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Benefits of using virtual energy storage system for power system frequency response ☆

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HIGHLIGHTS

- The VESS is proposed to facilitate the conversion to a low carbon power system.
- A VESS consisting of flexible demand and conventional FESS is firstly formulated.
- The VESS is controlled to provide fast firm amount of dynamic frequency response.
- The VESS provides frequency response at a lower cost compared with only using FESS.
- The VESS reduces the costly spinning reserve capacity from fossil-fuel generators.

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ABSTRACT

This paper forms a Virtual Energy Storage System (VESS) and validates that VESS is an innovative and cost-effective way to provide the function of conventional Energy Storage Systems (ESSs) through the utilization of the present network assets represented by the flexible demand. The VESS is a solution to convert to a low carbon power system and in this paper, is modelled to store and release energy in response to regulation signals by coordinating the Demand Response (DR) from domestic refrigerators in a city and the response from conventional Flywheel Energy Storage Systems (FESSs). The coordination aims to mitigate the impact of uncertainties of DR and to reduce the capacity of the costly FESS. The VESS is integrated with the power system to provide the frequency response service, which contributes to the reduction of carbon emissions through the replacement of spinning reserve capacity of fossil-fuel generators. Case studies were carried out to validate and quantify the capability of VESS to vary the stored energy in response to grid frequency. Economic benefits of using VESS for frequency response services were estimated.

1. Introduction

The power system is rapidly integrating smart grid technologies to move towards an energy efficient future with lower carbon emissions. The increasing integration of Renewable Energy Sources (RES), such as the photovoltaic and the wind, causes uncertainties in electricity supply which are usually uncontrollable. Hence, it is even more challenging to meet the power system demand. More reserve from partly-loaded fossil-fuel generators, which are costly and exacerbate the carbon emissions, is consequently required in order to maintain the balance between the supply and demand.

The grid frequency indicates the real-time balance between generation and demand and is required to be maintained at around 50 Hz (for the Great Britain (GB) power system). The integration of RES through power electronics reduces the system inertia. A low inertia power system will encounter faster and more severe frequency deviations in cases of sudden changes in supply or demand [1]. Therefore, the system operator is imperative to seek for smart grid technologies that can provide faster response to frequency changes.

The Energy Storage System (ESS) is one solution to facilitate the integration of RES by storing or releasing energy immediately in response to the system needs. A large-scale ESS is able to replace the spinning reserve capacity of conventional generators and hence reduces the carbon emissions. There are different types of ESS for different applications as shown in Fig. 1 [2]. In terms of the forms of ESS, ESS is classified as electrochemical, mechanical, electrical and thermal energy storage. In terms of the functions of ESS, ESS

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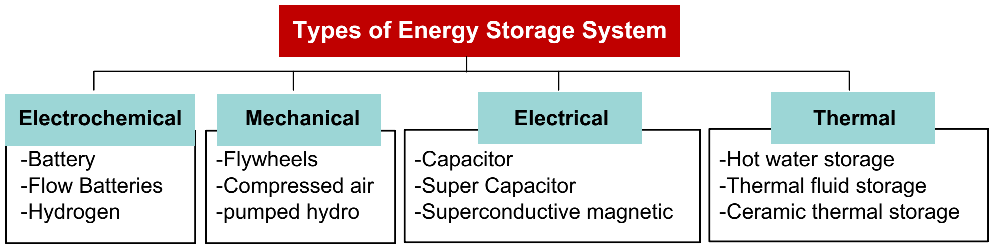

Fig. 1. Types of energy storage system [2].

is classified as high power rating ESS (e.g. flywheels, super capacity and conventional batteries) for power management applications and high energy rating ESS (e.g. compressed air and pumped hydro) for energy management applications [3].

The use of ESS for grid frequency regulation can be dated back to the 1980s [4,5], e.g. the Beacon Power Corporation has already implemented flywheels to provide fast frequency regulation services [6].

However, ESS remains to be an expensive technology although there are declinations in the cost in recent years. For instance, the cost of installing a 20 MW/10 MW h Flywheel Energy Storage Systems (FESS) is approx. £25 m–£28 m [7]. The large-scale deployment of ESS is still not feasible in a short term.

Aggregated Demand Response (DR) can resemble a Virtual Energy Storage System (VESS) because DR can provide functions similar to charging/discharging an ESS by intelligently managing the power and energy consumption of loads. By well-utilizing the existing network assets, i.e. the flexible demand such as the domestic fridge-freezers, wet appliances and industrial heating loads, DR can be deployed at scale with a lower cost compared with the installation of the ESS.

The control of demand to provide frequency support to the power system has been studied including both centralised and decentralised control. Centralised control of the flexible demand relies on the Information and Communications Technology (ICT) infrastructure to establish communications between the flexible demand and its centralised controller, such as an aggregator or Distributed Network Operator (DNO) [8]. To reduce the communication costs and latency, decentralised demand control has also been investigated. The controller in [9] regulates the temperature set-points of refrigerators to vary in line with the frequency deviations and therefore controls the refrigerator's power consumption. A dynamic decentralised controller was developed in [10] which changes the aggregated power consumption of refrigerators in linear with the frequency changes. The controller aims not to undermine the primary cold storage functions of refrigerators and the impact of the grid-scale DR on the grid frequency control was investigated.

Considering the availability of refrigerators to provide frequency response depicted by [11], it is estimated that 20 MW of response requires approx. 1.5 million refrigerators. The total cost is approx. £3 m [9]. This is far smaller than the cost of FESS (approx. £25 m–£28 m [7]) that also provides the 20 MW of response. It is estimated in [7] that DR has the potential to reduce the ESS market size by 50% in 2030.

However, the challenges of DR include the uncertainty of the response and the consequent reduction in the diversity amongst loads [11]. Simultaneous connection of loads may occur in several minutes after the provision of response to a severe drop in the frequency, which causes another frequency drop and hence challenges the system stability.

A number of studies have been conducted to investigate the capability of ESS or DR to provide frequency response to the power system. However, the combination of both technologies for grid frequency response while mitigating the impact of uncertainties of DR and reducing the capacity of the costly ESSs has not yet been fully explored. Therefore, in this research, a VESS is firstly formulated by coordinating large numbers of distributed entities of ESS and DR. The coordination of both technologies aims to provide fast and reliable firm amount of dynamic frequency response with a lower cost compared to conventional ESSs. Moreover, the idea of merging both technologies into a single operation profile is defined and the benefits of operating a VESS for the delivery of frequency response service is analysed.

In this paper, a VESS is formed as a single entity to provide the function of ESS for the delivery of frequency response in the power system. In Section 2, the concept and potential application of VESS is discussed. A VESS consisting of DR from domestic refrigerators in a large city and the response from small-size FESSs is modelled and controlled. The proposed control of VESS maintains the load diversity and the primary functions of cold storage of refrigerators while reducing the number of charging and discharging of each FESS and prolonging the lifetime of the costly FESS. Case studies were carried out in Section 3 to quantify the capability of VESS for frequency response. The results of using the VESS and the conventional FESS for frequency response were compared in Section 4. Discussions and the potential economic benefits of using VESS to participate in the GB frequency response market were also discussed.

2. Virtual energy storage system

2.1. Concept

A Virtual Energy Storage System (VESS) aggregates various controllable components of energy systems, which include conventional energy storage systems, flexible loads, distributed generators, Microgrids, local DC networks and multi-vector energy systems. Through the coordination of each unit, a VESS is formed as a single high capacity ESS with reasonable capital costs. It is integrated with power network operation and is able to vary its energy exchange with the power grid in response to external signals. A VESS allows the flexible loads, small-capacity ESS, distributed RES, etc. to get access to the wholesale market and to provide both transmission and distribution level services to the power system.

Different from the Virtual Power Plant (VPP) that aggregates distributed energy resources to act as a single power plant, VESS aims to store the surplus electricity or release the electricity according to system needs.

2.2. Potential applications

A VESS is able to form a synthetic ESS at both transmission and distribution levels with different capacities as a result of the aggregation. In the project "hybrid urban energy storage" [12], different distributed energy systems in buildings (e.g. heat pumps or combined heat and power systems (CHPs)), central and decentral