Applied Energy 203 (2017) 115–127

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Frequency response services designed for energy storage

D.M. Greenwood [a,*], K.Y. Lim [b], C. Patsios [a], P.F. Lyons [a], Y.S. Lim [b], P.C. Taylor [a]

[a] School of Electrical and Electronic Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[b] Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Jalan Genting Klang, 53300 Kuala Lumpur, Malaysia

HIGHLIGHTS

- The need for improved frequency response in future power systems is identified.
- An investigation into how energy storage can fulfil this need is presented.
- New experimental methods have been developed, using power hardware in the loop.
- Analysis of high-resolution frequency data from the British electricity system.
- Case study analysis of a new frequency response service designed for energy storage.

ARTICLE INFO

Article history:
Received 23 February 2017
Received in revised form 27 May 2017
Accepted 11 June 2017
Available online 17 June 2017

Keywords:
Energy storage
Power systems
Frequency response
Hardware-in-the-loop
Real-time simulation

ABSTRACT

Energy Storage Systems (ESS) are expected to play a significant role in regulating the frequency of future electric power systems. Increased penetration of renewable generation, and reduction in the inertia provided by large synchronous generators, are likely to increase the severity and regularity of frequency events in synchronous AC power systems. By supplying or absorbing power in response to deviations from the nominal frequency and imbalances between supply and demand, the rapid response of ESS will provide a form of stability which cannot be matched by conventional network assets. However, the increased complexity of ESS operational requirements and design specifications introduces challenges when it comes to the realisation of their full potential through existing frequency response service markets: new service markets will need to be designed to take advantage of the capabilities of ESS. This paper provides new methods to analyse and assessing the performance of ESS within existing service frameworks, using real-time network simulation and power hardware in the loop. These methods can be used to introduce improvements in existing services and potentially create new ones. Novel statistical techniques have been devised to quantify the design and operational requirements of ESS providing frequency regulation services. These new techniques are demonstrated via an illustrative service design and high-resolution frequency data from the Great Britain transmission system.

1. Introduction

Frequency is a crucial parameter in an AC electric power system. Deviations from the nominal frequency are a consequence of imbalances between supply and demand; an excess of generation yields an increase in frequency, while an excess of demand results in a decrease in frequency [1]. The power mismatch is, in the first instance, balanced by changes in the kinetic energy stored within the rotating mass of large, synchronous generators. This response mitigates the effects of the imbalance, but does not correct it; that is the role of primary and secondary frequency response control of the power system. If the frequency deviates too far, statutory and operational limits will be breached, generators will be forced to disconnect, resulting in catastrophic failures within the system. The legal and operational limits for the GB (Great Britain) power systems are illustrated in Fig. 1.

In future power systems, the regularity and severity of frequency events is expected to increase as high penetrations of renewable generation lead to more variable, less predictable supply, and a reduction in system inertia as conventional plant is supplanted by renewable generators [2]. However, the advent of ESS creates an opportunity to provide frequency response significantly faster than the existing primary response; this can mitigate the increasing challenges in frequency control, and help enable higher penetrations of renewable energy.

Frequency Response (FR) is a necessary part of any AC power system, and is usually procured via ancillary service markets. The

* Corresponding author.
E-mail address: david.greenwood@ncl.ac.uk (D.M. Greenwood).

http://dx.doi.org/10.1016/j.apenergy.2017.06.046
0306-2619/

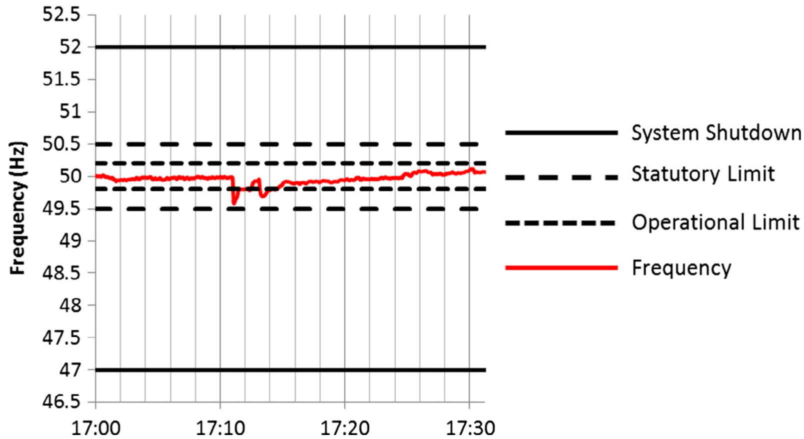

Fig. 1. The statutory and operational frequency limits relative to a real frequency response on the GB system.

FR markets in PJM; New-England; Great Britain; and Germany are compared in [3]. All of these markets are governed by a combination of frequency-based balancing services and slower reserve services. The GB market has a more structured and regulated approach to these services, particularly in the primary frequency regulation category. The Irish transmission system has an extremely high penetration of renewable generation, and is therefore already dealing with frequency issues that will affect larger synchronous power systems in the future. The TSO (Transmission System Operator), Eirgrid, has created the DS3 program [4] to evaluate and develop new system tools, services and policies to manage frequency, among other future network challenges.

ESS have significant operational differences – primarily due to their limited energy capacity – when compared with conventional providers of FR services, such as open cycle gas turbines and pumped hydro storage; it is therefore necessary to design new services to realise the benefits of ESS in maintaining the system frequency. There are research questions arising from the way these services will be designed. In this paper, the following research questions are addressed through a combination of analysis of historical frequency data and experiments using Power Hardware-in-the-Loop (PHIL):

- How quickly can an ESS deliver power in response to a frequency event?
- Can an ESS effectively manage its SoC, therefore ensuring that sufficient energy is available to fulfil its service obligations?
- How does the delivery threshold (deviation from the nominal frequency at which the ESS must respond) affects the service performance, from the perspective of ESS operators and the TSO?
- To what extent can ESS reduce the impact of severe frequency events? How is this power capacity and influenced by the delivery threshold?
- At what SoC should an ESS rest when not providing a service to ensure service delivery while maximising efficiency and minimising battery degradation?
- How can storage be combined with conventional FR providers? And how will new services influence investment in ESS?

The primary contribution of this paper is a methodolgy which can address these questions. The methodology was then used to provide answers for the UK case, and a world leading FR grid service, designed by National Grid, the GB TSO, explicitly for fulfilment by ESS. However, the methods presented here could be used to design frequency services for fulfilment by ESS in power systems throughout the world.

The remainder of this paper is structured as follows: Section 2 contains a review of previous research in which ESS are used for frequency regulation, and a description of a new Enhanced Frequency Response service. Section 3 contains statistical analysis of historical frequency data. In Section 4, new experimental methods are described, which have been devised for evaluating FR services designed for fulfilment by ESS; in Section 5, results and analysis are presented from the GB case study; detailed discussion and suggested avenues for future research are provided in Section 6; finally, conclusions and suggest avenues for future research are explored in Section 7.

2. Background

2.1. Frequency response and energy storage systems

There have been a number of previous studies into the use of ESS to provide FR; the aims, methods, and findings of these studies are summarized in this section. Authors have used modelling approaches ranging from simple transfer functions and integrators [5,6], through to equivalent circuit models [7], and models which attempt to predict system lifetime and battery degradation [7,8].

A variety of ESS technologies have also been evaluated. While lithium ion batteries are the most commonly used storage medium [5,6,9], other modelled technologies include alternative lithium batteries [7], lead-acid, Ni-Cad, NMH, and vanadium redox flow batteries, flywheels [10], super capacitors [9], and superconducting magnets [11]. While there are advantages and disadvantages to each technology, these were all able to provide sufficiently fast responses to provide FR. It is possible that a combination of ESS technologies, or a hybrid of ESS and a conventional or renewable generator, could provide the best compromise; various authors have adopted this approach using virtual power plant techniques [6,7,12].

Although the focus of this paper is regulating the frequency of a large, interconnected transmission system, research on smaller, islanded systems is also relevant. These systems typically have more variable demand and lower inertia than centralized power systems, meaning frequency control is critical. This type of system has also been studied extensively, using a variety of control systems and technologies [9,11,13]. The control approach has been a focus of various studies, including the use of droop control [9,14], control accounting for battery degradation [5,8], and coordinated control between a number of smaller ESS [15,16] or electric vehicles (EVs) [17,18].