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Virtual Energy Storage System for Smart Grids

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Abstract

This paper forms a Virtual Energy Storage System (VESS) and validates that VESS is a cost-effective way to provide the function of energy storage through the utilization of the present network assets represented by flexible demand. As a solution to convert to low carbon cities, a VESS is firstly modelled to store and release energy in response to regulation signals by coordinating the demand response (DR) from domestic refrigerators in London and the conventional flywheel energy storage systems (FESS). The coordination of DR and FESS mitigates the uncertainties of DR and reduces the capacity of costly FESS. The VESS is applied to provide ancillary services to the power system and contributes to the reduction of carbon emission through the replacement of spinning reserve capacity of fossil fuel generators. Case studies were carried out to validate and quantify the capability of the VESS to vary the stored energy in response to grid frequency. Economic benefits of using VESS for frequency response services were firstly estimated and a potential saving of £91m-£103m is expected.

Peer-review under responsibility of the organizing committee of CUE 2015

Keywords: Virtual energy storage system, Low carbon cities, Smart grids

Nomenclature

Abbreviation

DR	Demand Response
ESS	Energy Storage system
FESS	Flywheel Energy Storage System
RES	Renewable Energy Source
VESS	Virtual Energy Storage System

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1. Introduction

Cities are 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. It is therefore more challengeable to meet the power system demand. More reserve is required from partly-loaded fossil-fuel generators which are usually costly and exacerbate the carbon emissions.

In addition, the integration of RES through power electronics reduces the system inertia. Frequency indicates the balance between generation and demand. A low inertia power system will encounter more severe frequency stability issues in cases of sudden changes in supply or demand [1]. Therefore, faster response to frequency changes is required.

Energy Storage System (ESS) is one solution to facilitate the integration of RES by immediately varying the stored energy. In terms of the functions of ESS, ESS is classified as high power rating for power quality applications and high energy rating for energy management applications. In terms of the forms of ESS, ESS is classified as mechanical, chemical, electrical and thermal categories [2]-[3].

However, ESS remains to be an expensive technology although in recent there is declination in the cost. For instance, the cost of installing a 20MW/10MWh Flywheel Energy Storage Systems (FESS) is approx. £25m-£28m [4].

Aggregated Demand Response (DR) can act as virtual energy storage because DR can provide functions similar to the energy storage by intelligently managing the power and energy consumption of loads. By utilizing the existing network assets, DR can be deployed at scale with lower cost. A cost of £1.97/household/year of using domestic refrigerators and freezers for frequency response is shown in [5] based on the 2013 GB electricity market rates. Considering the availability of refrigerators to provide frequency response [6], it is estimated that 20 MW of response requires approx. 1.5m refrigerators. Therefore, the total cost of 20 MW of DR is 3m. This is far smaller than the cost of FESS (approx. £25m-£28m [4]) to also provide the 20 MW of response. It is estimated in [4] 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 [6]. Simultaneous connection of loads may occur in several minutes after the provision of response to a frequency drop. This will worsen the system stability.

In this paper, a VESS is formed as a single entity to provide functions of energy storage. The VESS utilizes the capacity of DR to reduce the capacity of costly ESS whilst reducing the impact of DR's uncertainties. A VESS consisting of DR from domestic refrigerators in London and of FESS is modelled and controlled. The proposed control of VESS maintains the load diversity and the primary functions of cold storage of refrigerators, and reduces the number of charging and discharging of each FESS. Case studies were carried out to quantify the capability of VESS for frequency response services and to compare the capability of VESS with FESS. The potential economic benefit is also estimated.

2. Virtual Energy Storage System

2.1. Concept

A VESS aggregates a cluster of flexible loads, ESS and can also extracts energy from Distributed Generators via smart grid technologies. Through the coordination of each unit, a VESS acts as a single high capacity ESS with lower capital costs.

A VESS allows the small-capacity ESS, flexible loads and distributed energy resources to get access to the wholesale market and to provide transmission level services to the power system. Because VESS forms a synthetic ESS at the transmission/distribution level through the aggregation, the high power and high energy ratings of the VESS makes it suitable for a wide spectrum of applications including the maintenance of power quality, power system stability and protection, energy management and the mitigation of network reinforcements.

Compared to the Virtual Power Plant concept that aggregates DGs to act as a single power plant, VESS aims to store surplus electricity or release electricity according to system needs.

2.2. VESS model and control

A VESS model is formed to provide a required amount of frequency response (similar to an ESS) to the power system in order to participate in the GB frequency response market as an aggregator. DR of domestic refrigerators in a city is implemented and conventional FESS is used to compensate for the uncertainties caused by DR. Other units with similar characteristics can be added further to increase the total energy storage capacity.

2.2.1. Model of FESS

FESS is a mechanical ESS with high power density. An FESS is formed as an electrical machine connecting to the grid through back-to-back converters. The electromechanical equation of the electrical machine is:

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

where J ($Kg.m^2$) is the flywheel inertia, ω (rad/s) is the rotating speed, T_{in} (Nm) is the input torque of the flywheel, P_{out} (Watts) is the output power that is controlled by converters (P_{elec}).

A first-order lag is used to simplify the control of the power converter on given reference power P_{ref} (Watts). T_{delay} is the time constant of the power converter control loop

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

A simplified model of an FESS was developed as shown in Figure 1. It has been validated with a detailed model which includes all the elements and control. The simplified model provided accurate results with significant reduction in computational time. It facilitates the system level studies considering large numbers of small flywheels.

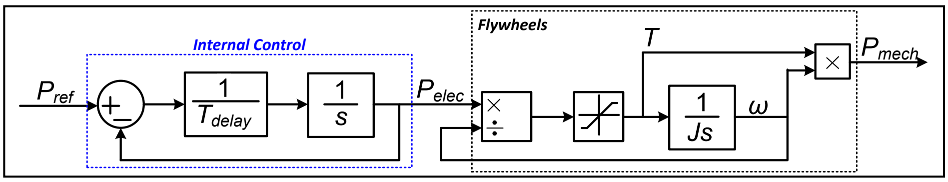

Figure 1: A simplified model of a FESS

2.2.2. 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 [6].

The internal temperature (T) of a refrigerator is modelled and dynamically compared with the temperature set-points T_{low} and Thigh. When a refrigerator is ON, it is equivalent to charging an energy storage which decreases *T*. An OFF-state refrigerator is considered as a discharging process that increases T. In a refrigerator, temperature controls the charging and discharging process.

2.2.3. Distributed control in a VESS

A control algorithm is developed for VESS to provide certain amount of response to regulation signals. In this paper, grid frequency (*f*) is used as the regulation signal.

A general local controller for refrigerators and FESS is developed as shown in Figure 2. 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 UK.

If f is 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.

If f is 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 Figure 2. For FESS, ω indicates SoC. For refrigerators, T indicates *SoC*. A higher T indicates a lower *SoC* and vice versa. When f rises, the units will start charging from the one with the lowest *SoC*. When f drops, the units will start discharging from the one with the highest *SoC*. Hence, the more f drops, the more power will be generated from FESS and the more power consumption of refrigerators will be reduced. Vice versa for f rises.

The final state of a unit is determined by a set of logic gates. The inherent control of each unit takes the priority to make the decision. The temperature control of refrigerators and the charging control of FESS limiting the maximum and minimum ω are the inherent control.

The control in Figure 2 is a local control on each unit, but is coordinated by assigning frequency set-points based on *SoC*. This reduces the number of charging/discharging cycles and each unit has equal opportunity to charge/discharge. The lifetime of units is hence prolonged. Specifically for refrigerators, the control does not undermine the cold storage. The diversity amongst refrigerators is maintained.

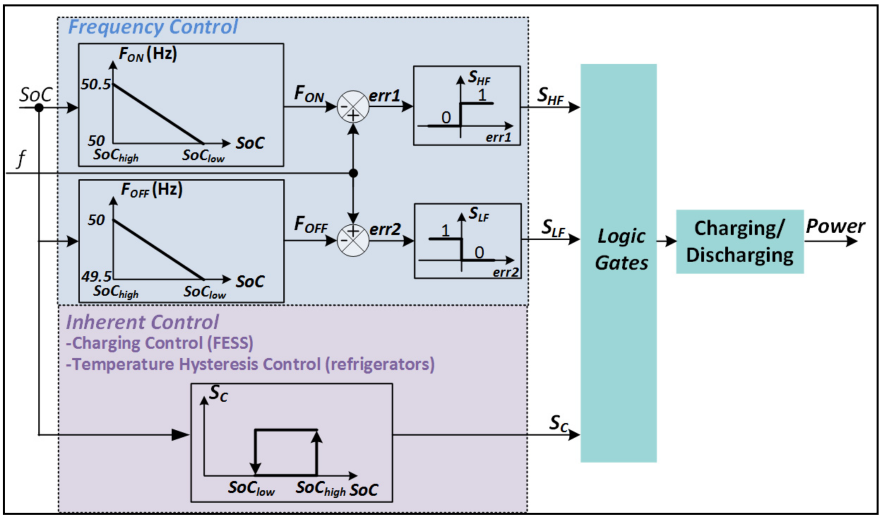

Figure 2: Controller of VESS

2.2.4. Coordination of refrigerators and FESS in a VESS

As discussed in Section 1, the high cost of FESS limits the grid-scale deployment. The uncertainty of DR makes it difficult to ensure the provision of certain amount of response. The coordination of FESS and DR in a VESS aims to provide certain amount of frequency response at low costs.

For refrigerators, f in Figure 2 is grid frequency. For FESS, f is the output of a droop setting as illustrated below.

The difference between the required frequency response of VESS (P_{req}) and the response of refrigerators (P_r) is input to the droop setting. The droop parameter (R) is:

$$R = \frac{50Hz - 49.5Hz}{P_{FESS}} \tag{3}$$

where P_{FESS} (MW) is the total capacity of FESS.

Namely, FESS responds to the mismatch between P_{req} and P_r in order to compensate for the uncertain response of refrigerators.

3. Case Study – Smart city, London

There are 3,220,300 households in London in 2014 [7]. It is assumed that the refrigerator (0.1 kW) in each household is equipped with the frequency controller in section 2.2.

The amount of frequency response from refrigerators is estimated considering the time of day [6]. A maximum reduction in power consumption 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 possible.

Therefore, VESS is promised to provide a linear frequency response of a maximum of 60 MW (*Preq*) to the power system over a day when frequency drops outside the limit (49.5 Hz). For the periods that refrigerators cannot provide 60 MW of response, FESS compensates for the maximum mismatch of 20 MW.

The following three case studies were undertaken on a GB power system model representing a low inertia future power system as developed in [8]. System base was 20 GW.

- **Case1** assumes there is no VESS.
- **Case2** connects 1,200 FESS with the rating of 50 kW. This case uses conventional FESS to provide the 60 MW of frequency response.
- **Case3** connects the VESS including refrigerators in London and 400 FESS with the rating of 50 kW. The FESSs provide 20 MW of response to the mismatch between *Preq* (60 MW) and *Pr*.

Simulations were carried out by applying a loss of generation of 1.8 GW in each of the three cases.

4. Results and Discussions

In Figures 3-4, the frequency drop is reduced with 60 MW of response from either FESS (case2) or VESS (case3). As 60 MW is small in a 20 GW system, the improvements of frequency is not obvious. If the capacity of VESS is higher, frequency drop will be more greatly reduced. The number of FESS in case3 was only one third of that in case2, however, VESS provided similar amount of frequency response as in case2. The reduced capacity of FESS in case3 will reduce the cost significantly compared to case2.

Figure 5 depicts that power consumption of refrigerators (left axis) reduced from 62 MW to 22 MW following the frequency drop. After 15 min, power consumption of refrigerators recovers and exceeds the initial 62 MW. FESS in the VESS increases the power output to reduce the effect of reconnections of refrigerators. The total frequency response from VESS is in linear relationship with frequency deviations as indicated in Figures 3-4.

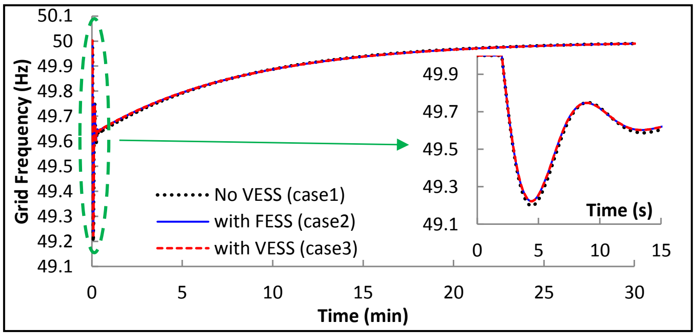

Figure 3: Variation of grid frequency

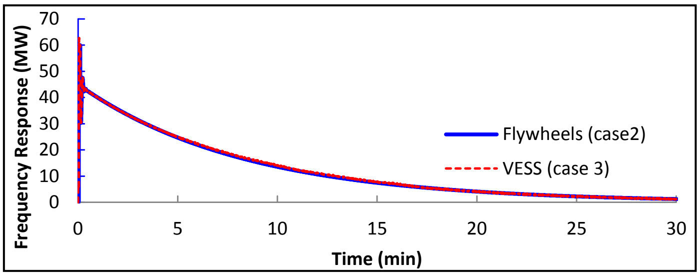

Figure 4 Frequency response from FESS (case2) and VESS (case3) 30 min after the generation loss

To provide frequency response of 60 MW, the total cost of FESS in case2 is £150m-£168m [4]. If the VESS is used for 60 MW of frequency response, the cost of refrigerators (40-60 MW) is £9.66m [9] and the cost of FESS (20 MW) is £50m-£56m. A potential saving of £91m-£103m is obtained.

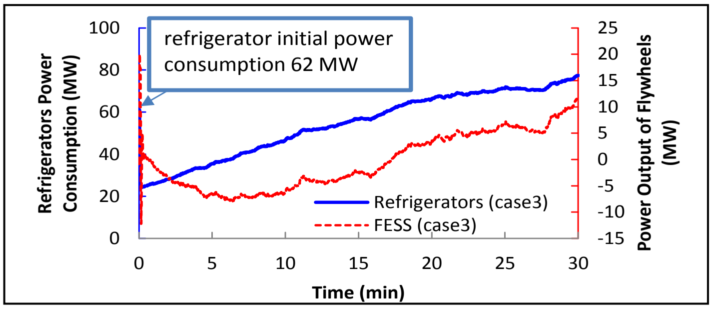

Figure 5 Change in power consumption of refrigerators and power output of FESS in VESS (case3)

5. Conclusions

To facilitate the integration of RES and move towards a low carbon city, a VESS is formed by coordinating the DR of domestic refrigerators and FESS to provide functions similar to conventional ESS with higher capacity and lower cost. A model and control algorithm of the VESS was developed. 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 maintains the load diversity amongst population. Case studies were undertaken to evaluate the capability of VESS for frequency response by connecting to a simplified GB power system model. Simulation results showed that VESS provides frequency response in a manner similar to FESS. Compared with the case that only uses FESS to provide a 60 MW of frequency response, a potential saving of around £91m-£103m was obtained by employing the VESS.

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Biography

Meng Cheng received the B.Sc. degrees in electrical and electronic engineering from Cardiff University, U.K. and North China Electric Power University (Beijing), China, in 2011, and the Ph.D. degree from Cardiff University in 2015. She is currently a Research Associate with Cardiff University. Her research interests include smart grids and dynamic demand.