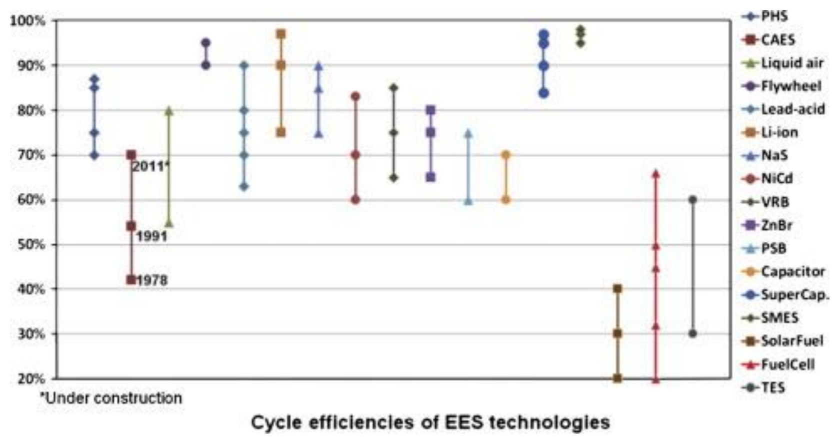

Figure 3.4 Comparisons of ESS [28].

3.2.1.3 Low Self-Discharge

Self-Discharge is energy dissipated in the in the form of electrochemical losses in batteries, mechanical losses in flywheel and heat losses in SMES. The rate at which energy is lost from the ESS is regarded as self-discharge. The magnitude of the self-discharge is a crucial factor in deciding the most appropriate ESS technology for EFR operations. Additionally, SMES, flywheel, and supercapacitors have very high self-discharge ratios estimated at 10% -100%, as such can be utilised for short-term storage as the energy stored can dissipate within a short time window.

3.2.1.4 Fast Response Time

The EFR tender states the ESS should respond to frequency deviations within 1s of detection time; this is key in negating frequency events.

3.3 Conclusion

This study uses a generic BESS model to calculate the amount of Energy and Power **required** for EFR operations, characteristics of the BESS such as high-density, low self-discharge, and high cycling efficiency are not considered during EFR operations, these attributes are assumed in the model."

The EFR tender received 68 submissions from a wide variety of parties with a total capacity submitted over 1.3GW; 888MW of the total capacity chose BESS as the form of ESS. Thus, approximately about (66%) of EFR providers chose the BESS as the preferred choice for EFR operations because of cheap maintenance, low discharge rates, rapid response time, and high cycling efficiency [18].

Chapter 4

EFR Design

4.1 EFR

The EFR purpose is to replace the inertia response derived from synchronous generators by delivery a proportional active power response to frequency. Active power must be delivered as a proportional response to a change in system frequency outside the DB. The proportion of the response means active power increase or decrease must be proportional to frequency deviations according to service envelopes, while frequency is within the DB the ESS is not required to deliver active power proportionally. The delivery envelopes and ramp-rates serve as a guide for EFR design. The frequency response data is provided by NGET and analyzed in Matlab/Simulink environment. The service envelope utilized in this study is the wide service envelope because of limited Energy storage [20]. Fig (4.1) gives additional detail on EFR operation.

EMS services are required for the optimized and economical operation of a power system, the EMS are designed to follow a strict set of constraints required for the grid to operated without violation of constraints which could affect operations and system stability.

Two Energy Management Schemes are proposed in this study which is based on EFR design specifications. The Energy Management schemes is aimed towards modelling the power exchange between the ESS and the grid. This model would give insight to other specifications such as ROCOP and size of the ESS medium (Energy).

The original frequency data used to size the EFR are from the years 2014-2016. A comparison is made to give more detail on EFR storage when comparing pre-EFR years and post-EFR years.

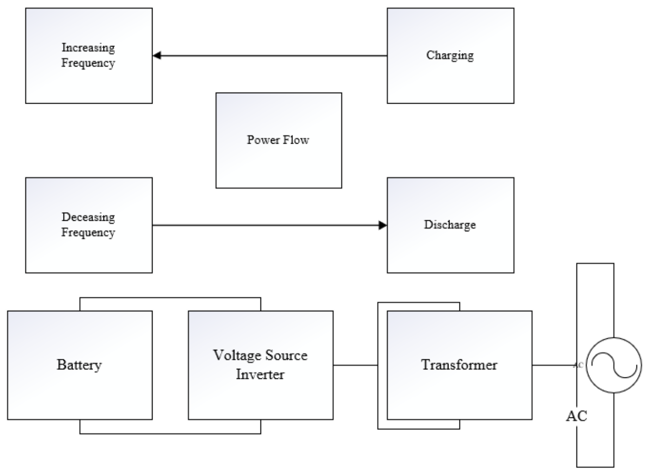

Figure 4.1 EFR Power Flow

4.1.1 DB Theory

The DB is the only region within the EFR envelopes, which does not require a proportional response from the ESS. The DB region gives the EFR operator the flexibility to vary power output between ±9% of the maximum output. Two BESS management schemes have been designed based on the variation of DB. The assumption that the majority of the frequencies occur within the deadband is proven in [12]. Subsequently, a histogram is presented in Fig (4.2) to show the majority of the frequencies occur within the DB for May2017. Table (4.1) shows the classification of months based on metrological seasonal. The DB theory is applied in two methods, namely the Variable DB Scheme (VDS) and Constant DB Scheme (CDS).

Table 4.1 Season Classifications

Meteorological Season	Months
Spring	March, April and May
Summer	June, July, and August
Autumn	September, October and November
Winter	December, January and February

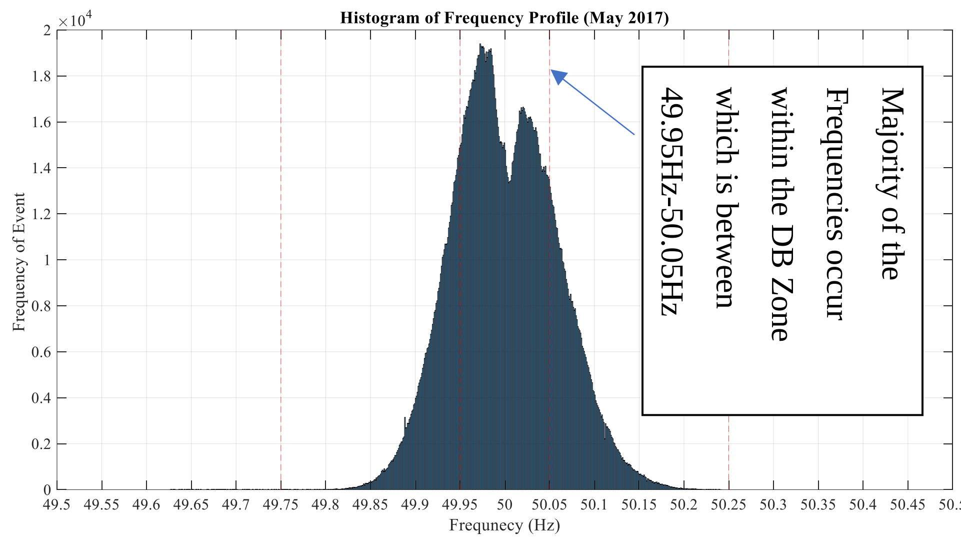

Figure 4.2 October 2017 Histogram

4.1.2 System Specification

Table 4.2 EFR Simulation Parameters

Parameter	Value
Nominal Frequency	50Hz
Delivery Envelope	±0.05Hz
BESS Rated Capacity/Peak Power	1MWh/1MW
Max/Min EFR Power	±1MW

4.1.3 BESS Sizing

Cumulative energy is defined as a total measure of energy resources necessary for the supply of a product or service. In regards to EFR operations is the amount of energy needed to perform EFR operations efficiently. Cumulative energy is also referred to as primary energy consumption. Fig (4.2) shows a 96Hr period of BESS energy variation in responds to network frequency.

The information required to calculate cumulative energy is extracted from Fig (4.2) and highlighted in Table (4.3). The sizing of BESS is derived through cumulative energy magnitude. The study considers two equations for sizing BESS for EFR operation. These Equations are highlighted in Equations (4.1) and (4.2). Equation (4.1) takes into consideration the modulus of the highest cumulative energy, while Equation (4.2) uses the difference of highest and lowest cumulative energy. For illustration Fig. (4.3) is used to calculate the BESS size based on the proposed equation.

The BESS size is approximately doubled when comparing the solutions from the respective equations. Method 2 is the preferred method for ESS sizing in this study because the method considers the full cycle of the exchange of energy between the Grid and BESS.

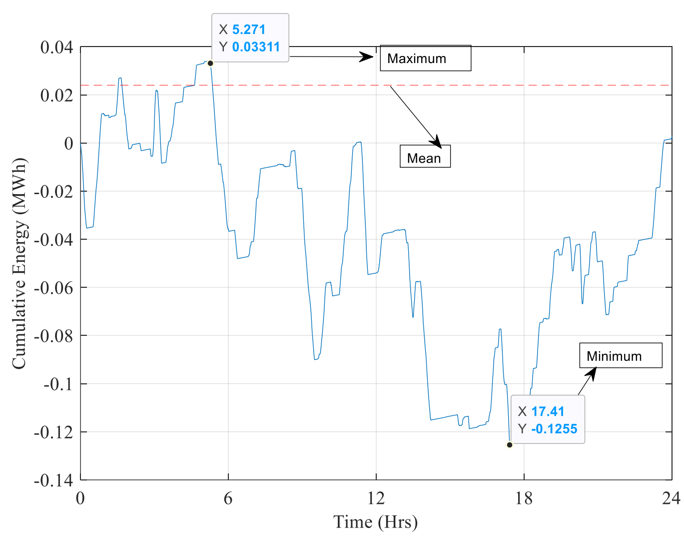

Figure 4.3 BESS Energy Variation

Table 4.3 Tabulation of BESS Energy Variation

X_1(Hrs)	5.271
X_2 (Hrs)	17.41
Y_1 (MWh)	0.03
Y_2 (MWh)	-0.12

Method 1	$\lvert Y_{Max} \rvert$	0.12MWh	(4.1)
Method 2	Y_1-Y_2	0.15MWh	(4.2)

4.1.3.1 BESS Sizing (ROCOP)

ROCOP is the measure of the difference between each iteration of power exchange between the grid and BESS. The ROCOP is calculated using Equation (4.3). The ROCOP indicates the rate at which the BESS is doing work. The information required to calculate ROCOP is tabulated in Table (4.5) and derived from Fig (4.4). From Table (4.6) and Fig (4.4), the BESS specification would give provision for a change of power of approximately ±0.24MW/s.

Table 4.4 Tabulation of BESS Energy Variation

X_1(Hrs)	10.995
X_2 (Hrs)	11.5347
Y_1 (MWh)	0.10236
Y_2 (MWh)	-0.14135

Table 4.5 ROCOP Calculations

$Y_1 - Y_2$	±0.24MW/s	(4.3)

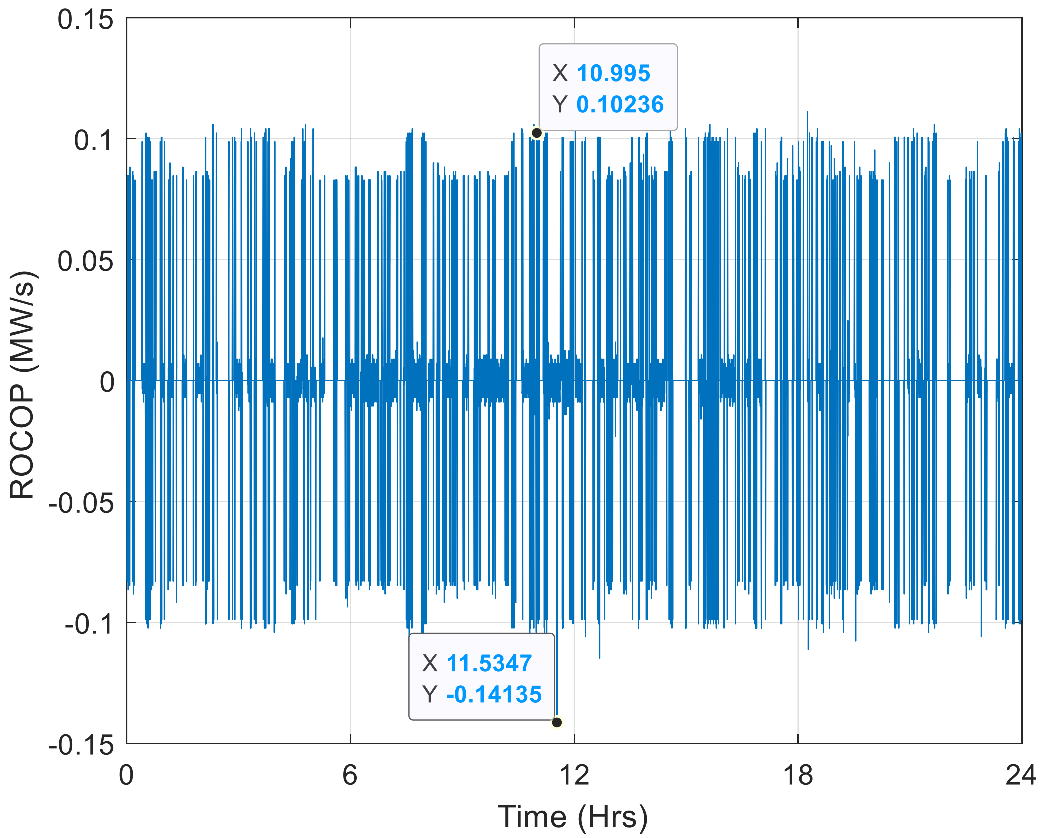

Figure 4.4 ROCOP during EFR Operations

4.1.4 BESS Sizing Methodology

The BESS peak power is fixed by the National Grid specification tender to between 1 and 10 MW. In this study, 1 MW peak power has been chosen. The energy specification is the responsibility of the contractor and is influenced by the choice of deadband. This study provides a method to evaluate the deadband for typical frequency variations, and thus, helps the contractor arrive at a suitable BESS energy content rating."

The ESS sizing methodology is based on EFR specification detailed in Table (4.6) and deduced from the NGET specifications. The input into the sizing methodology is network frequency, which was provided by NGET, the output is Energy. The delivery envelopes are the relationship between Power and Frequency for the BESS. This relationship can be modelled using the Equation of the line and represented in Equations (4.3)- (4.8), using Table (4.6) to represent the information required to obtain Frequency and BESS relationship.

Table 4.6 Extraction of Delivery Envelopes

Y_1	44.44
Y_2	100
X_1	49.75
X_2	49.5

$$Y = MX + C \quad 4.3$$

$$100 = (\frac{Y_2 - Y_1}{X_2 - X_1})f + C \quad 4.4$$

$$100 = (\frac{100 - 44.44}{49.5 - 49.75})f + C \quad 4.5$$

$$100 = (555.6)(49.5) + C \quad 4.6$$

$$C = 11000.88 \quad 4.7$$

$$Y = -222.4f + 11000.88 \quad 4.8$$

The factors to consider for BESS sizing are the power and Energy, in terms of power train equipment the Inverter and Battery Energy, respectively. These factors are important to minimize the cost of BESS. Number of Cycles and State of Charge (SOC) are the two main factors which affect BESS life span. The main research goal is to reduce the size of the BESS, thereby reducing cost [28].

The sizing methodology utilized in this thesis is based on National Grid Frequency data provided by NGET and EFR specifications such a Ramp Rate and delivery envelopes. The VDS and CDS have time factors built within the algorithms to size the system based on

time, the time variables which have been selected have been the monthly, weekly, and daily time audits. These time audits have been selected to show the difference in BESS size.
In [32], the ESS sizing methodology is based on using the system inertia and power/frequency characteristics provided by National Grid to target power balance or ROCOF.

The approach utilized in this thesis and the method used in [32], are similar because both methods consider the power and frequency characteristics (delivery envelopes).
Regarding frequency control for grid services, the delivery envelopes must be developed using mathematical methods such as Equation of the line to calculate the corresponding power to frequency magnitude, to respond to the breach between supply and demand.
Although the sizing method in this thesis takes into account the delivery envelopes the sizing method does not take into account primary, secondary and high-frequency response.

4.2 Variable Dead-band Scheme (VDS)

The VDS is designed based on the assumption that the majority of the frequencies occur within the DB, as such the ROCOP is not expected to be high in magnitude; additionally, allows for active power variations while frequency is in the DB region. The scheme begins with logging the frequency data into Matlab for zone assignment based on delivery envelopes. Zone assignments is an integral part of the VDS scheme, during this process the frequency is assign to respective delivery envelopes based on magnitude of the frequency.

The BESS responds are calculated using Equation of the Line this is detailed in Equation (4.3), the equation limits are designed to fit the delivery envelopes.

$$Y = Mx + C \tag{4.3}$$

Where *Y* is Power, *M* is Gradient, *X* is Frequency in Hz and *C* is Y intercept.

Finally, an integration of power will derive energy. The energy derived is an indication of BESS size. The flowchart for the VDS is presented in Fig (4.5) and instantaneous power Equations highlighted in Table (4.7)

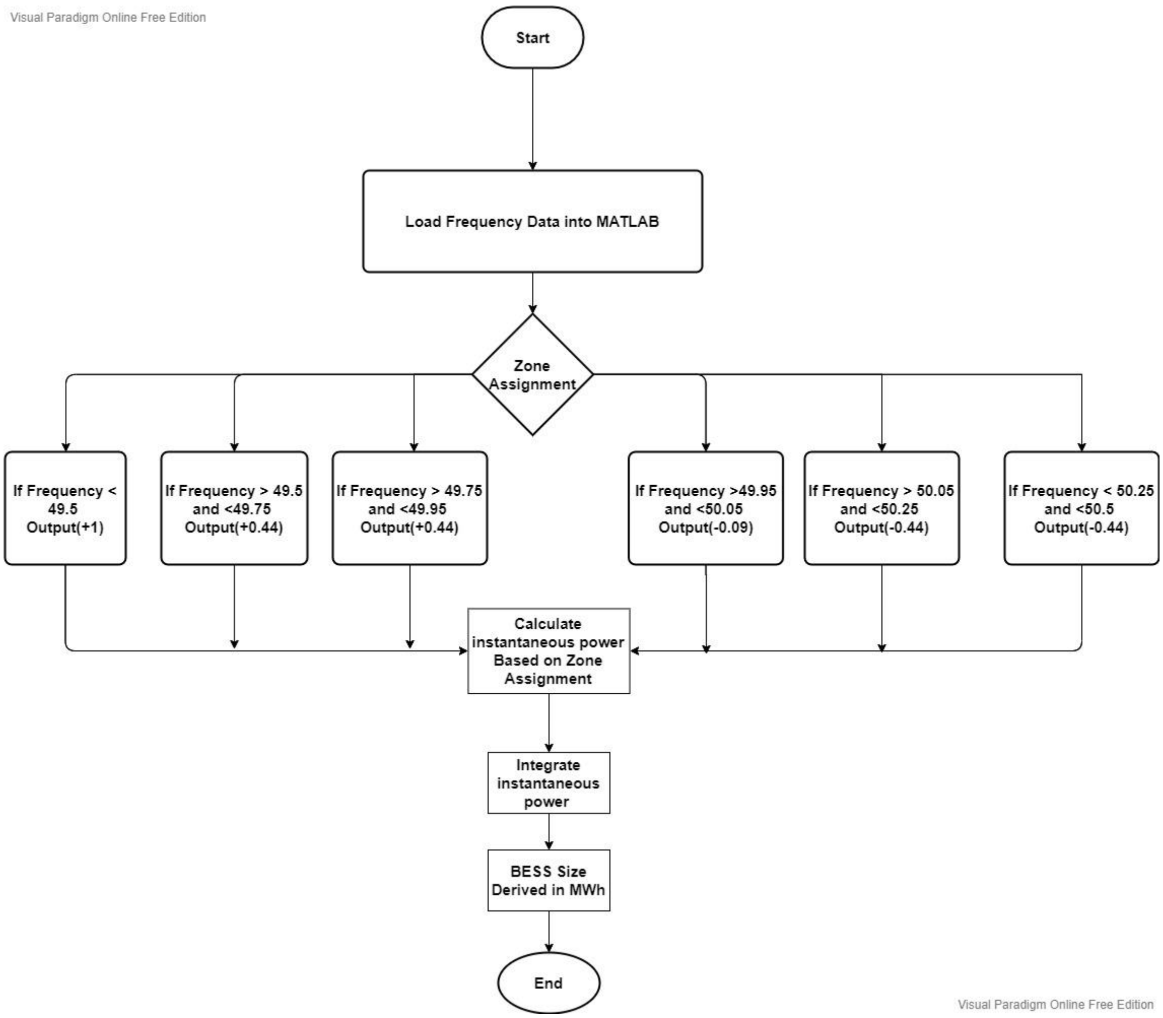

Figure 4.5 VDS Flowchart

Table 4.7 Equations for Calculating Power in EFR Design

Frequency (Hz)	Region	Frequency Band
49.5-49.75	A-B	$-222.24 \cdot f + 11100.88$
49.75-49.95	B-C	$177 \cdot f + 8850.15$
49.95-50.05	C-D	$-180 \cdot f + 9000$
50.05-50.25	D-E	$177.2 \cdot f + 8859.86$
50.25-50.5	D-F	$222.4 \cdot f + 11123.12$

Where f is Frequency (Hz)

4.2.1 BESS Sizing Based on Monthly Analysis (VDS)

This is the general overview from Fig (4.6) and (4.7):

The highest demand recorded in UK is recorded during the three and half settlement period between 4:00PM -7:00PM between the months of November to February. A triad can occur if the highest demand recorded is separated by ten-day interval.

Based on the meteorological classification of season, from November to February is classed as autumn to winter. The period of maximum demand within a calendar year is experienced usually during the winter and autumn months, and lower demand is seen during the months of spring and summer respectively.

Although in the summer and spring months less synchronous generation is utilised from coal because of the reduction in demand as such RES and nuclear energy are used to absorb the electrical demand which coal could have provided during this period. The months of spring and summer have high cumulative energies because of lower demand and high penetration of RES, which would result in low system inertia. Thus, more energy would be required from the EFR to operate.

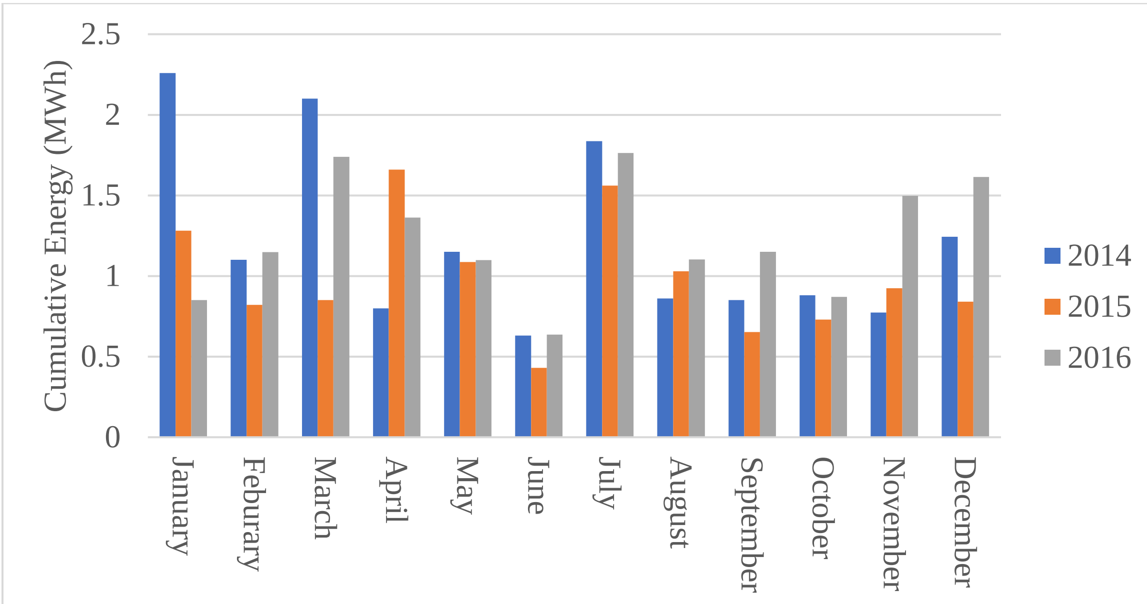

Figure 4.6 Method 1 BESS Size Based on Monthly Analysis, $|E_{Max}|$

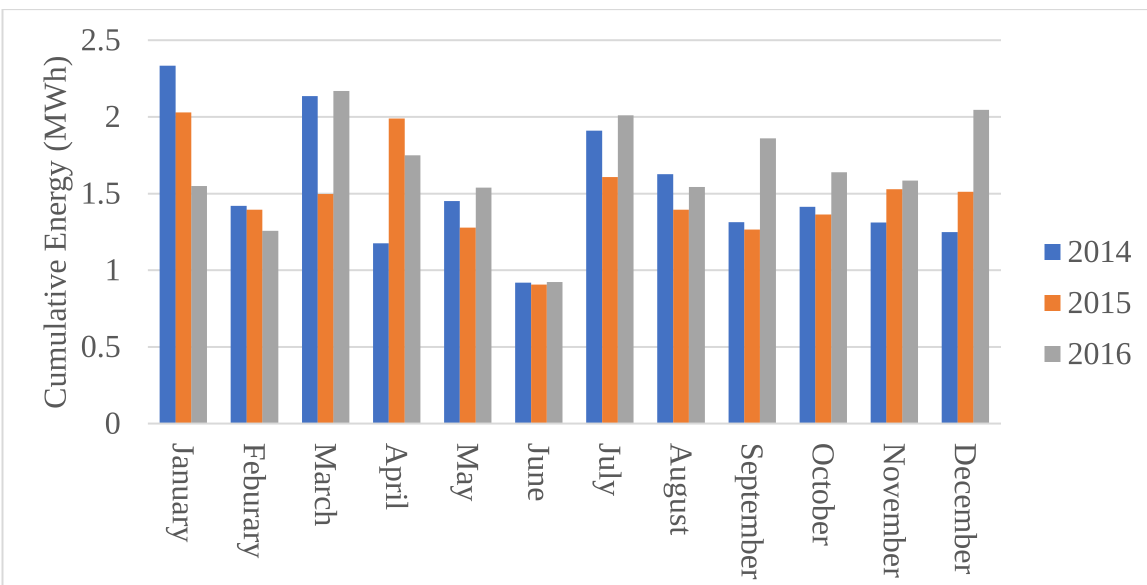

Figure 4.7 Method 2 BESS Size Based on Monthly Analysis, $|E_1-E_2|$

2.34MWh is the highest cumulative energy recorded; this occurred in January 2014. January 2014 is taken as the worst-case scenario as such a more detailed time audits will give more insight in EFR sizing speciation based on ROCOP and energy. The BESS is assumed to have an initial SOC of 50%. Fig. (4.8) shows the relationship between SOC and Cumulative energy, the SOC is approximately 80%. The EFR only has 20% of rated capacity to negate frequency events which would occur in later times during EFR operations.

Fig (4.9) gives graphical insight into the ROCOP for January 2014. The BESS should be able to provide approximately ±0.2MW/s change in active power within a second to effectively respond to frequency events. Table (4.8) shows the BESS sized based on a monthly analysis.

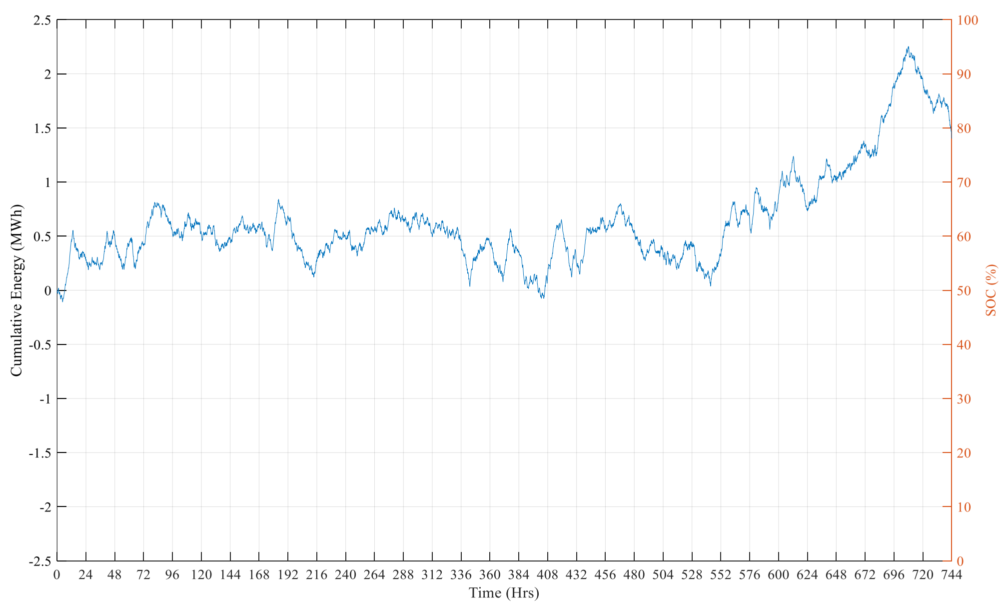

Figure 4.8 January 2014 Cumulative Energy Monthly Analysis

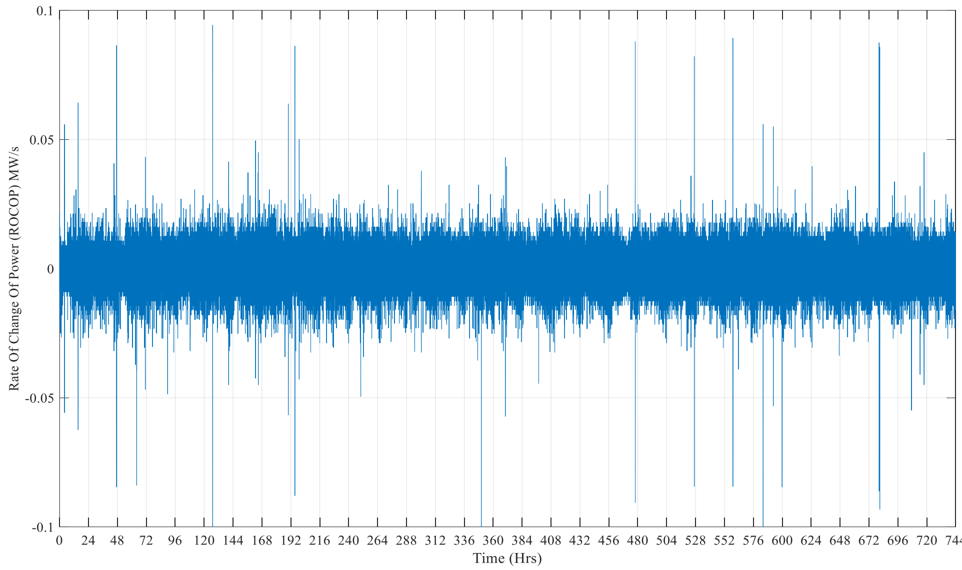

Figure 4.9 January 2014 ROCOP Monthly Analysis

Table 4.8 January 2014 BESS Size Based on Monthly Analysis

Time Audit	BESS Size (MWh)	ROCOP (MW/s)
Month	2.34	±0.2

4.2.2 BESS Sizing Based on Weekly

Fig (4.10) describes the weekly exchange of energy between the EFR and the grid for an entire month. The month analysed was January 2014 because this month had the highest cumulative energy. The weekly analysis shows a significant variation of cumulative energy. Using Method (2), the BESS size for the weekly analyses is denoted in Table (4.9). Week 4 has the highest cumulative energy, with approximately 1.5 MWh and Week 2 the lowest with approximately 0.6MWh. The cumulative energy varies during the weeks although he

ROCOP is very much similar. The BESS would require a change of ±0.2MW/s for the EFR to function.

Table 4.9 BESS Size Based on Weekly Analysis

Time Audit	BESS Size (MWh)	ROCOP (MW/s)	SOC
Week 1	0.7	±0.2	70
Week 2	0.9	±0.19	65
Week 3	0.8	±0.18	62
Week 4	1.5	±0.2	100

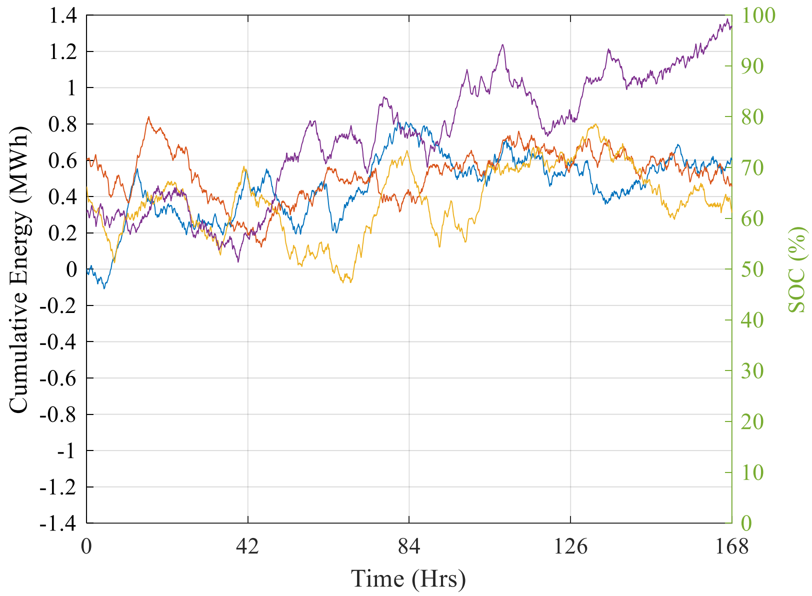

Figure 4.10 January 2014 Weekly Analysis (Change)

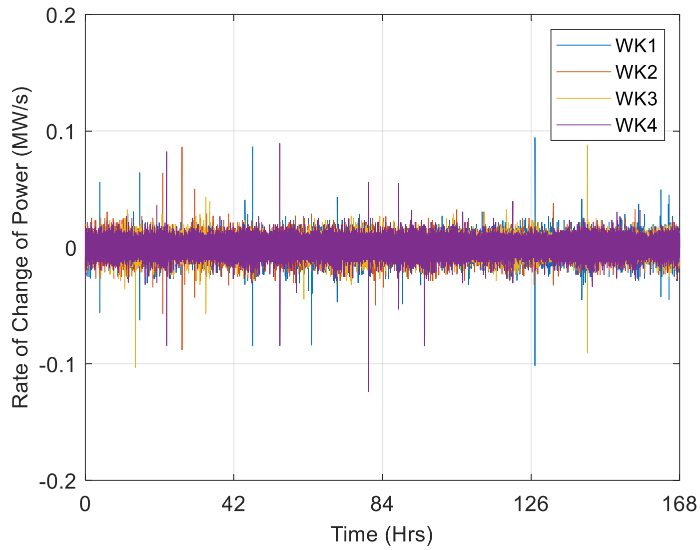

Figure 4.11 January 2014 weekly ROCOP

4.2.3 BESS Sizing Based on Daily Analysis

Fig (4.12) describes the daily exchange of energy between the EFR and the grid for each day in the month. The month analysed for daily analysis is January 2017 because this month had the highest cumulative energy. The amount of energy required daily does not vary significantly throughout the month. Additionally, the state of charge at the end of each day is approximately 70%. The cumulative energy for the daily analysis is very much similar in terms of magnitude for every day in the month, whereas ROCOP is much less when comparing the monthly, weekly and daily analysis. The Table (4.11) gives a summary of the BESS size for the VDS daily analysis.

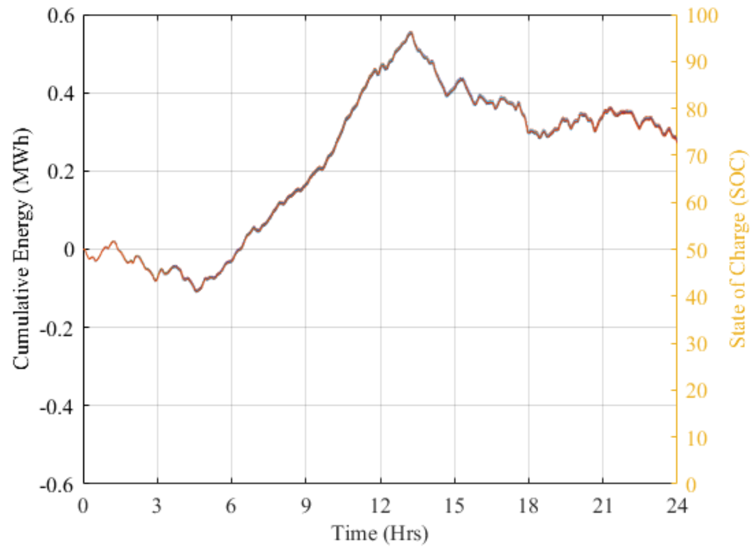

Figure 4.12 January 2014 Daily Analysis

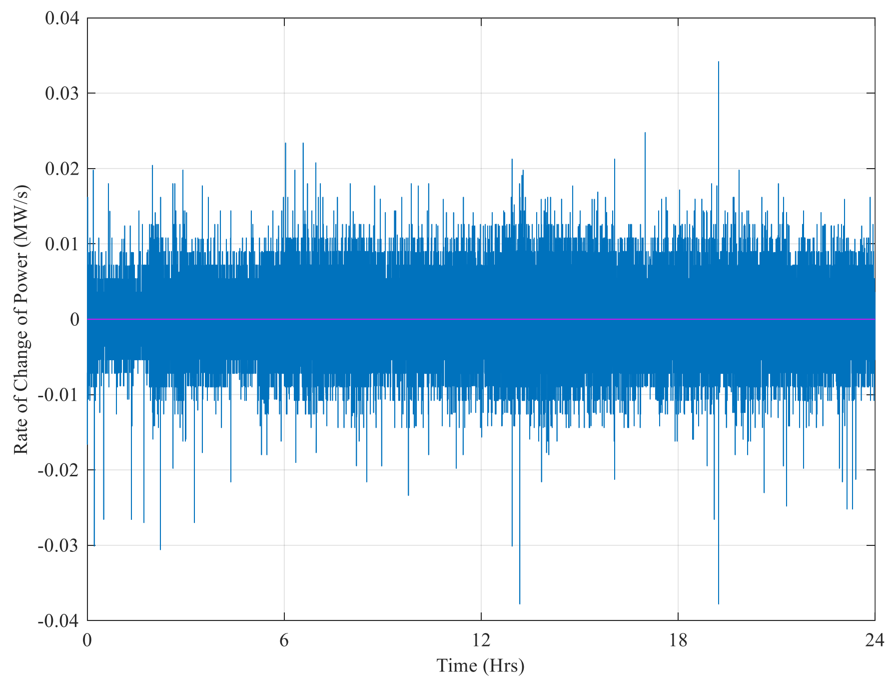

Figure 4.13 January 2014 Daily ROCOP

Table 4.10 VDS Daily Analysis Summary

Time Audit	BESS Size (MWh)	ROCOP (MW/s)
Month	2.34	±0.007

4.2.4 VDS Summary

The VDS analysis revealed the SOC at the end of each time; the SOC is not the same.The best SOC from the VDS analysis is 62%, as such the EFR only has 38% of rated capacity to respond to frequency events which would occur in later times during EFR operations. In order to successfully prepare for over and under frequency events the BESS SOC would need about 50% at the end of the time audit.50% because the BESS can absorb an equal amount of energy based on rated capacity, thus the BESS has an equal capacity to curtail both over and under frequency events.

4.3 Constant DeadBand Scheme (CDS)

The CDS is designed on the DB theory. The CDS does not allow for active power variations while frequency is within the DB region, unlike the VDS, which allows active power variations. The scheme aims to maintain a SOC of approximately 50% on a given time audit such as monthly, weekly and daily. There is a direct relationship between cumulative energy, DB and SOC. This relationship is highlighted in Fig (4.14).

The relationship between DB, SOC and Cumulative energy is the novel aspect of this study. The relationship between DB, SOC and cumulative energy is the basis of the CDS. To achieve a SOC of approximately 50%, a constant active power based on maximum BESS capacity is injected into the system while frequency is in the DB region. Fig (4.14) also explains different constant DB that will derive different SOC's. The size of the BESS will increase significantly as the DB gets bigger or smaller.

The algorithm begins with the logging of frequency data into Matlab, and a frequency zone assignment is performed to assign frequencies to different zones. The algorithm is time-dependent as such a time frame should be selected. The zone assignment is dependent on the magnitude of frequency. Define search space for DB-output based on NGET specifications and obtain DB output; if the selected DB-output does not derive a ~0MWh energy at the end of the time frame, the search space should be expanded but should not exceed DB limits issued by NGET. Finally, integrate power based on selected DB output to derive ~0MWh at the end of the selected time frame. The flow chart for the CDS algorithm is shown in Fig (4.15). The CDS aims to ensure at the end of any time frame the BESS SOC should be at approximately 50%.The Equations for calculating power for the CDS analysis is shown in Table (11).

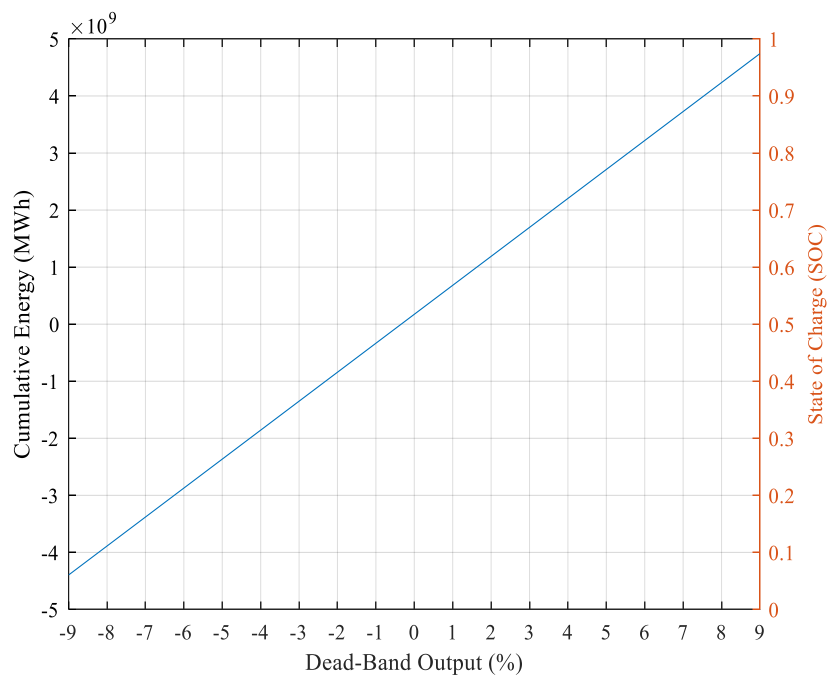

Figure 4.14 Relationship Between DB, Cumulative Energy and SOC

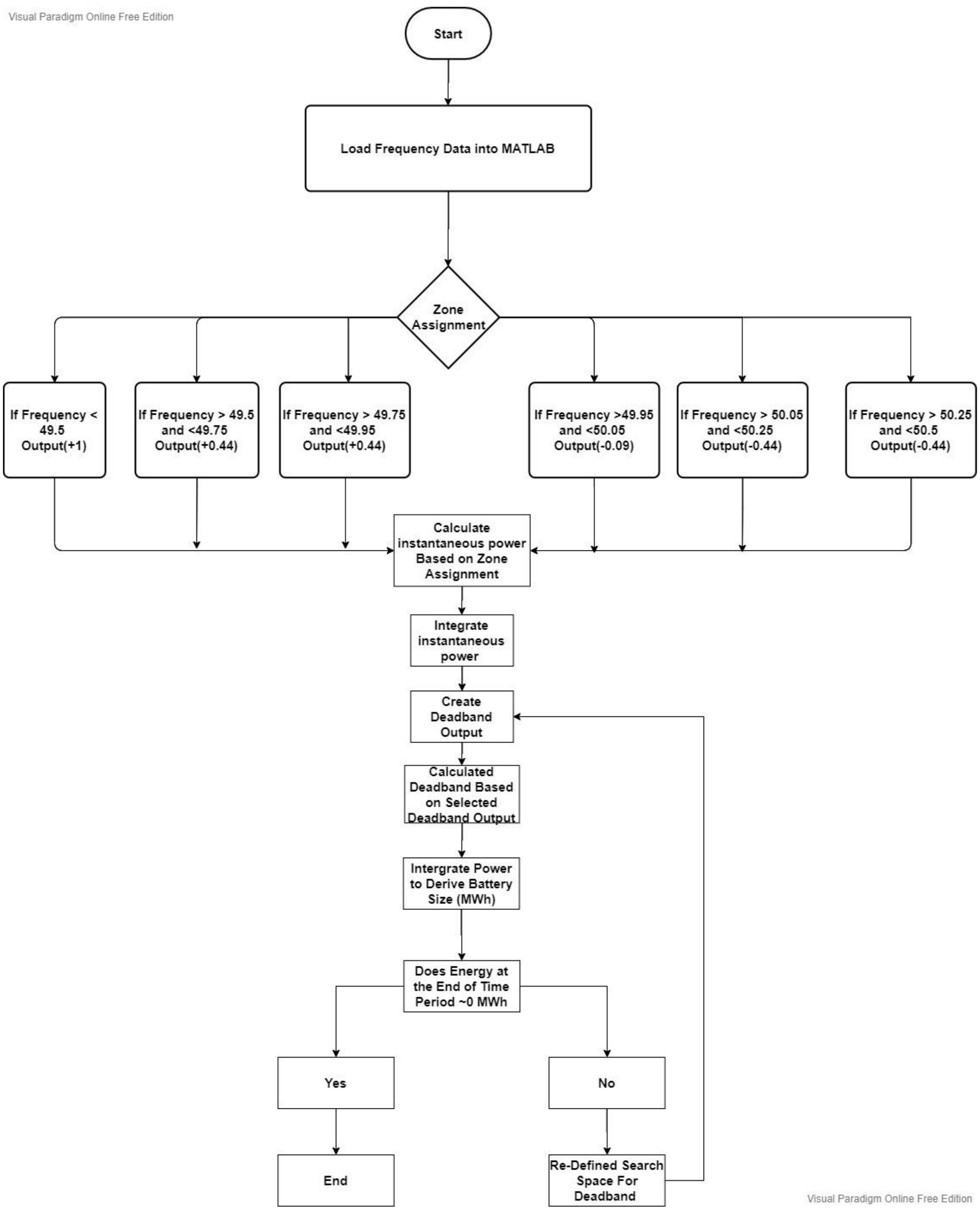

Figure 4.15 CDS Flowchart

Table 4.11 Equations for Calculating Power in CDS Analysis

Frequency (Hz)	Region	Frequency Band
49.5-49.75	A-B	$-222.24 \cdot f + 11100.88$
49.75-49.95	B-C	$177 \cdot f + 8850.15$
49.95-50.05	C-D	$-180 \cdot f + 9000$
50.05-50.25	D-E	$177.2 \cdot f + 8859.86$
50.25-50.5	D-F	$222.4 \cdot f + 11123.12$

Where *f* is Frequency (Hz)

4.3.1 BESS Sizing Based on Monthly Analysis

The general overview from Fig (4.16) and (4.17) is presented int eh paragraph below:
The highest demand recorded in UK is recorded during the three and half settlement period between 4:00PM -7:00PM between the months of November to February. A triad can occur if the highest demand recorded is separated by ten-day interval.
Based on the metrological classification of season, from November to February is classed as winter to autumn. The period of maximum demand within a calendar year is experienced usually during the winter and autumn months, and lower demand is seen during the months of spring and summer respectively.
Although in the summer and spring months less synchronous generation is utilised from coal because of the reduction in demand as such RES and nuclear energy are used to absorb the electrical demand which coal could have provided during this period. The months of spring and summer have high cumulative energies because of lower demand and low penetration of synchronous generation. Thus, more energy would be required from the EFR to operate.

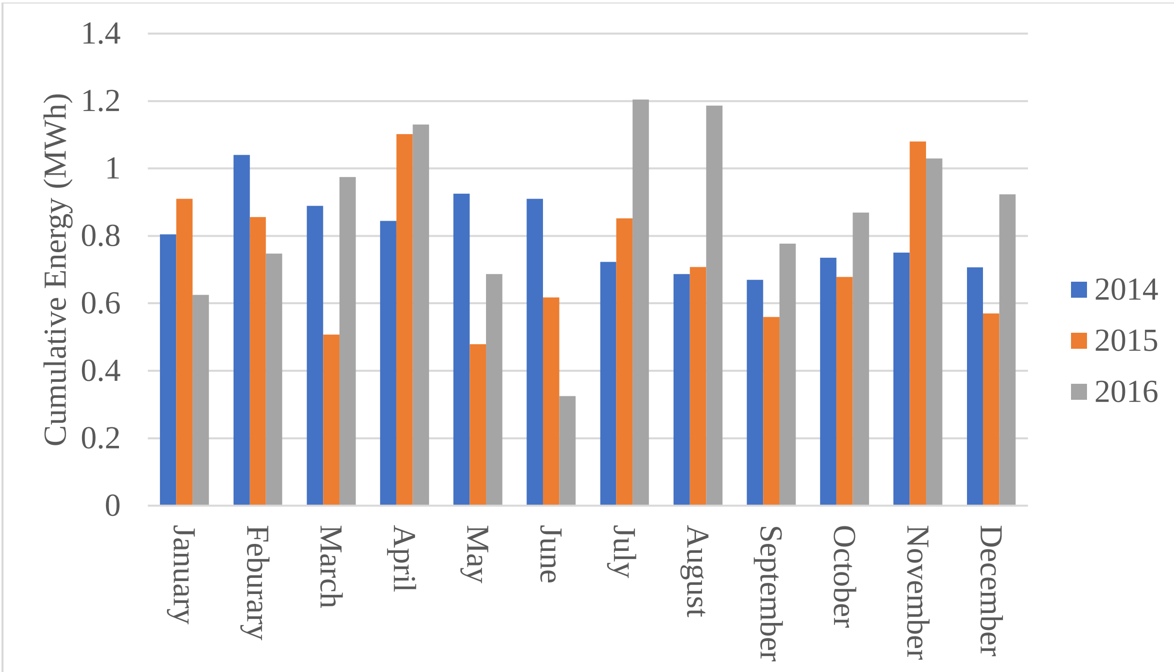

Figure 4.16 CDS Monthly Analysis (Method 1), $|E_{max}|$

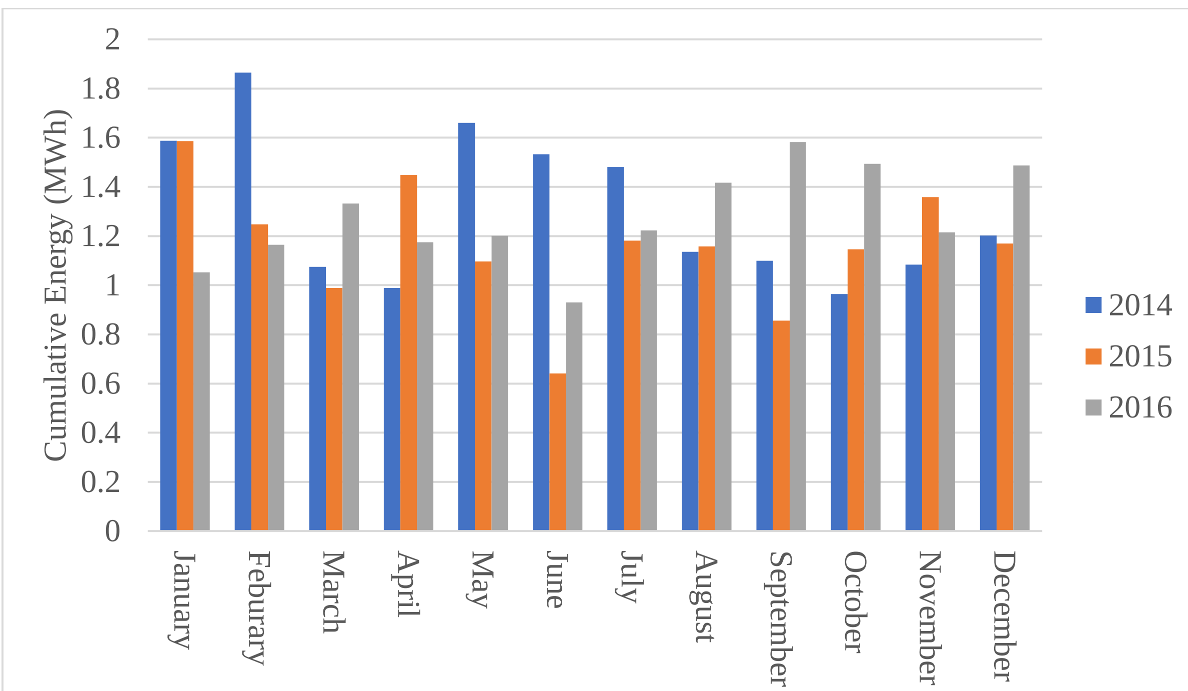

Figure 4.17 CDS Monthly Analysis (Method 2), E_1-E_2.

1.8MWh is the highest cumulative energy recorded, which was recorded in February 2014. Through the energy analysis derived from the frequency data, February 2014 is taken as the worst-case scenario as such a more detailed time audits will give more insight in EFR sizing speciation based on energy and ROCOP, this is shown in Fig (4.18). Fig. (4.19) shows the relationship between SOC and Cumulative energy, at the end of the month, the SOC is set at approximately 50%. Based on Fig. (4.19) the BESS should be able to deliver ±0.45MW/s within a second, as this is the maximum ROCOP which occurs within the month. Fig (4.19). Table (4.12) highlights the summary of the CDS monthly analysis.

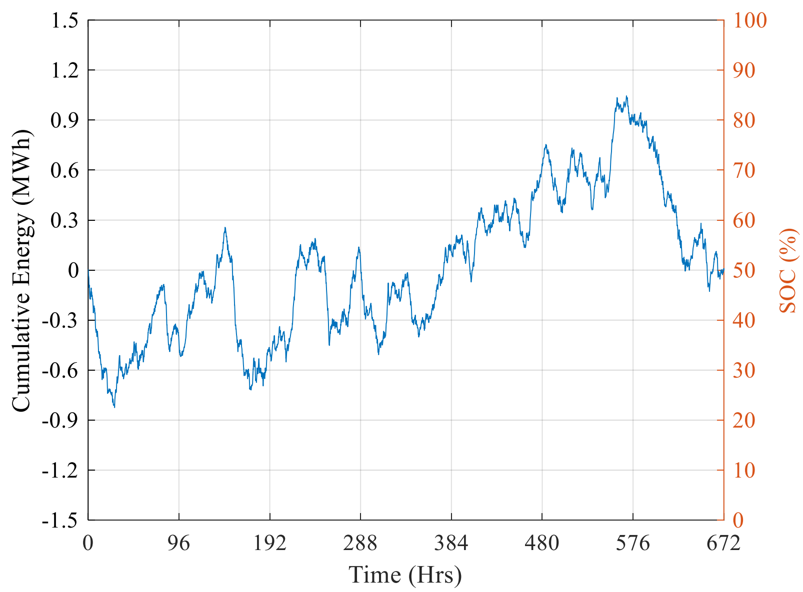

Figure 4.18 February 2014 Cumulative Energy Monthly Analysis

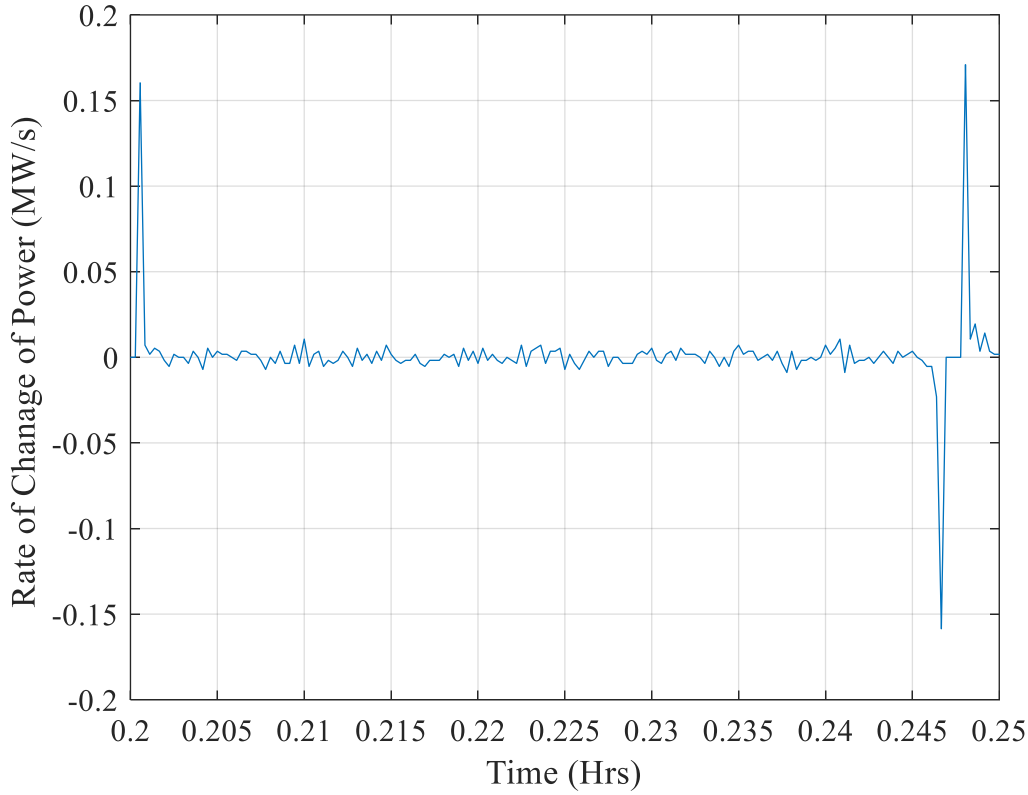

Figure 4.19 February 2014 ROCOP Monthly Analysis

Table 4.12 BESS based on Monthly Analysis

Time Audit	BESS Size (MWh)	ROCOP (MW/s)
Month	1.8	±0.45

4.3.2 BESS Sizing Based on Weekly Analysis

Fig (4.20) describes the weekly exchange of energy between the EFR and the grid for each week in the month. The month analyzed for daily analysis is February 2014 because this month had the highest cumulative energy. The week with the most energy consumption is WK1, whereas other weeks are approximate 0.6MWh. Based on Fig. (4.20) the BESS should be able to deliver ±0.88MW/s within a second according to Fig (4.21), as this is the maximum ROCOP that occurs within the month. Table (4.13) highlights the summary of the CDS weekly analysis.

Table 4.13 BESS Size Based on Weekly Analysis

Time Audit	BESS Size (MWh)	ROCOP (MW/s)	SOC
Week 1	1.3	±0.2	50%
Week 2	0.63	±0.25	50%
Week 3	0.64	±0.63	50%
Week 4	0.63	±0.88	50%

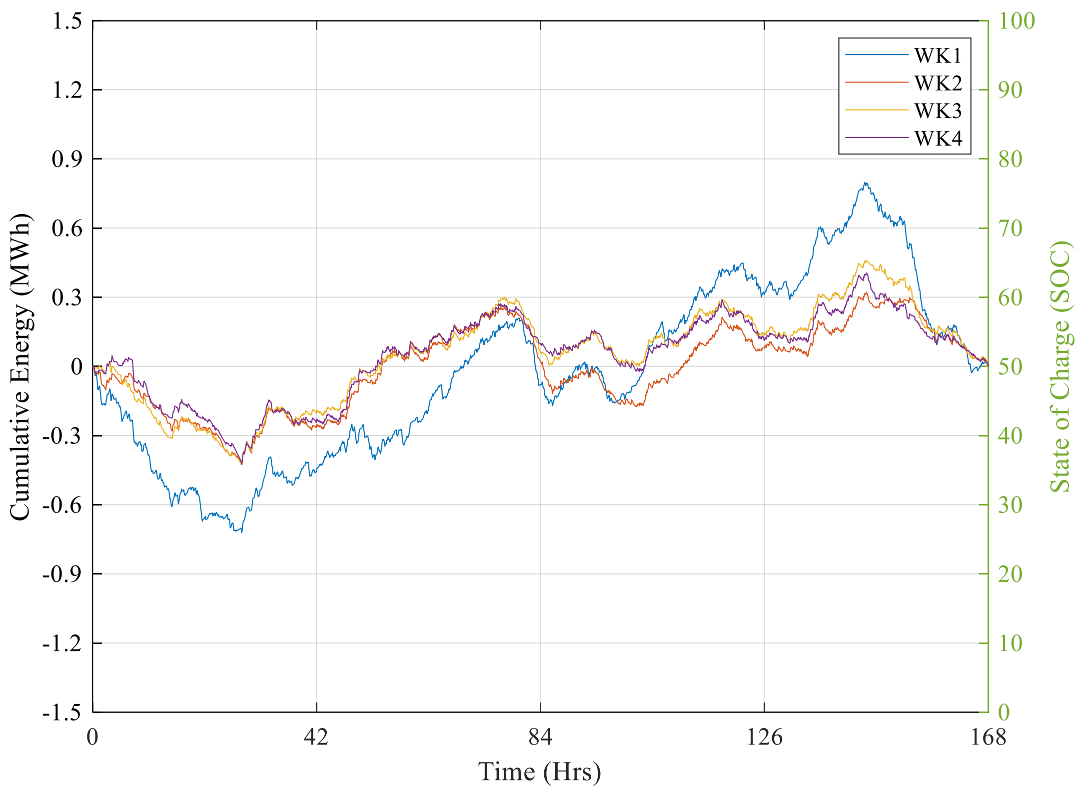

Figure 4.20 February 2014 Cumulative Energy Weekly Analysis

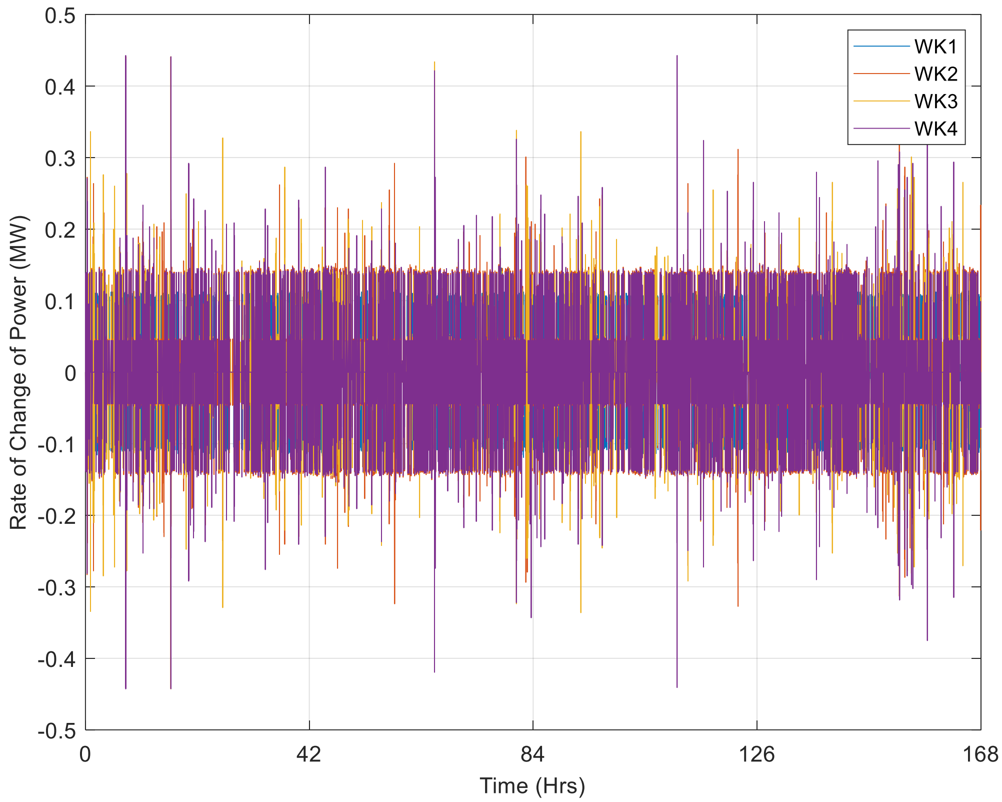

Figure 4.21 February 2014 ROCOP Weekly Analysis

4.3.3 BESS Sizing Based on Daily Analysis

Fig (4.22) describes the daily exchange of energy between the EFR and the grid for an entire month. The month analysed for daily analysis is February 2014 because this month had the highest cumulative energy. The amount of energy required daily does not vary significantly throughout the month.

Additionally, the state of charge at the end of each day is approximately 50%. The cumulative energy for daily analysis is similar in terms of magnitude. The ROCOP on Fig

(4.23) is much less when comparing the monthly, weekly and daily analysis for the CDS analysis.

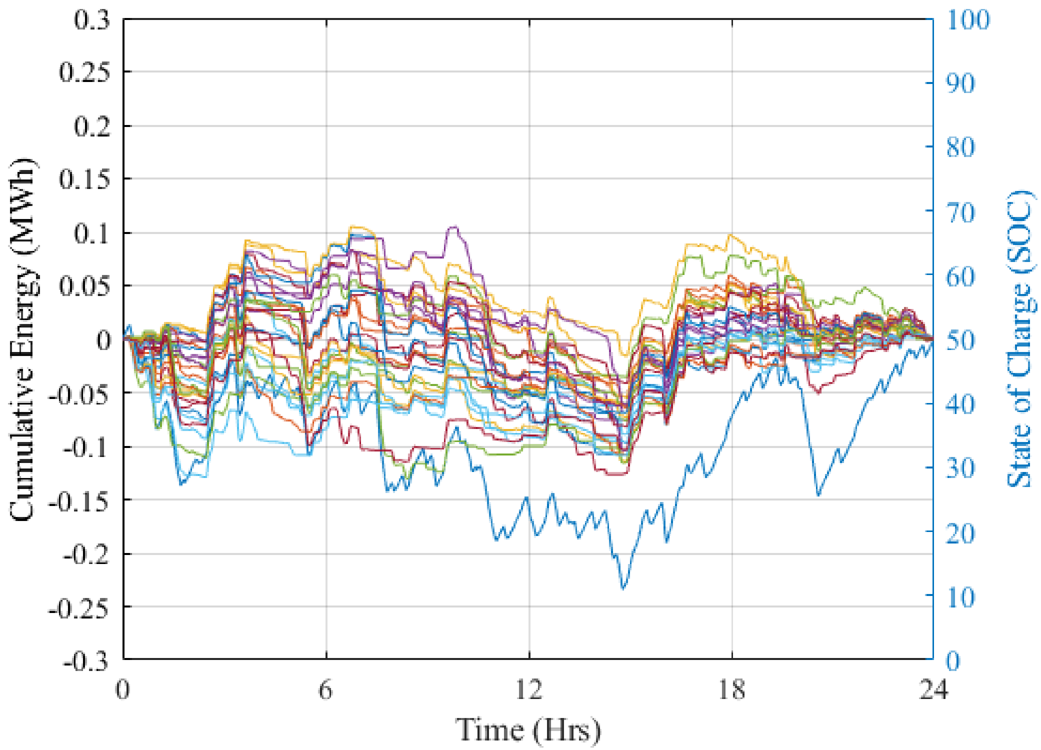

Figure 4.22 February 2014 Cumulative Energy Daily Analysis

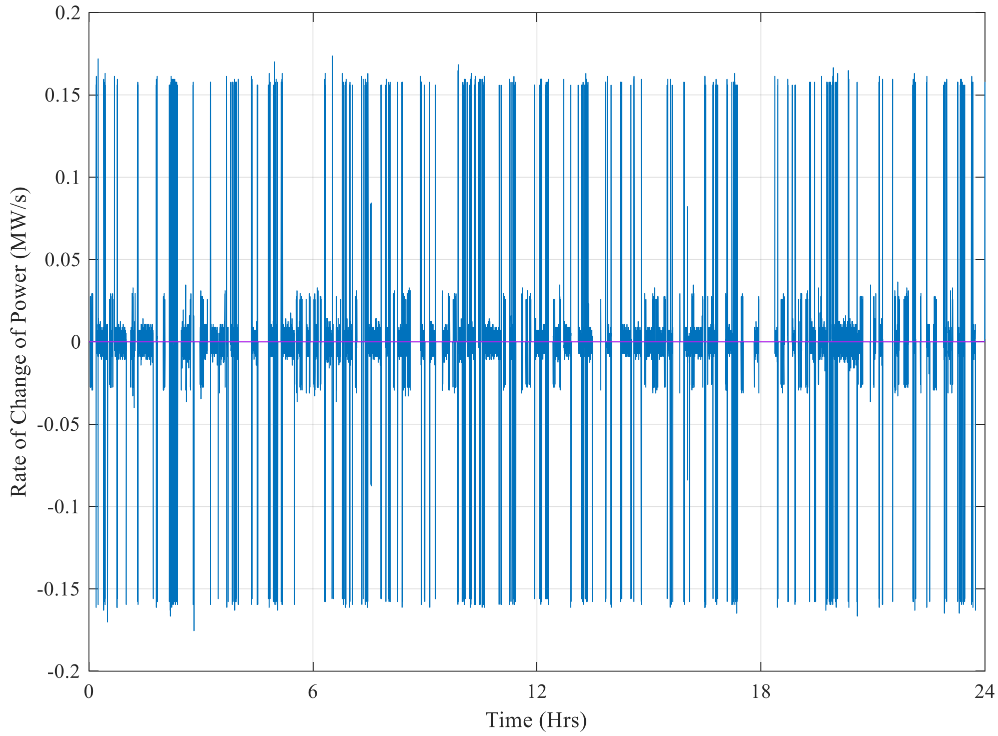

Figure 4.23 February 2014 ROCOP Daily Analysis

4.3.4 CDS Summary

The unique relationship between DB, SOC and cumulative energy, the relationship as mentioned above between DB, SOC and cumulative energy gives the SO flexibility to pick a specific SOC and cumulative energy based on a specific DB. The CDS aims to improve on BESS's SOC management by ensuring the SOC ends at 50% at all time audits, ensuring the BESS has enough rated capacity to curtail both over and under frequency events equally.

4.4 Discussion

The comparison between the VDS and CDS results and DB output variables for both yearly and daily time audits is discussed below

4.4.1 Comparing Energy Management Philosophies and Discussion

Two EMS have been used to process Frequency response data from the National Grid, the EMS will be accessed based on three criteria such as the ability to manage the state of charge of BESS, Size of BESS (MWh), and ROCOP (MW/s). Using Table (4.14) to give a complete overview of both EMS.

The VDS requires more energy dissipation but less ROCOP while the CDS reduces the energy requirements but increases the ROCOP. The reason for the rapid change of power while operating on the CDS scheme is attributed to the operation philosophy. Majority of frequencies occur within the DB region as such a constant power is injected into the system while frequency lies within the DB. If system frequencies leave the DB zone a change of power occurs from a maximum power of ±9% to maximum ±100%.

The VDS does not experience a rapid change of power because a variation of power is allowed while the frequency is within the DB region. Thus, the analysis suggests systems operators have the flexibility to operate the EFR on different constant DB variables on a periodical basis to improve SOC management.

The VDS analysis revealed the difference in BESS size when comparing the monthly, weekly and daily analysis of EFR operations. The best time audit to use for BESS is the daily analysis as the daily analysis shows the actual energy consumption and required ROCOP from the BESS. The daily analysis from the VDS explains the magnitude in energy consumption and ROCOP is uniform during the month.

The CDS analysis revealed the difference in BESS size when comparing the monthly, weekly and daily analysis of EFR operations, the best time audit to use for BESS is the daily analysis as the daily analysis shows the exact energy consumption and required ROCOP from the BESS. The daily analysis from the VDS explains the magnitude in energy consumption and ROCOP is uniform during the month.

Table 4.14 Comparison of BESS Sizes for EMS

EMS	Monthly BESS Energy (MWh)	Monthly BESS ROCOP (MW/s)	Weekly BESS Energy (MWh)	Weekly BESS ROCOP (MWh)	Daily BESS Energy (MWh)	Daily BESS ROCOP (MW/s)	State of Charge (SOC) (%)
VDS	2.34	0.2	1.4	0.43	0.6	0.065	Variable
CDS	1.84	0.43	1.3	0.88	0.35	0.3	50%

4.4.2 Discussion Based on Time Audits

The BESS will grossly be oversized because the energy required from the monthly, weekly and daily analysis is significantly different for both the CDS and VDS. Table (4.15) explains the difference in BESS size when comparing different time audits.

Using the CDS analysis, the daily time audit is the most accurate time audit for EFR system sizing because the system dynamics are easier to control on daily basis rather than a weekly or monthly basis. Additionally, the daily Time audit will reduce the size of the BESS for EFR operations from 1.8MWh to 0.3MWh which is an approximate reduction in BESS size by 600%. The daily time audit also gives a clear indication that 1MWh is sufficient to perform EFR services on the utility network on a daily basis.-

Table 4.15 CDS Time Audit Summary

Period	BESS Size (MWh)	ROCOF (MW/s)	Difference in Size with respect Daily Time Audit (%)
Month	1.8	0.45	600%
Week	1.3	0.88	433%
Daily	0.3	0.30	0%

4.4.2.1 Constant DB for Daily Analysis

February 2014 DB constants are presented in Fig (4.24). Although the cumulative energy is approximately the same for each day, the DB constant varies each day. The DB constants for the daily analysis of the for February 2014 is shown in Fig (4.24). The highest DB constant is the data outlier within the data set; however, after the first day of the month, the DB constants are within a band of DB constants ranging from 0.69 –2.45. The DB constant for the weekly analysis is shown in Fig (4.25).

The CDS operates on the assumption that the majority of the frequencies occur within the DB region of the delivery envelopes. However, other regions of the delivery envelope can affect the DB constant. The regions of the delivery envelopes are displayed in Table (4.16).

Table 4.16 Delivery Envelopes Frequency Band

Frequency (Hz)	Region	Frequency Band

49.5-49.75	A-B	Lower Band
49.75-49.95	B-C	Low-Band
49.95-50.05	C-D	Dead-Band
50.05-50.25	D-E	High-Band
50.25-50.5	D-F	Higher-Band

Fig (4.26) is a histogram of the first four days in the month of February 2014, Day 1 to Day 4 have the majority of the frequencies occurring within the DB. However, frequencies in the higher Band of Frequency occur with a higher cumulative density compared to the other three days highlighted. The EFR responds to Higher and High Band Frequencies by sinking active power from the grid to the BESS. Alternatively, the EFR perceives all high and higher band frequencies as positive integers and low and lower band frequencies as negative integers. During the first day of the month, higher and high band frequencies have higher cumulative densities, as such more energy is needed to drive the SOC to 50%, this is the reason why on the first day of each month the DB is much higher than other days in the month.

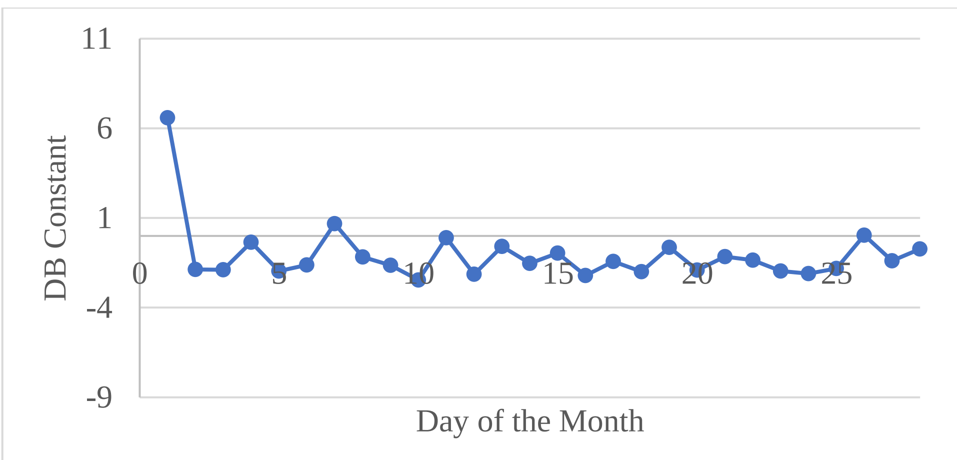

Figure 4.24 Daily DB Constant for February 2014

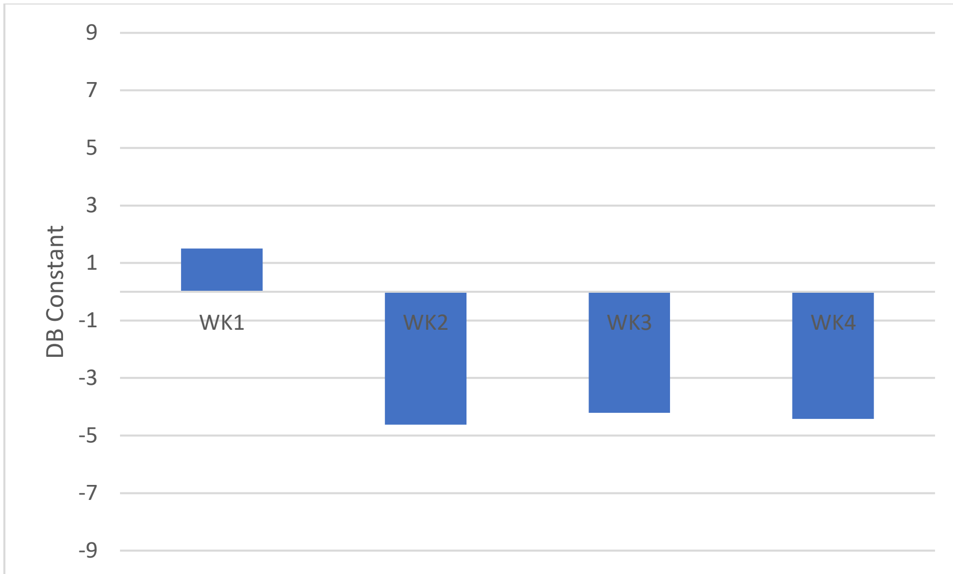

Figure 4.25 February 2014 (Weekly DB constant)

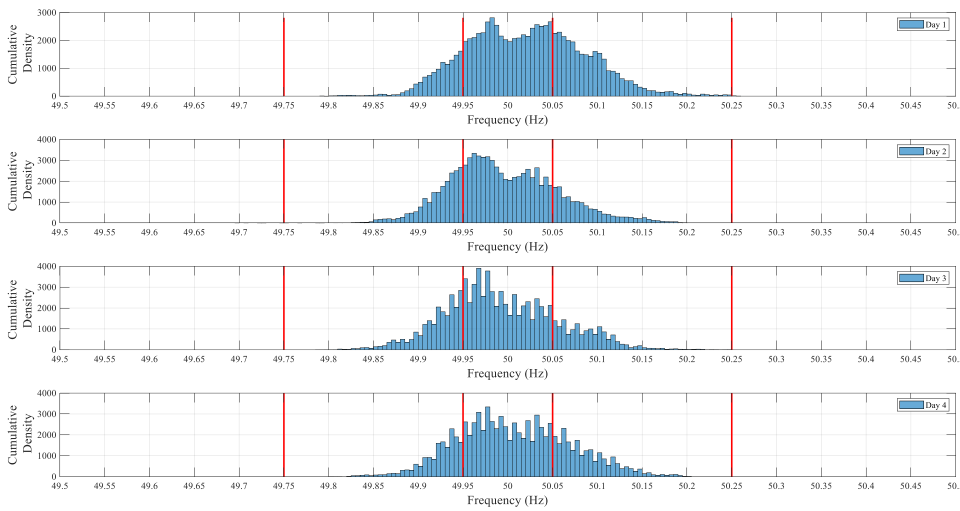

Figure 4.26 Histogram February 2014, Day 1-4

4.5 Pre EFR and Post EFR comparison

The Pre-EFR is the planning ERA, the frequency profiles analyzed for the Pre-EFR era are the years 2014-2016, the post EFR era are subsequently year the EFR has been in operation from 2016- 2018. This section discusses a brief companion of both time frames. A seasonal analysis is looking at the variation of RES penetration from 2014-2018. Both the VDS and CDS monthly analysis on Fig (4.30) and Fig (4.31), shows vividly an increase in cumulative energy from the Pre-EFR and Post-EFR eras, respectively. The increase in EFR size is because of an increase in RES on the utility network. The VDS analysis has higher cumulative energy which occurs in October 2017 while the CDS occurred in October 2017, both months occur during the winter season. According to Figure (4.28) and Figure (4.29) for the VDS and CDS monthly analysis respectively for the Pre and Post EFR analysis. The EFR unit will need to increase the Energy content of the BESS by 25% and 57% for the CDS and VDS respectively in order to curtail frequency events in the post EFR era effectively. This increase is evidence that National Grid will require more Fast Frequency Response services to achieve stability while increasing penetration for RES on the utility grid.

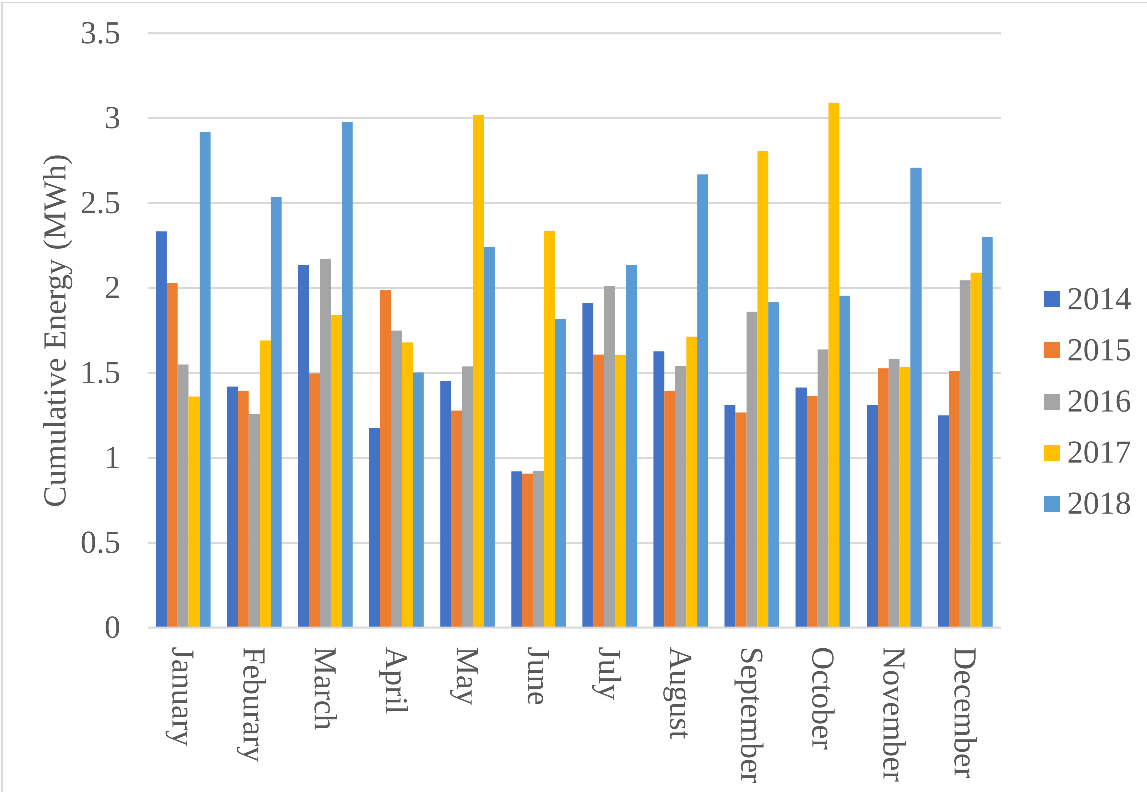

Figure 4.27 VDS Comparison of Pre and Post EFR Planning

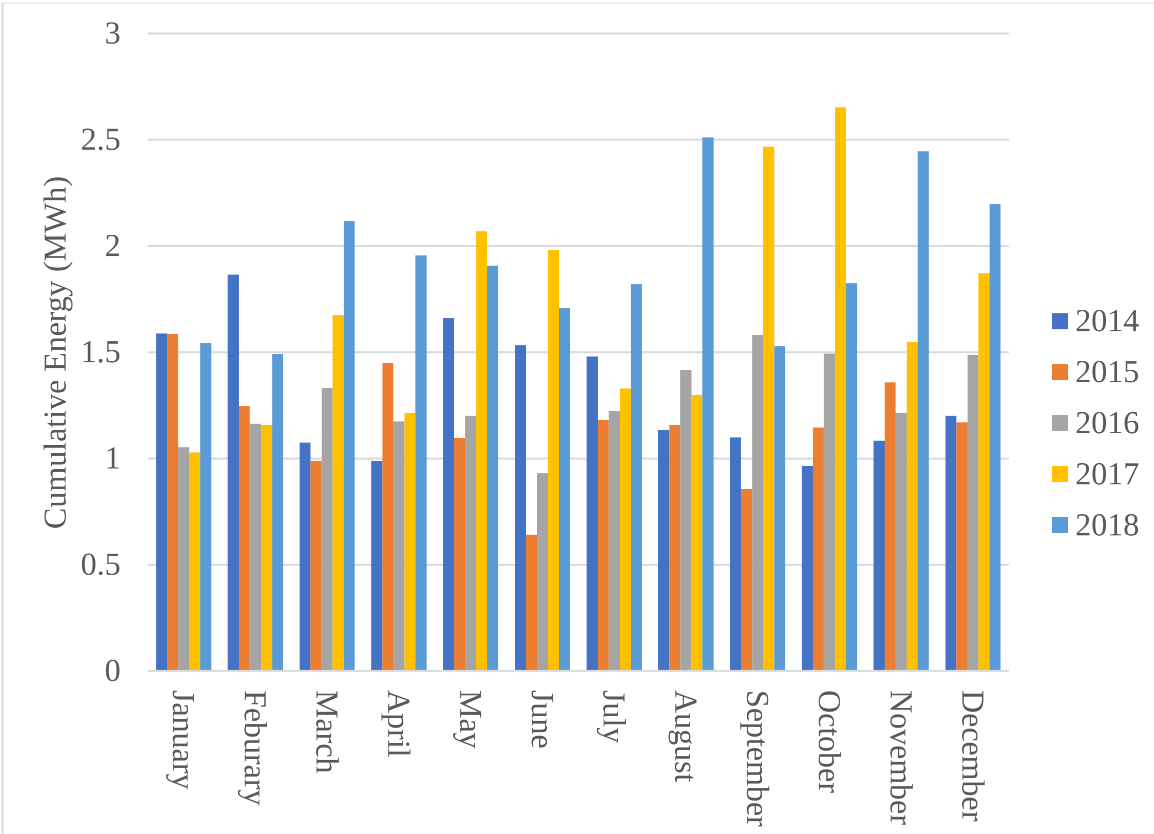

Figure 4.28 CDS Comparison of Pre and Post EFR Era's.

4.6 Comparison between Proposed BESS size and On-Going EFR Projects.

The proposed BESS size from the CDS analysis only utilizes approximately 30% of the SOC of the proposed BESS size for EFR specification. Other EFR projects like ENERCON have tried to match the power and energy rating whereas Vanttenfall did not match the energy and power of the BESS rather opted for a 100% power and 60% energy split. Finally, project at Sheffield settle on for a 100% and 50% on energy. According, the CDS analysis the BESS would only require maximum of 30% SOC during EFR operations, this projects EMS shows a 100% Power and 30% Energy split is effect for EFR operation. Due to BESS degradation this scheme would suggest a 100% power and 60% Energy BESS split to improve BESS life span and reduce unnecessary waste of investment (£) as matching or increasing the power to energy ratio. The benefit of using this scheme to plan for an EFR unit is tied to monetary savings the cost of 1kWh of Lithium Ion battery is about £600/kWh the proposed system would save approximately £240,000 of investment by only investing in 60% of energy rather than 100%.

Table 4.17 Comparison of Proposed BESS Sizes and On-Going EFR Projects

Project	Power (MW)	Energy (MWh)	Power to Energy Ratio	Cost of System (£)	References
PhD Study	1	0.6	1:3	360,00	[23]
Proposed BESS	1	1	1:1	600,00	[7]
Enercon	10	10.79	1:1	642,000	[30]
Vanttenfall	22	15.5	1:41	700,000	[31]
Sheffield	2	1	2:1	600,000	[22]

4.7 Conclusions

"The CDS is a better EMS for EFR operation because the scheme has reduced cumulative energy in comparison to the VDS and better SOC management for frequency curtailment, since the CDS at all time increments provides the equal capacity to curtail both under and over frequency events at the end of any time period. From the CDS analysis the approximate sizing mechanism for the BESS should be a 100% Power and 60% Energy.

> Additionally, the DB constant is dependent on the frequency distribution during the time increment. Negative DB constants occur when majority of the frequencies occur within the low and lower band frequencies and alternatively positive DB constants occur when majorities of the frequencies occur between the higher and high band frequencies".

The results from the Pre and Post EFR analysis and Energy mix in the UK indicate, the increase in EFR size is directly proportional to the raid increase of RES generators which are utilized on the National Grid Network. This increase is evidence that the grid will require approximately 57% more energy to ensure frequency stability. While using the CDS scheme.

Chapter 5

Conclusions

5.1 Conclusions

The rapid increase in RES on the utility grid is causing a decrease in system inertia; the result is a system with larger frequency deviations and higher transient power exchanges for frequency control. NGET introduced EFR as a means to curb the rapid frequency deviations and maintain network frequency closer to 50Hz by utilizing ESS to breach the gap between demand and supply. NGET introduced EFR as the solution to add synthetic inertia on the network as RES is replacing synchronous generators.
The critical analysis from this thesis explains the future grid will require more Fast Frequency Response services to achieve stability while increasing penetration for RES on the utility grid.

Further research was conducted to find the most suitable ESS for EFR operation, considering technologies such as SMES, flywheel, BESS and superconducting. The BESS is the most suitable form of ESS energy storage but specifically the Li-ion Battery because this BESS technology has a high energy density, low cost of energy, high round trip efficiency medium discharge rate.

The daily audit also revealed for both the VDS and CDS analyses the magnitude of energy exchanged is similar, although the CDS DB constants are variable during the month.
The design of the CDS is centred around the assumption that majority of the frequencies occur within the DB region. This study uses the resource of DB control to improve SOC

and to propose a novel relationship between DB, SOC and cumulative energy. This relationship is the cause of the reduction in cumulative energy and improved BESS availability from 62% to 50% at the end of all-time audits, allowing BESS operators to have equal capacity to curtail both under and over frequency events. From the CDS analysis the approximate sizing mechanism for the BESS should be a 100% Power and 60% Energy.

The preferred CDS is the preferred solution developed in this thesis will reduce the amount energy required to effectively curtail breach in demand and supply by 40%. This reduction will subsequently reduce the investment required to purchase an EFR system by 40%.
The major drawback of the CDS Scheme is the power requirement when frequencies leaves the DB region, in this event the CDS scheme requires a four times a much power to operate compare to the VDS scheme.

Finally, from the Pre and Post EFR analysis, the increase in Energy content of the BESS by 25% and 75% for the CDS and VDS respectively is evidence that NGET will require more Fast Frequency Response services to maintain stability while increasing penetration of RES on the Utility Grid.

5.2 Future Research Work

- Both the VDS and CDS should be tested on exemplary power systems to validate and test whether the EMS can used for frequency curtailment effectively.
- The data provided was from the National Grid which was previous frequency data. A prediction for frequency on a daily time audit on the utility grid could improve the CDS performance.
- Future research objective would include designing a hybrid ESS super-capacitor and battery model for EFR design.

5.3 Publications from Thesis

Contribution to Publications:

The contribution to this publication is the design and implementation of the VDS and CDS energy management schemes for Battery sizing and management.

[1]L. Shobayo, Y. Hu, N. Schofield and N. Zhao, "Utilization of Battery Storage Technology to Assist Renewable Energy Networks", in Wind Integration Workshop, Stockholm, 2018.

Contribution to Publications:

The improved results from the CDS schemes was used as demand data to investigate transient energy storage for electrical power systems.

[2]Y. Hu, N. Schofield, L. Shobayo and N. Zhao, "Investigation of Transient Energy Storage Sources for Support of Future Electrical Power Systems", IET Renewable Power Generation, 2020. Available: 10.1049/iet-rpg.2019.0666.

References

[1] X. Shengfeng, X. sheng, Z. tianxing and Z. xuelli, "The Relationship between Electricity Consumption and Economic Growth in China", Physics Procedia, vol. 24, pp. 56-62, 2012.

[2] J. Ambrose, "UK to be left with five coal power stations after latest closure", the Guardian.[Online].Available:https://www.theguardian.com/environment/2019/jun/13/mild-but-windy-winter-was-greenest-ever-for-uk-energy-use. [Accessed: 24- Jul- 2019].

[3] D. Group, "Drax Electric Insights", Drax Electric Insights. [Online]. Available: https://electricinsights.co.uk/#/dashboard?_k=1yhn9a. [Accessed: 24- Jul- 2019].

[4] S. Johnson, D. Papageorgiou, D. Mallapragada, T. Deetjen, J. Rhodes and M. Webber, "Evaluating rotational inertia as a component of grid reliability with high penetrations of variable renewable energy", Energy, vol. 180, pp. 258-271, 2019.

[5] N. Grid, "Frequency response services | National Grid ESO", Nationalgrideso.com. [Online]. Available: https://www.nationalgrideso.com/balancing-services/frequency-response-services. [Accessed: 24- Jul- 2019].

[6A] OFGEM Licence conditions [Online]. Available, [online] Available: https://www.ofgem.gov.uk/licences-codes-and-standards/licences/licence-conditions.

[6] J. Vieira, W. Freitas, Z. Huang, W. Xu and A. Morelato, "Formulas for predicting the dynamic performance of ROCOF relays for embedded generation applications", IEE Proceedings - Generation, Transmission and Distribution, vol. 153, no. 4, p. 399, 2006. Available: 10.1049/ip-gtd:20045205.

[7] N. Grid, "Enhanced frequency response (EFR) | National Grid ESO", Nationalgrideso.com,2019.[Online].Available: https://www.nationalgrideso.com/balancing-services/frequency-response-services/enhanced-frequency-response-efr?technical-requirements.

[8A] A. Ulbig, T. Borsche and G. Andersson, "Impact of Low Rotational Inertia on Power System Stability and Operation", IFAC Proceedings Volumes, vol. 47, no. 3, pp. 7290-7297, 2014 [Online].

[9]X. Meng, J. Liu and Z. Liu, "A Generalized Droop Control for Grid-Supporting Inverter Based on Comparison Between Traditional Droop Control and Virtual Synchronous Generator Control", IEEE Transactions on Power Electronics, vol. 34, no. 6, pp. 5416-5438, 2019 [Online].

[10] W. Stevenson, Elements of power system analysis. New Delhi: McGraw Hill Education (India), 2015, pp. 378-379.

[11]" Paralleling of Generators and Synchronization", Electrical Equipment. [Online]. Available: http://engineering.electrical-equipment.org/electrical-distribution/paralleling-generators-synchronization.html. [Accessed: 31- Jan- 2020].

[12]H. Saadat, Power system analysis, 3rd ed. [United States]: PSA Pub, 2010, pp. 100-115.

[13]Z. OBAID, L. CIPCIGAN, L. ABRAHIM and M. MUHSSIN, "Frequency control of future power systems: reviewing and evaluating challenges and new control methods", Journal of Modern Power Systems and Clean Energy, vol. 7, no. 1, pp. 9-25, 2018. Available: 10.1007/s40565-018-0441

[14] National Grid (2016) System operability framework. http://www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/System-Operability-Framework/. Accessed 15 February 2017

[15]N. Grid, "Frequency response services | National Grid ESO", Nationalgrideso.com. [Online]. Available: https://www.nationalgrideso.com/balancing-services/frequency-response-services.

[16] N. Grid, "Firm frequency response (FFR) | National Grid ESO", Nationalgrideso.com. [Online]. Available: https://www.nationalgrideso.com/balancing-services/frequency-response-services/firm-frequency-response-ffr.

[17] N. Grid, "Mandatory response services | National Grid ESO", Nationalgrideso.com, 2019. [Online]. Available: https://www.nationalgrideso.com/balancing-services/frequency-response-services/mandatory-response-services.

[18] N.Grid, "Enhanced frequency response (EFR) | National Grid ESO", Nationalgrideso.com, 2019. [Online]. Available: https://www.nationalgrideso.com/balancing-services/frequency-response-services/enhanced-frequency-response-efr.

[19]A. Cooke, K. Forkasiewicz and D. Strickland, "Energy storage for enhanced frequency response services", in 2017 52nd International Universities Power Engineering Conference (UPEC), 2017.

[20]F. Sanchez, D. Bogdanov and F. Gonzalez-Longatt, "Probabilistic Assessment of Enhanced Frequency Response Services Using Real Frequency Time Series", in 2018 20th International Symposium on Electrical Apparatus and Technologies (SIELA), Bulgaria, 2017.

[21]S. Canevese ; and L. Pellegrino, "Simulation of enhanced frequency response by battery storage systems: The UK versus the continental europe system", in S. Canevese ; D. Cirio ; A. Gatti ; M. Rapizza ; E. Micolano ; L. Pellegrino 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2017.

[22] B. Mantar Gundogdu, S. Nejad, D. Gladwin, M. Foster and D. Stone, "A Battery Energy Management Strategy for U.K. Enhanced Frequency Response and Triad Avoidance", IEEE Transactions on Industrial Electronics, vol. 65, no. 12, pp. 9509-9517, 2018. Available: 10.1109/tie.2018.2818642.

[23] L. Shobayo, N. Schofield, Y. Hu and N. Zhao, "Utilization of Battery Storage Technology to Assist Renewable Energy Networks.", 2018.

[24]H. IBRAHIM, A. ILINCA and J. PERRON, "Energy storage systems—Characteristics and comparisons", Renewable and Sustainable Energy Reviews, vol. 12, no. 5, pp. 1221-1250, 2008.

[25] Faure F. Suspension magnétique pour volant d'inertie. Thèse de doctorat. Institut National Polytechnique de Grenoble, France; Juin 2003.

[26] X. Luo, J. Wang, M. Dooner and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation", Applied Energy, vol. 137, no. 1-26, pp. 511-536, 2015.

[27] Yuan W. Second-generation high-temperature superconducting coils and their applications for energy storage. Springer theses. Ph.D. thesis by the University of Cambridge 201

[28] H. Chen, T. Cong, W. Yang, C. Tan, Y. Li and Y. Ding, "Progress in electrical energy storage system: A critical review", Progress in Natural Science, vol. 19, no. 3, pp. 291-312, 2009.

[29]Electrical energy storage: white paper. Technical report. Prepared by electrical energy storage project team. International Electrotechnical Commission (IEC), Published December 2011.

[30] J. Person and F. Daraiseh, "Pen Y Cyoedd Delivery of Enhanced Frequency Response in UK by a Battery Energy Storage", Wind and Solar Conference, Stockholm, 2018.

[31] A. Linder and B. Lenz, "Balancing by Wind and Energy Storage", Wind Conference Stockholm, 2018.

[32] V. Knap, S. Chaudhary, D. Stroe, M. Swierczynski, B. Craciun and R. Teodorescu, "Sizing of an Energy Storage System for Grid Inertial Response and Primary Frequency Reserve", *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 3447-3456, 2016. Available: 10.1109/tpwrs.2015.2503565.