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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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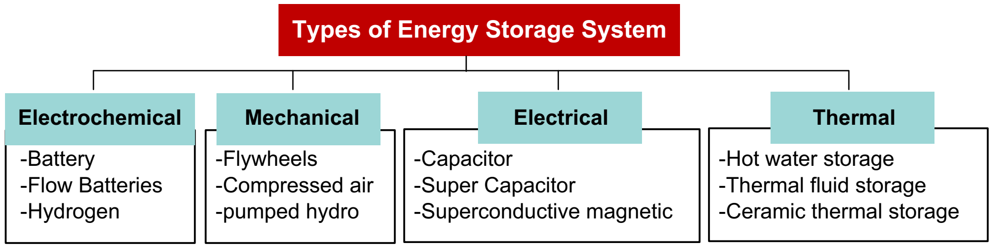

Fig. 1. Types of energy storage system [2].

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 energy storage systems are coordinated to create a Virtual Energy Storage System (VESS). The resources utilise the existing potentials of energy balancing components in cities for grid ancillary services with reduced costs. A VESS therefore presents the characteristics of both high power rating ESS and high energy rating ESS, and hence covers a wide spectrum of applications. The potential capabilities of VESS are listed below based on [13]:

- Facilitate the integration of RES in the distribution networks

A VESS can charge/discharge to smooth the power output variations of renewable generation [14,15]. Additionally, it can increase the distribution network hosting capacity for RES [16], where the integration of RES is limited by the voltage and thermal constraints [17].

- Defer transmission networks reinforcements

A VESS can increase the utilization of transmission networks by providing immediate actions following a system contingency [18,2]. Additionally, a VESS can effectively mitigate the potential network congestions, and therefore postpones the transmission reinforcements.

- Reduce generation margins

A VESS can reduce the required spinning reserve capacity and increase the generators loading capacity [18]. With smart grid technologies, the available VESS capacity can be reported to the system operator in advance and even every second [19,20].

- Provide ancillary services

During system contingencies and system emergencies [21], a VESS can provide voltage support and frequency support. In addition, primary frequency response requirements which are at present mainly met by the costly frequency-sensitive generation is expected to increase by 30–40% in the next 5 years in the GB power system [13]. A VESS is technically feasible to provide such services because it is able to provide faster response, higher ramp rates and higher flexibilities than the conventional generating units [22].

2.3. Model and control of VESS

A VESS is formed to firmly provide the required amount of frequency response to the power system in order to participate in the GB Firm Frequency Response (FFR) market as an aggregator. The FFR market is considered as the most lucrative ancillary services available on the MW basis [23] in the GB power system.

DR from domestic refrigerators in a city is implemented to meet the required amount of frequency response while the conventional FESS is used to compensate for the uncertainties caused by the DR. Other units with similar characteristics and capability of storing energy, such as EVs [22] or other ESS types, can be added further to increase the total VESS capacity.

2.3.1. Model of FESS

FESS is a mechanical ESS with high power density. FESS is essentially an electrical machine coupled with a high inertia flywheel and is connected to the grid through back-to-back converters. The electromechanical equation of the electrical machine is:

$$J\frac{d\omega}{dt} = -T_{in} = -\frac{P_{elec}}{\omega} \tag{1}$$

where J is the moment of inertia of the electrical machine rotor plus the flywheel (kg m^2), ω (rad/s) is the rotating speed, T_{in} (N m) is the input torque of the flywheel and P_{elec} (W) is the electrical machine power that is controlled by converters.

A first-order lag is used to simplify the control of the power converters on a given reference power P_{ref_FESS} (W). T_{delay} (s) is the time constant of the power converter control loop:

$$P_{elec} = P_{ref\_FESS}\left(\frac{1}{1+sT_{delay}}\right) \tag{2}$$

A simplified model of FESS was developed as shown in Fig. 2. It has been validated with a detailed model which includes all the main components and control of converters [24,25]. The simplified model provided accurate results with a significant reduction in the computational time. The simplified model facilitates the system level studies considering large numbers of small-size distributed flywheels.

2.3.2. Model of domestic refrigerators

In order not to undermine the cold storage function of each refrigerator, a thermodynamic model of refrigerators was developed as illustrated in [11].

Fig. 3 shows the temperature control of refrigerators. The variation of internal temperature (T) of a refrigerator with time is modelled and dynamically compared with the temperature set-points T_{low} and T_{high}. If T rises to T_{high}, a refrigerator is switched on. When a refrigerator is at ON-state, it is equivalent to the charging of an energy storage unit which consumes power and causes the decrease of T. Alternatively if T decreases to T_{low}, a refrigerator is switched off. An OFF-state refrigerator is considered as a discharging process which causes the increase of T. In a refrigerator,

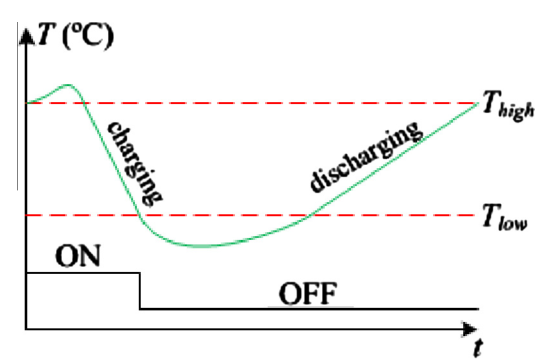

Fig. 3. Temperature control of On/Off state of refrigerators.

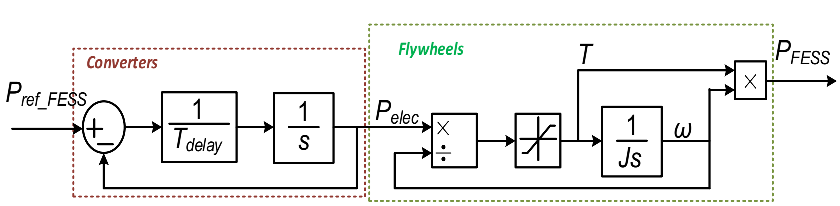

Fig. 2. Simplified model of FESS.

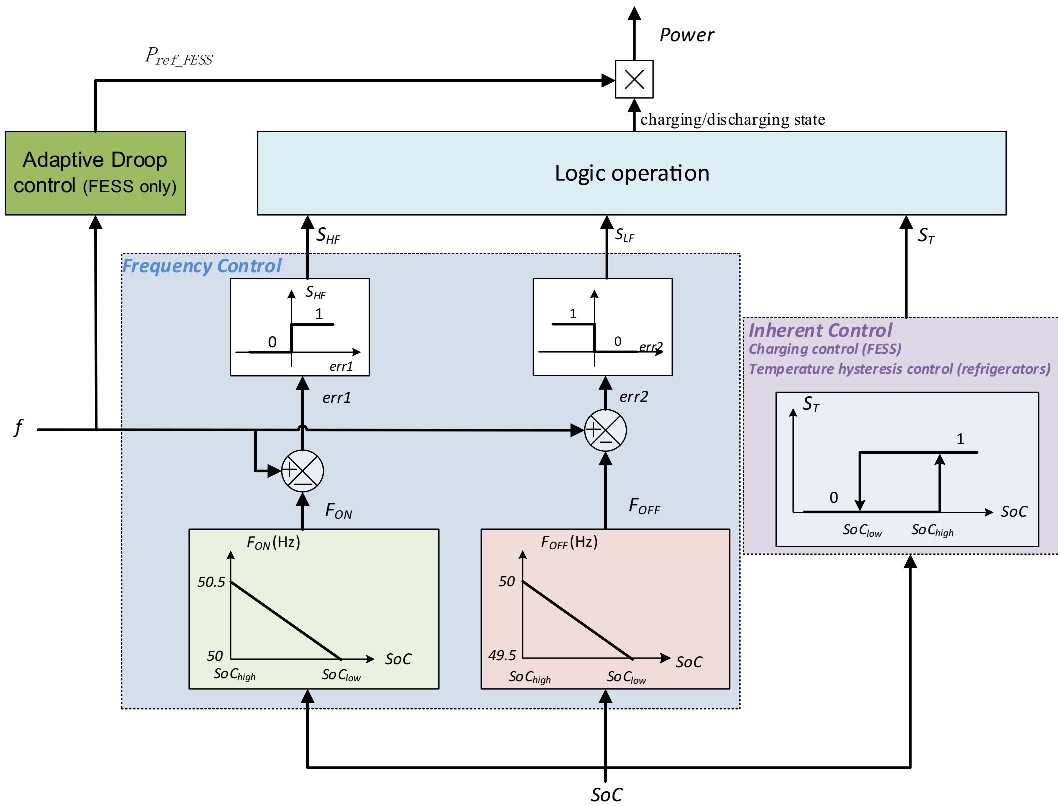

Fig. 4. Local controller of each unit in a VESS.

temperature inherently controls the charging and discharging process.

2.3.3. Distributed control in a VESS

A control algorithm is developed for the units in a VESS to charge/discharge in response to regulation signals. In this paper, grid frequency (f) is used as the regulation signal.

A general local controller that can be applied to both refrigerators and FESS is developed as shown in Fig. 4. The control measures f constantly. For an FESS, the output is the change of power output. For a refrigerator, the output is the change of On/Off state and hence the power consumption.

Each unit in the VESS is assigned a pair of frequency set-points, F_{ON} and F_{OFF}. The range of F_{ON} is 50–50.5 Hz and the range of F_{OFF} is 49.5–50 Hz which is consistent with the steady-state limits of grid frequency in the GB power system.

The input f constantly compares with the set-points F_{ON} and F_{OFF}. If f rises higher than F_{ON} of a unit, the unit will start charging/switch on as a result of the frequency rise. If f is higher than 50 Hz but lower than F_{ON}, the unit will standby.

Alternatively, if f drops lower than F_{OFF}, the unit will start discharging/switch off as a result of the frequency drop. If f is lower than 50 Hz but higher than F_{OFF}, the unit will standby.

F_{ON} and F_{OFF} vary linearly with the State of Charge (SoC) of each unit as shown in Fig. 4. For FESS, ω indicates SoC. A low ω designates a low SoC and vice versa. For refrigerators, T indicates SoC. A high T indicates a low SoC and vice versa. When f drops, the units in the VESS will start discharging from the one with the highest SoC. The more f drops, the more number of units will be committed to start discharging. Therefore, the more power will be discharged from FESS and the more power consumption of refrigerators will be reduced. Alternatively, when f rises, the units will start charging from the one with the lowest SoC. The more f rises, the more number of units will be committed to start charging. Therefore, the more power will be consumed by the refrigerators and the more power will charge the FESS. A set of logic gates ('Logic operation' in Fig. 4) is used to determine the final state of each unit.

The control considers a priority list based on SoC when committing the units. Compared with the conventional frequency control of FESS, in which all units will start charging/discharging simultaneously according to the frequency deviations using the droop control, the proposed control with a priority list of commitment will reduce the number of charging/discharging cycles and hence prolongs the lifetime of units.

However, when the frequency deviation is small, the proposed control based on the priority list will commit fewer FESS units (i.e. not all FESS units) to start charging/discharging according to frequency deviations using the droop control. The total power output from FESS is therefore smaller than that without the proposed control which commits all FESS units. To mitigate this impact and increase the output from FESS units even when the frequency deviation is small, an adaptive droop control is applied to replace the conventional droop control when determining the amount of power output changes of each committed FESS unit as shown in Fig. 4.

The adaptive droop control value ($R_{adaptive}$) is inversely proportional to frequency deviations as shown in (3). This is because a small frequency deviation (df) triggers only a small number of FESS units to commit. Therefore, a droop value $R_{adaptive}$ greater than the conventional droop value R is required in order to increase the change of power output. When the frequency deviation increases and reaches the frequency deviation limits (±0.5 Hz in the GB power system), all FESS units will be triggered to commit. The droop value $R_{adaptive}$ equals to R.

$$R_{adaptive} = \frac{df_{\max}}{df} \times R \tag{3}$$

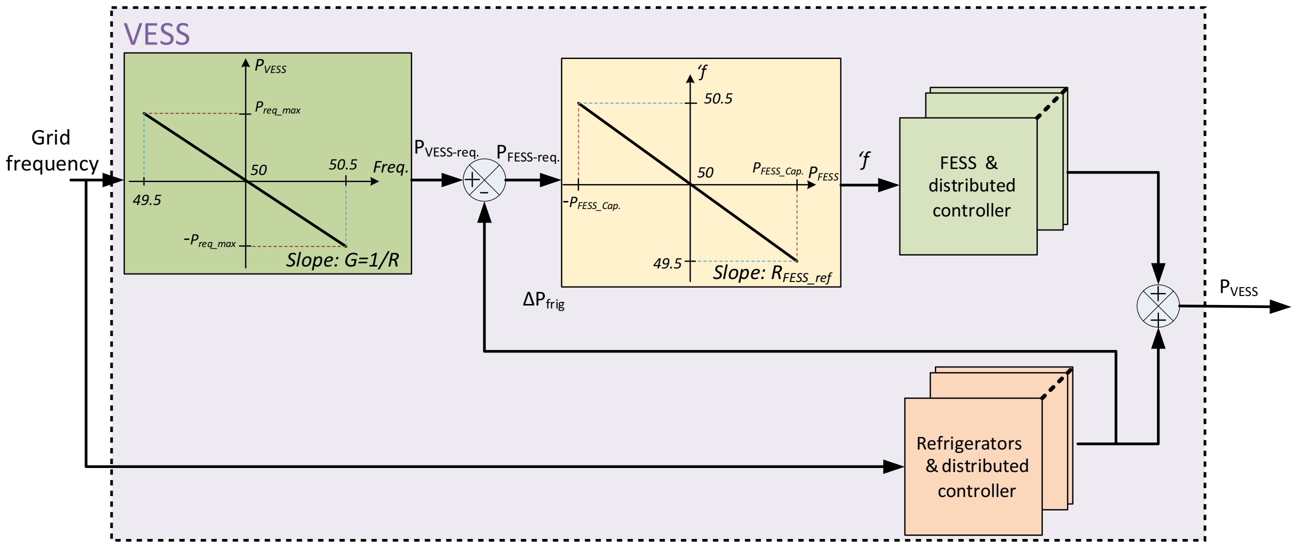

Fig. 5. Coordination of refrigerators and FESS in the VESS.

where $df_{\max}$ is the steady-state limit of grid frequency (0.5 Hz in the GB power system). R is the conventional droop value and is set to 1%. This indicates that a FESS will provide 100% power output change if frequency deviation is equal to or higher than 1% of the nominal frequency value.

It is to be noted that, the inherent control of each unit takes the priority in determining the final charging/discharging state. For refrigerators, the inherent control refers to the temperature control as illustrated in Fig. 3. For FESS, the inherent control is the charging control which limits the minimum and maximum rotating speed of each FESS.

In summary, the proposed control in Fig. 4 is a distributed control on each unit in a VESS, but it is coordinated amongst all units by assigning frequency set-points based on *SoC*. The proposed control ensures that the aggregated response from a population of units is in linear with frequency deviations. This is similar to the droop control of frequency-sensitive generators. Each unit in the VESS has equal opportunity to charge/discharge. The lifetime of units is hence prolonged. Specifically for refrigerators, the control does not undermine the cold storage and the impact of the reduction in load diversity is mitigated.

2.3.4. Coordination of refrigerators and FESS in a VESS

If a VESS tenders for the participation in the FFR market, the VESS is required to illustrate the firm capability of providing a constant amount of dynamic or non-dynamic frequency response (at least 10 MW in the GB power system) during a specific time window [26]. However, the high cost of ESS limits the grid-scale deployment. The uncertainty of DR makes it difficult to ensure the provision of a constant amount of response at all times. Therefore in a VESS, the coordination of FESS and DR aims to provide the capability of delivering a certain amount of frequency response at a lower cost.

In this study, a two-way communication network is assumed to be available for the centralized VESS controller. The communication can be established through the Internet network protocols [27], smart meter infrastructure or other smart grid technologies [28,29] in the near future.

In the coordination, the VESS tenders for the provision of dynamic FFR. The maximum response is constantly fixed (determined by the total installed capacity of units in a VESS) when the frequency changes outside the limits, i.e. ±0.5 Hz. Within the frequency limits, the response varies dynamically with frequency deviations.

Therefore, the amount of frequency response of VESS (P_{VESS_req} (MW) in Fig. 5) is determined by the grid frequency through the droop control with the value of 1% as shown in Fig. 5. The distributed controller of refrigerators responds to the grid frequency f through the distributed controller (depicted in Fig. 4). While the distributed controller of FESS units responds to the power mismatch ($P_{FESS\text{-}req.}$ (MW) in Fig. 5) between the required frequency response P_{VESS_req} and the aggregated response of refrigerators (ΔP_{frig} (MW) in Fig. 5) in order to compensate for the uncertain response of refrigerators. This power mismatch $P_{FESS\text{-}req.}$ is converted to a modified frequency value f' (Hz) through the droop setting R_{FESS_ref} in (4). The distributed controller of FESS (Fig. 4) then responds to the modified frequency f' rather than the grid frequency f'

$$R_{FESS\_ref} = \frac{df_{\max}}{P_{FESS\_capacity}} \tag{4}$$

where $P_{FESS\_capacity}$ (MW) is the total capacity of FESS, $df_{\max}$ is the steady-state limit of grid frequency (0.5 Hz in the GB power system). f' is hence obtained by (5):

$$f' = R_{FESS\_ref} \times P_{FESS\_req} \tag{5}$$

3. Case studies

The performance of the model and control of VESS for the provision of frequency response service is evaluated by a series of simulations. The design of the case study is illustrated below.

There are 3,220,300 households in London in 2014 [30]. It is assumed that the refrigerator (0.1 kW) in each household is equipped with the frequency controller in Section 2.3.3. The amount of frequency response from refrigerators is estimated considering the time of day as shown in Fig. 6 [11]. A maximum reduction in power consumption (‘red[1] line’) is 18.5% at 18:00 and a minimum reduction is 13.2% at 6:00. Considering the number of refrigerators in London, a maximum power reduction of 60 MW and a minimum power reduction of 40 MW is expected. Similarly, an availability of refrigerators to be switched on is approx. 50–56% which expects a minimum power increase of approx. 160 MW and a maximum power increase of approx. 180 MW from all refrigera-

[1] For interpretation of color in Fig. 6, the reader is referred to the web version of this article.

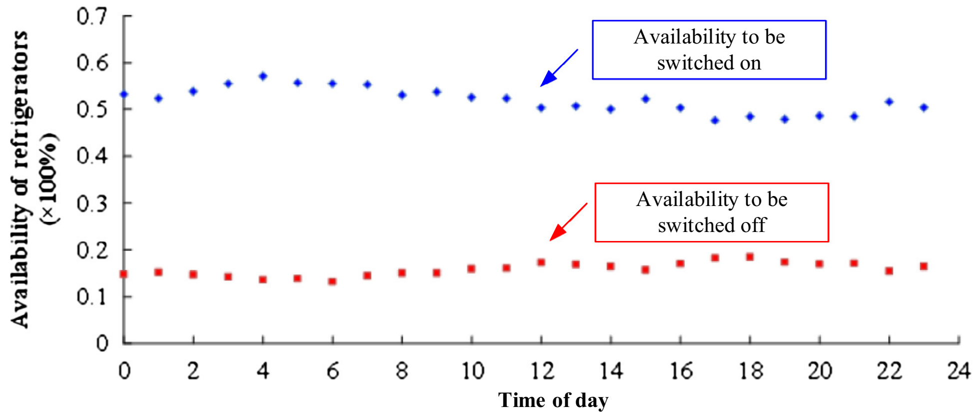

Fig. 6. Availability of refrigerators to be switched on and off over a day based on field measurements [11].

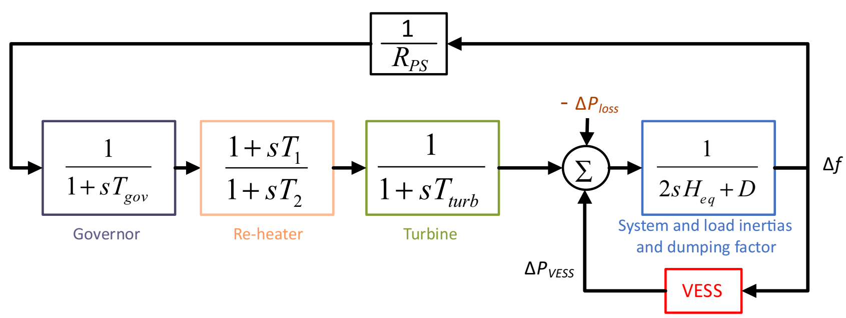

Fig. 7. Simplified GB power system.

tors. This reveals that refrigerators have more potential to provide response to the frequency rise than to the frequency drop.

Therefore, the VESS is planned to provide a linear dynamic frequency response of a maximum of 60 MW (P_{req}) to the power system when frequency drops outside the limit (49.5 Hz) and of 180 MW when frequency rises outside the limit (50.5 Hz) over a day. For periods of the day that refrigerators cannot provide the required response, FESS is used to compensate for the mismatch between P_{req} and ΔP_r. Because the maximum mismatch is 20 MW, 400 FESS (50 kW/30 kW h) are used in the VESS.

The VESS is connected to a simplified GB power system model (see Fig. 7) [31] to assess the VESS capability to provide low frequency response and high frequency response to the power system. In the GB power system model (Fig. 7), the synchronous power plants (coal, gas, hydro, etc.) characteristics are modelled as governor, actuator and turbine transfer functions [32]. The system inertia is represented by H_{eq} and the damping effect of frequency-sensitive loads was represented by a damping factor (D) [32,33]. The flow of active and reactive power in transmission networks are assumed independent and only the active power is considered.

The time constants of the governor, re-heater, turbine, and the load damping constant were set to: T_{gov} = 0.2 s, T_1 = 2 s, T_2 = 12 s, T_{turb} = 0.3 s and D = 1.

Based on [34], the system inertia was estimated to be 4.5 s and the equivalent system droop (R_{PS}) was 9%. The parameters of the model were calibrated with a real frequency record following a 1220 MW loss of generation on the GB power system [35].

Three case studies were carried out: **Case 1** – low frequency response, **Case 2** – high frequency response and **Case 3** – continuous frequency response. Case 1 and Case 2 were undertaken on the simplified GB power system model. The system demand was 20 GW representing a summer night and the following three scenarios were compared.

Scenario 1: S1 ('No ESS/VESS'): assumes that there is no ESS or VESS connected to the power system.

Scenario 2: S2 ('ESS'): connects 1200 FESS units each of 50 kW/30 kW h to the GB power system and tenders for the provision of 60 MW of frequency response. This case uses only conventional ESS.

Scenario 3: S3 ('VESS'): connects the VESS model including all refrigerators in London and 400 FESS units (50 kW/30 kW h) to the GB power system and tenders for the provision of 60 MW of frequency response. The FESS provides a maximum of 20 MW of response to the mismatch between P_{req} and ΔP_r.

In Case 3, the behaviour of VESS in the provision of continuous frequency response is studied.

4. Results and discussions

4.1. Case 1: low frequency response

The VESS is procured to provide a proportional low frequency response of a maximum of 60 MW. Simulations were carried out by applying a loss of generation of 1.8 GW to the GB power system. This case simulates the discharging phase of the VESS. Results are shown in Figs. 8–10.

The frequency drop in Fig. 8 is reduced with 60 MW of response (see Fig. 9a)) from either ESS (S2) or VESS (S3). Since 60 MW of response is small in a 20 GW system, the improvements of frequency is approx. 0.01 Hz and seems hardly noticeable. If the

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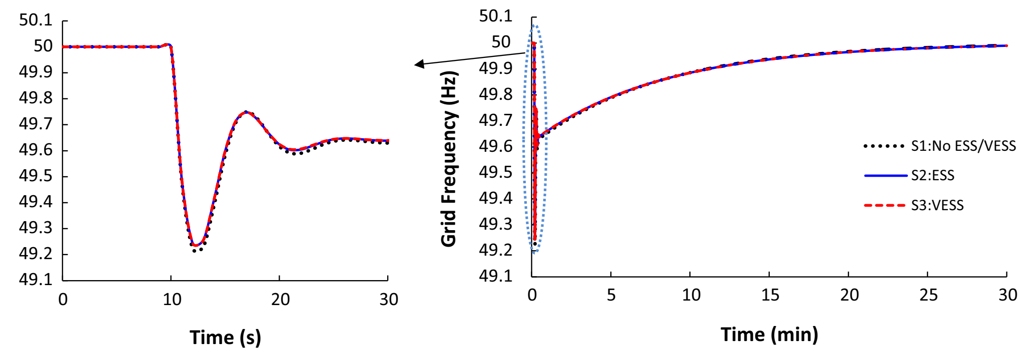

Fig. 8. Variation of grid frequency after the loss of generation.

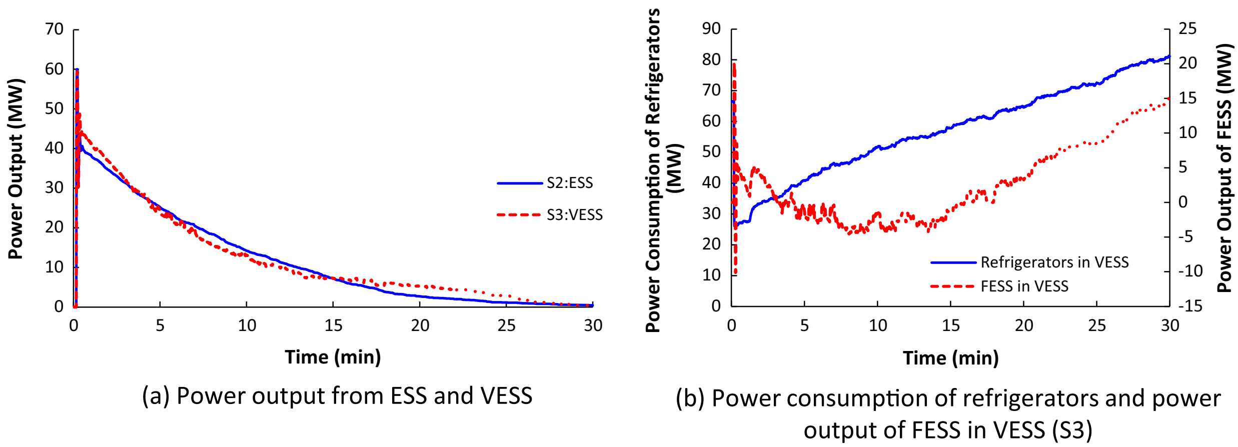

Fig. 9. (a) Change in power output of VESS, ESS; (b) change of power consumption of refrigerators and FESS power output in the VESS.

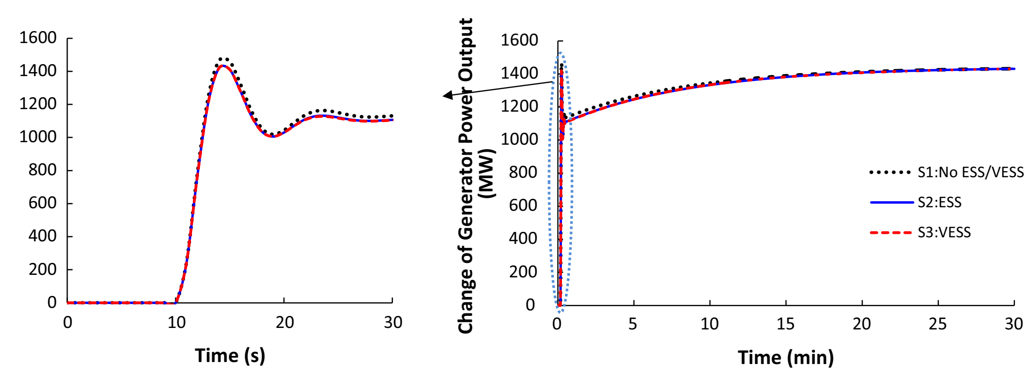

Fig. 10. Change of power output of generators after the loss of generation.

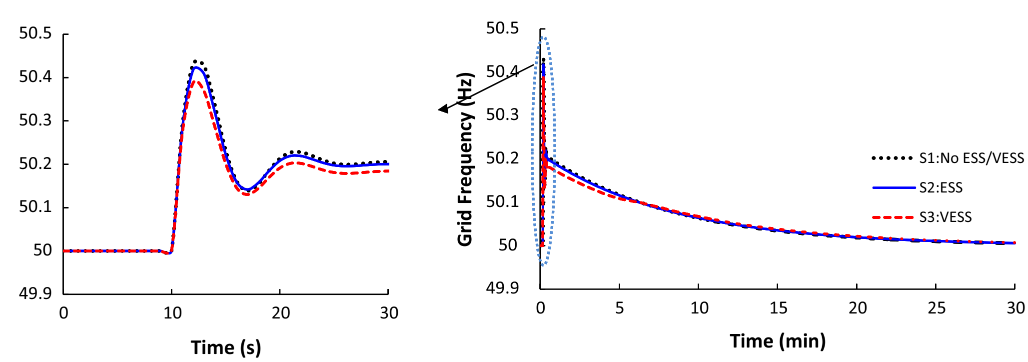

Fig. 11. Variation of grid frequency after the loss of demand.

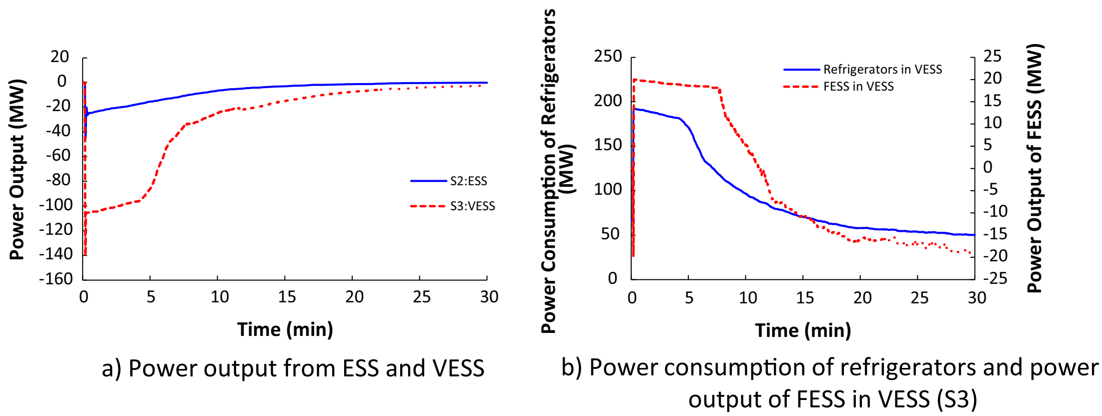

Fig. 12. Change in power output of (a) VESS, ESS, (b) in VESS power consumption of refrigerators and FESS power output in VESS.

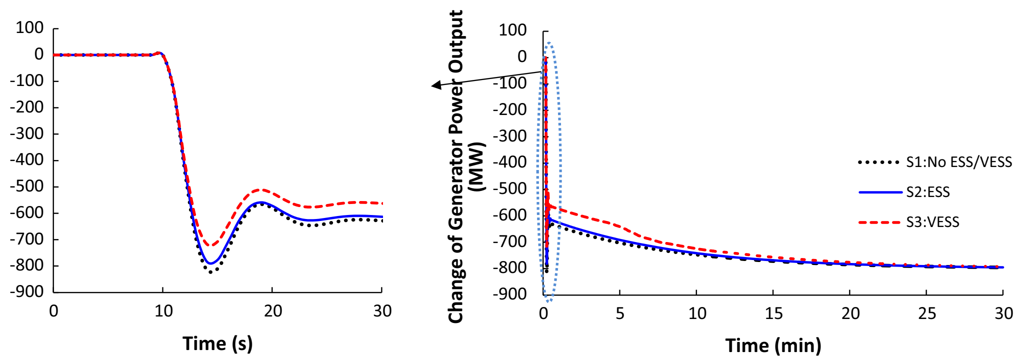

Fig. 13. VESS and ESS power output comparison.

installed capacity of units in the VESS is higher, the frequency drop will be significantly reduced. The number of FESS in the VESS (S3) was only one third of that in S2, however, VESS provided similar amount of frequency response to that of ESS in S2. The reduced capacity of FESS in S3 will reduce the cost significantly compared to S2.

Fig. 10 shows the change of power output of generators in the three scenarios. It can be seen, with ESS (S2) or VESS (S3), the required capacity of the costly frequency-responsive generators is reduced.

4.2. Case 2: high frequency response

The VESS is acquired to provide a maximum of 180 MW of high frequency response to the power system over a day when frequency rise outside the limit (50.5 Hz). A sudden loss of demand of 1 GW was applied to the GB power system. This case depicts the charging phase of the VESS. Results are shown in Figs. 11–13.

In Figs. 11 and 12, ESS in S2 provides approx. 45 MW of response (see Fig. 12a)) from the 1200 FESS and the maximum frequency rise is slightly reduced by 0.01 Hz compared with s1. However, the VESS in S3 provides approx. 140 MW after the sudden loss of demand which is much higher than the response of ESS in S2 and the frequency rise is reduced by 0.05 Hz. In Fig. 12b, following the sudden loss of demand, the power consumption of refrigerators is increased by approx. 120 MW from 66 MW to 186 MW while the power output of FESS in S3 is 20 MW (charging). By the response from both VESS and generators, the frequency is recovered to 50.2 Hz almost immediately. As a number of refrigerators were switched on following the frequency rise, their temperature started to drop. It took several minutes before the temperature reached the low set-point and refrigerators started to switch off. Therefore, FESS start discharging following the frequency recovery. Because of the limitation of the capacity of FESS (20 MW), the total response was not in linear with the frequency recovery. However, the VESS in S3 provides much more response following the frequency rise than that of ESS in S2. This is specifically critical for the future power system with a low inertia.

Fig. 13 also depicts that both ESS and VESS are able to reduce the required capacity of spinning reserve of frequency-responsive generators. The VESS in S3 shows a greater reduction compared with the ESS in S2.

4.3. Case 3: continuous frequency regulation

The VESS is applied to provide continuous frequency response in proportion to frequency changes. The VESS have maximum charging power of 60 MW when grid frequency drops to 49.5 Hz and maximum discharging power of 180 MW when grid frequency increases to 50.5 Hz. Simulations were implemented by injecting a profile recording the GB power system frequency into the VESS [36]. The behaviour of the VESS in response to the continuous fluctuations of frequency is shown in Fig. 14.

It can be seen, the power output of VESS dynamically changes following the frequency deviations. Because refrigerators have greater capability to be switched on, the VESS is able to provide greater high frequency response than low frequency response as depicted by Fig. 14.

4.4. Benefits of VESS

The VESS coordinates different types of distributed energy resources, such as ESS, flexible loads and DGs, in order to facilitate the connection of intermittent generation and also to provide

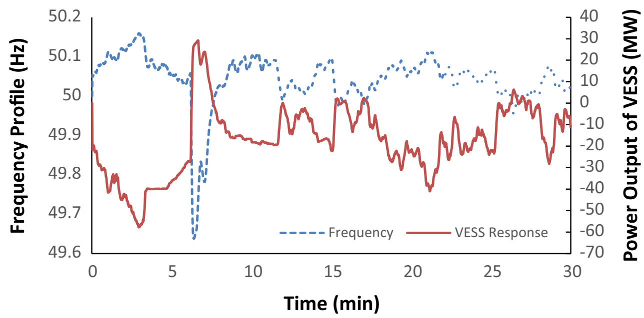

Fig. 14. Variation in grid frequency and VESS response.

services to network operators, energy suppliers and service aggregators. Therefore, the benefits of using VESS for different services can be massive. In this paper, the benefit of VESS for the provision of frequency response service is briefly estimated as an example.

The investment costs of FESS in S2 and of VESS in S3 were roughly estimated first. It is assumed that the lifetime of FESS is approx. 20 years and the lifetime of refrigerators is 13 years [37]. Considering a timescale of 20 years and using the investment costs shown in Table 1, the investment cost of FESS in S2 providing 60 MW of response is estimated to be approx. **£75m–£84m** [7]. The investment cost of VESS in S3 providing 60 MW includes the cost of installing controllers on 3,220,300 refrigerators which is approx. £9.66 m [9] for 13 years and therefore will be approx. £14.86 m for 20 years (see Table 1). In addition, the cost of FESS in the VESS providing 20 MW of response is approx. £25 m–£28 m. Therefore, the investment cost of VESS in S3 is approx. **£39.8m–£42.8m** which is less costly compared with the cost of ESS in S2. However, establishing the VESS communications was not considered in the VESS total investment costs.

The economic incomes of using ESS and VESS for frequency response services are calculated based on the present regulation of the GB frequency response market. The payment of participating in the FFR service [38,39] consists of the availability fee per day and the utilization fee per day. The availability fee (£/MW h) is the payment to the service provider to make a certain amount of response service available for the tendered hours of a day. The utilization fee (£/MW h) is the payment to the service provider for the utilization volume during the tendered hours of a day. The utilization volume is the amount of response that has been delivered to the system and it depends on the system frequency changes. Table 2 provided the unit price of the availability fee and the utilization fee. The payments of both ESS in S2 and VESS in S3 are therefore calculated by (6) for the availability fee and by (7) for the utilization fee.

$$\begin{aligned} Availablity\_fee = {} & MW_{primary} \times t_{primary\_utilization} \\ & \times availability\_unit\_price_{primary} \\ & + MW_{secondary} \times t_{secondary\_utilization} \\ & \times Availability\_unit\_price_{secondary} \\ & + MW_{high} \times t_{high\_utilization} \times Availability\_unit\_price_{high} \end{aligned} \tag{6}$$

$$\begin{aligned} Utilization\_fee = {} & MW_{primary} \times t_{primary\_utilization} \times Utilization\_unit\_price_{primary} \\ & + MW_{secondary} \times t_{secondary\_utilization} \\ & \times Utilization\_unit\_price_{secondary} \\ & + MW_{high} \times t_{high\_utilization} \times Utilization\_unit\_price_{high} \end{aligned} \tag{7}$$

where the meaning and value of all parameters are listed in Table 2. Based on (6) and (7), the income of ESS in S2 providing 60 MW of primary, secondary and high response is £29.168 k/day. For 20-year timescale, the total income is hence **£213m**. The income of VESS in S3 providing 60 MW of primary and secondary response and 180 MW of high response is £43.946 k/day. For 20-year timescale, the total income is **£321m** which is greater than the ESS because the VESS is able to provide much more high frequency response. Therefore, it is predicted that VESS will achieve more economic benefits in the long term.

5. Conclusions

A VESS is formed by coordinating the DR of domestic refrigerators and the response of FESS in order to provide functions similar

Table 1
Investment costs for different scenarios.

Scenario	VESS unit	Unit price	Capacity or no. of units	Total investment cost for 20 years	
S2	FESS	£1.25 m–£1.4 m/MW [7]	60 MW	**£75m–£84m**	
S3	FESS Refrigerator's controller	£1.25 m–£1.4 m/MW [7] £3 [9]	20 MW 3,220,300	**£25m–£28m** • £9.66 m for 13 years lifetime • **£14.86m** for 20 years lifetime (£9.66 m × 20 year/13 year)	**£39.8m–£42.8m**

Table 2
Parameters and values of calculating the income of providing frequency response services in the GB power system.

Parameters	Meaning	Value	Unit
$MW_{primary}$	Amount of primary response	60	MW
$MW_{secondary}$	Amount of secondary response	60	MW
MW_{high}	Amount of high response	60 (ESS) or 180 (VESS)	MW
$t_{primary\_utilization}$	Nominated hours of primary response per day	15.97	h
$t_{secondary\_utilization}$	Nominated hours of secondary response per day	11.53	h
$t_{high\_utilization}$	Nominated hours of high response per day	18.66	h
Availability unit price$_{primary}$	Unit price of available primary response per day	8.7791	£/MW h
Availability unit price$_{secondary}$	Unit price of available secondary response per day	8.7791	£/MW h
Availability unit price$_{high}$	Unit price of available high response per day	4.3896	£/MW h
Utilization unit price$_{primary}$	Unit price of utilized primary response per day	4.4204	£/MW h
Utilization unit price$_{secondary}$	Unit price of utilized secondary response per day	4.4204	£/MW h
Utilization unit price$_{high}$	Unit price of utilized high response per day	2.2102	£/MW h

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to conventional ESS with higher capacity and lower costs. The model and control algorithm of the VESS were developed. Amongst the population of distributed units in the VESS, the control is coordinated in order to provide an aggregated response which varies in linear with the regulation signals. The control minimizes the charging/discharging cycles of each unit and hence prolongs the lifetime of each unit. The control also maintains the primary function of loads and mitigates the impact of the reduction in load diversity amongst the population. Case studies were undertaken to evaluate the capability of VESS to provide the frequency response service by connecting the VESS model to a simplified GB power system model. Simulation results showed that VESS is able to provide low, high and continuous frequency response in a manner similar to the conventional ESS. The economic benefits of using ESS and VESS were compared considering the timescale of 20 years. Compared with the case that only uses ESS, VESS is estimated to obtain higher profits.

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