Virtual Power Plant Solution for Future Smart Energy Communities

Edited by Ehsan Heydarian-Forushani,
Hassan Haes Alhelou and
Seifeddine Ben Elghali

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Chapter 6

Virtual Energy Storage Systems for Virtual Power Plants

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6 Virtual Energy Storage Systems for Virtual Power Plants

Saif S. Sami, Yue Zhou, Meysam Qadrdan, and Jianzhong Wu
School of Engineering, Cardiff University,
Cardiff, United Kingdom

CONTENTS

NOMENCLATURE

ΔP_{VESS_req}	the required power change of the virtual energy storage system (VESS) (MW)
R_{VESS}	the droop control value of the VESS
ΔP_{FESS}	the power change of flywheel energy storage system (FESS) units (MW)

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f	the grid frequency (Hz)
f'	the modified frequency for controlling FESS units (Hz)
R_{FESS}	the droop control value of FESS units
Δf	the frequency deviation (Hz)
T_{Ca}	the cavity temperature of a refrigerator (ºC)
T_{low}, T_{high}	the set-points of the temperature controller of a refrigerator or a bitumen tank (ºC)
S_T	the state signal of the temperature controller of a refrigerator or a bitumen tank
F_{ON}, F_{OFF}	the set-points of the frequency controller of a refrigerator (Hz)
S_H, S_L	the state signals of the frequency controller of a refrigerator
ω	the velocity of a FESS unit (rad/s)
F_{Chrg}, $F_{Dischrg}$	the set-points of the coordinated frequency controller of a FESS unit (Hz)
S_{Chrg}, $S_{Dischrg}$	the state signals of the coordinated frequency controller of a FESS unit
$R_{adaptive}$	the adaptive droop control value of a FESS unit
Δf^{max}	the maximum frequency deviation (Hz)
$P_{FESS\_capacity}$	the rated power capacity of a FESS unit (MW)
T_{BT}	the temperature of the bitumen in a bitumen tank (ºC)
V	the voltage of a busbar (p.u.)
V_{ON}, V_{OFF}	the set-points of the voltage controller of a bitumen tank (p.u.)
S_{HV}, S_{LV}	the state signals of the voltage controller of a bitumen tank
V_{high},V_{low}	the set-points of the voltage controller of the BESS (p.u.)
ΔP_{ES}	the change in the active power of the BESS (p.u.)
$\Delta \mathrm{Q}_{\mathrm{ES}}$	the change in the reactive power of the BESS (p.u.)
M_{i_ES}	the voltage sensitivity factor with regard to active power (voltage p.u./active power p.u.)
N_{i_ES}	the voltage sensitivity factor with regard to reactive power (voltage p.u./reactive power p.u.)
BESSp	the active power output of the BESS (MW)
BESSq	the reactive power output of the BESS (MVAr)

6.1 THE CONCEPT OF VESS

A virtual energy storage system (VESS) is defined as cooperation between different controllable distributed energy resources (DERs), such as flexible demand units and small-capacity energy storage units, to provide efficient power services. A VESS, through virtually sharing DERs' storage potential, functions similarly to a large-capacity conventional energy storage system. Other DERs such as distributed generation (DG) and multi-vector energy resources, e.g. combined heat and power (CHP) systems, can also be included in the VESS, as shown in Figure 6.1. The VESS scheme addresses the uncertainty associated with the response from flexible demand by the coordination with energy storage systems (ESSs). Unlike a virtual power plant (VPP), a VESS coordinates DERs to operate as a single large-capacity ESS, which stores the surplus electricity energy and releases it based on the system requirements.

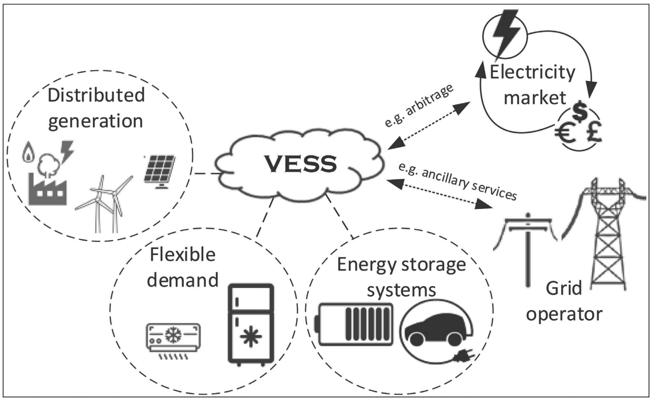

FIGURE 6.1 The concept of a virtual energy storage system (VESS) in smart grids, where a VESS can provide various services within several markets and for different operators.

A VESS is realised through an aggregator, allowing small-capacity flexible demand, ESSs and other DERs to access the wholesale market and provide ancillary services to electricity transmission and distribution networks. A VESS aggregator is an intermediate between a power system operator or service recruiter and a group of VESS components such as flexible demand or ESS owners.

Other definitions for VESS are presented by several researchers recently, referring to a single flexible demand unit, i.e. residential air conditioners [1], or an aggregation of flexible demand units, such as refrigerators [2], air-conditioning loads [3, 4] and electric vehicles [5, 6]. However, without ESS, these systems exhibit a high degree of response uncertainty. In contrast, a successful adoption of the VESS concept, which refers to an aggregation of ESS, PV systems and flexible demand units, was used for the voltage regulation of distributed networks based on dynamic pricing [7].

6.2 COMPONENTS OF VESS

6.2.1 Flexible Demand Units

Demand response (DR) is a change in the electricity consumption of loads from their normal consumption patterns. This shift in electricity consumption can be in response to electricity price changes or incentives paid by power system operators to improve system reliability [8].

Based on the amount of electricity consumption, flexible demand can be classified into (1) large industrial, commercial and other non-domestic demands, (2) small industrial, commercial and public demands and (3) residential demand. A large flexible demand often participates directly in DR programmes, while small flexible demand units are commonly aggregated by intermediaries which are called DR providers (DRPs), curtailment service providers (CSPs) or aggregators of retail customers (ARC) [9].

The use of different flexible demands to support power systems is well established. These include industrial demand such as steelworks, public utility demand such as water supply and wastewater treatment plants, health and educational buildings such as hospitals and universities and commercial demand such as retailers [10]. However, the share of domestic demand in DR programmes has been limited since the associated costs are high per participation capacity. Economic benefits are also considered small to these consumers as many have flat electricity prices [11]. Yet, a study of Great Britain (GB) revealed that the acceptance of DR programmes at the domestic level is expected to reach 80% in 2050, mainly through smart home appliances which can shift approximately 11% of their peak demand through time-of-use programmes [12].

DR programmes are commonly classified into price-based and incentive-based programmes based on how flexible demand is recruited. A comparison of different programmes is depicted in Table 6.1 [8, 13]. In the price-based DR programmes, consumers adjust their electricity consumption to changes in the electricity price. While incentive-based DR programmes are implemented through interruptible or curtailment contracts, in which consumers are paid to reduce or shift their electricity consumption. These DR programmes are deployed at different time scales within the power system, as shown in Figure 6.2. Sustaining the power system security and reliability is the main motivation for establishing incentive-based programmes, while economic aspects drive the price-based programmes. Typically, DR in incentive-based programmes is activated by events such as large frequency deviations, while changes in electricity prices often trigger DR in price-based programmes. Currently, flexible demand provides different services in several European countries and the USA, which include frequency regulation, congestion management and voltage regulation to a transmission system operator (TSO) at the transmission system level and congestion management and voltage regulation to a distribution system operator (DSO) at the distribution network level [14].

For example, in the USA, the potential flexible DR through incentive-based DR programmes at the system peak hour exceeded 30 GW in 2018, which consists of approximately 15 GW from the industrial, 7 GW from the commercial and 8 GW from the residential flexible demand. Additionally, the participation of DR in a regional transmission organization (RTO) or an independent system operator (ISO) wholesale DR programmes in 2019 exceeded 32 GW, which was approximately 6.6% of peak demand [15].

6.2.2 ENERGY STORAGE SYSTEMS

ESSs are typically classified based on the stored energy form into electrical, mechanical, electrochemical and thermal ESSs, as shown in Figure 6.3 [16] and Table 6.2 [10]. ESSs can also be categorised based on the power and energy densities or ratings into high-energy density ESSs and high-power density ESSs. The high-energy density ESSs include pumped hydro ESS, compressed-air ESS, thermal ESS and hydrogen-based ESS, which are typically used for energy management applications. The high-power density ESSs include supercapacitor ESS, flywheel ESS and superconducting magnetic ESS, which are often used for power management applications. Many types of battery ESS have high energy and power densities, and hence, they might be suitable for both power and energy management applications.

TABLE 6.1
Demand Response Programmes [8, 13]

Programme Name		Description	+Advantage/−Disadvantage
Price-based	Time-of-use	This programme uses different electricity prices for different time blocks, typically predefined for a 24-hour day.	– A price scheme is offered to all customers with different consumption levels.
	Real-time pricing	This programme often provides an hourly fluctuating electricity price to reflect changes in the wholesale electricity price.	– Customers should respond rapidly to prices changes.
	Critical peak pricing	In this programme, the electricity price is based on the time-of-use programme. However, certain defined conditions trigger much higher event prices that replace the normal prices.	
Incentive-based	Direct load control	In this programme, on short notice, the programme operator remotely controls customers' electrical appliances.	– Customers must grant the operator a level of authority to shift or curtail certain loads.
	Interruptible/curtailable service	In this programme, consumers agree to reduce load during system contingencies. The curtailment options are integrated into retail tariffs.	– Failing to curtail contracted loads leads to penalties.
	Demand bidding/buyback	In this programme, consumers offer bids for load curtailment based on wholesale electricity market prices.	
	Emergency demand response	In this programme, consumers are offered incentive payments to reduce their loads during periods when the system is short of reserve.	+ Consumers incur a credit or electricity price discount.
	Capacity market	In this programme, consumers are offered incentive payments to reduce their loads as a replacement to conventional generation. Customers normally receive intra-day notice of events.	+ Incentives include upfront payments.
	Ancillary services market	In this programme, consumers bid for load increase or curtailments. If their bids are accepted, they are paid for committing to be on standby and when their load curtailments are required.	

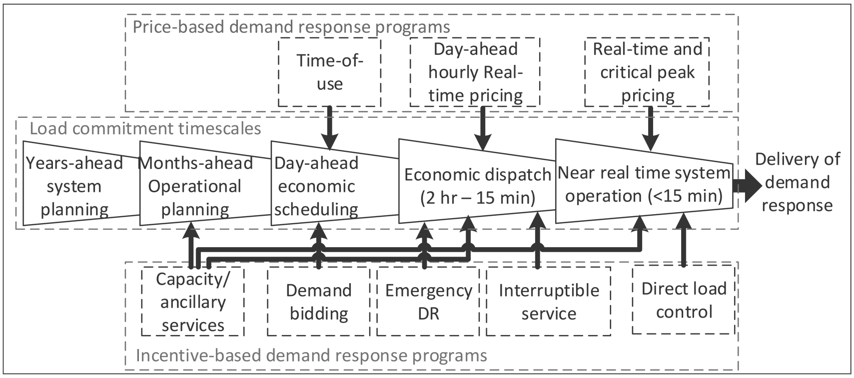

FIGURE 6.2 The deployment of demand response in power systems [8].

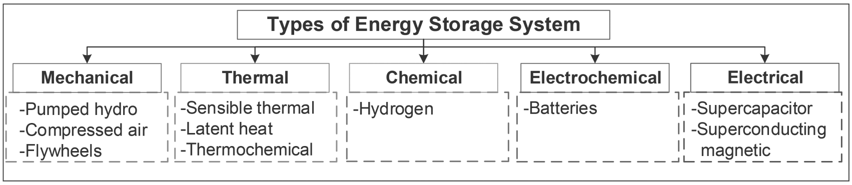

FIGURE 6.3 Energy storage systems used in the power system [17].

TABLE 6.2
Types of Energy Storage Systems for Power Systems [10]

Type	Description	+ Advantages/– Disadvantages
Pumped hydro energy storage (PHES)	The energy is stored by pumping water from the lower reservoir to the upper reservoir and deployed when water is discharged in the opposite direction through the turbine. The energy stored depends on the height difference between the reservoirs.	+ Zero emissions produced, a long life, a large storage scale, a fast reaction and low maintenance. – The geographical constraint and the capital costs.
Compressed air energy storage system (CAES)	The system compresses air, i.e. the medium of storage, normally in underground salt caverns to store energy. The energy is regained when the stored air is decompressed and heated by a combustion gas turbine.	+ Can be deployed at a large scale. – The necessity of a fuel source and the geographical constraint.
Flywheel energy storage system (FESS)	The system consists of a large inertia flywheel coupled with an electrical machine. The conversion of electrical to mechanical energy occurs through accelerating the velocity of the flywheel and retrieved by decelerating the velocity.	+ Has a large number of charging and discharging cycles, i.e. a long life, and a fast response. – Has a high self-discharge.

(Continued)

TABLE 6.2 *(Continued)*
Types of Energy Storage Systems for Power Systems [10]

Type	Description	+ Advantages/– Disadvantages
Thermal energy storage system (TESS)	The energy is stored in the forms of cold, heat or their combination. The system is classified based on physical principles into A-latent heat storage, based on the phase change materials; B-sensible thermal energy storage, based on the temperature difference; C-thermochemical energy storage.	+ Inexpensive and has no geographical constraints. – Has a moderate efficiency.
Hydrogen-based energy storage system (HESS)	This system essentially consists of an electrolyser and fuel cells. Fuel cells generate electricity by composing hydrogen and oxygen into water, while electrolyser consumes electricity to decompose water.	+ Has a separate process for the generation, storage and deployment. – Has a low overall efficiency.
Lithium-ion battery energy storage system (Li-ion BESS)	The typical structure of a lithium-ion battery consists of a cathode made of lithium metal oxide, a graphite anode and an electrolyte consisting of a solution of a lithium salt in a mixed organic solvent embedded in a separator felt.	+ The system has a high power, high permissible depth of discharge. – Has a relatively high cost. Yet, the cost is declining rapidly in recent years.
Lead-acid battery energy storage system (Lead-acid BESS)	The system is made of stacked cells, immersed in an electrolyte of a dilute solution of sulphuric acid (H_2SO_4). The negative electrode of each cell is sponge lead (Pb), while the positive electrode is composed of lead dioxide (PbO_2).	+ This is the least expensive BESS. – Has a low permissible depth of discharge and a limited cycling capability.
Sodium–sulphur battery energy storage system (Na-S BESS)	The system operates at a temperature of about 300°C to keep the electrode materials in a molten state, hence reducing resistance to the sodium ions flow through the β-alumina solid (β-Al_2O_3) electrolyte.	+ Has a high efficiency and a low maintenance requirement. – Safety and thermal management are the key disadvantages.
Nickel battery energy storage system (Ni BESS)	The main system active materials of the positive and negative electrodes are nickel (Ni) and cadmium (Cd), respectively. Aqueous alkali solution is acting as the electrolyte.	– Has considerable costs, toxicity and the memory effect problem.
Flow battery energy storage system (Flow BESS)	The system consists of an electrolyte that contains one or more dissolved electroactive materials flowing through a power cell/reactor (i.e. where the chemical energy is converted to electricity). The three major types are vanadium redox battery (VRB), zinc–bromine battery (ZBB) and polysulphide bromide battery (PSB).	+ The ability to deliver long-term charging/discharging and a negligible self-discharge. – Has a moderate efficiency.

(Continued)

TABLE 6.2 *(Continued)*
Types of Energy Storage Systems for Power Systems [10]

Type	Description	+ Advantages/– Disadvantages
Super- or ultra-capacitors energy storage system	The system is based on two-conductor electrodes along with an insulator (electrolyte and a porous membrane). The energy stored is directly proportional to the capacitance capacity and the square of the voltage between its terminals.	+ Has a long life, no discharge depth limitations and relatively high-power capacity. – Has a small energy capacity and a high cost.
Superconducting magnetic energy storage (SMES)	The energy is stored in the magnetic field generated by the direct current flowing through a coiled wire at cryogenic temperature. The stored energy is proportional to the coil self-inductance and the square of the current passing through it.	+ Has a high efficiency and a rapid response, albeit for short periods of time. – Requires continuous energy to cool the coil, environmental issues related to the strong magnetic field.

ESSs can provide a wide range of services to bulk power systems and microgrids. For example, these services can improve the power quality and system stability and support the integration of renewable generation, as shown in Figure 6.4 [18].

6.3 ENABLING TECHNOLOGIES FOR VESS

The conceptual framework of the VESS involves the use of various smart technologies to facilitate VESS components' coordination and support the efficient monitoring and control. These enabling technologies are described as follows:

- **Smart switches**
  Smart switches are used to remotely control particular end-user loads, such as a refrigerator, or a [15] heating, ventilation and air conditioning (HVAC) system (in this particular case, it might be also known as smart thermostats). This smart thermostat can regulate room temperatures according to remote signals sent from the master controller of the VESS.

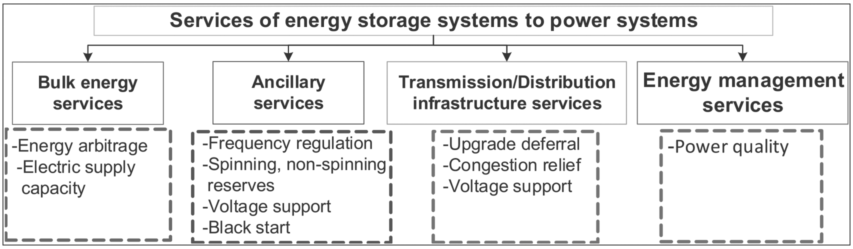

FIGURE 6.4 Potential applications of energy storage systems in power systems.

- **Smart building management technologies**
  These technologies enable an agent to aggregate all flexible loads within a building to act as a VESS component. The flexible loads can be dishwashers, washing machines, dryers, swimming pool pumps, EV charging stations, behind-the-meter ESSs, elevators and some types of lights. Through two-way communication systems, the agents receive control signals from the master controller of the VESS and report back all the information on available flexible demand considering customers' preferences and comfort levels.
- **Communication technologies**
  Communication systems are a vital part of implementing VESS control schemes. One-way communication systems are simple to implement and more cost-effective. However, an accurate verification of the response of VESS components is difficult to achieve. Two-way communication systems are more expensive, yet monitoring and identifying the available level of flexible loads and ESSs in near real time. These communication systems can include home area networks (HANs), neighbourhood area networks (NANs) and wide-area networks (WAN). Both wired and wireless communication technologies can be used to link different VESS components. Wired communication technologies include narrowband and broadband power line communications (PLCs) and fibre optics, while Zigbee (IEEE 802.15.4) and Wi-Fi (IEEE 802.15.4) are typical wireless communication technologies that can be adopted.

6.4 POTENTIAL APPLICATIONS OF VESS IN POWER SYSTEMS

Recent developments in integrated circuits, such as inexpensive smart switches and information and communications technologies, improve the advanced monitoring and control functionalities. These developments accelerate the realisation of the VESS concept. The VESS forms a synthetic ESS at distribution and transmission levels, and hence it can provide services at both levels. The VESS potential applications are presented as follows.

- **Facilitate the integration of DG in distribution networks**
  A VESS can smooth the variations in the power output of intermittent renewable generation. This is beneficial to increase the hosting capacity of DG in distribution networks. The hosting capacity is the total DG capacity allowed into the network without violating network constraints, e.g. voltage and thermal constraints, under the minimum loading condition. A VESS will address variations in the DG power output to restrict the voltage deviations and power flow below the limits.
- **Reduce reserve margins**
  A VESS can reduce the required spinning reserve capacity and increase the generators' loading level, since the available VESS capacity can be continuously reported to the system operator as a fast-acting spinning reserve.

- **Defer transmission and distribution systems reinforcement**
  Transmission and distribution systems are often sized to accommodate the expected peak demand. Therefore, reducing peak demand, through the VESS, allows the system reinforcement to be deferred. In addition, the VESS can increase the utilisation of transmission and distribution networks by providing immediate actions to avoid potential network congestions, and hence the transmission and distribution systems upgrade can be postponed.
- **Provide other ancillary services**
  As a result of aggregation, the VESS can provide different ancillary services to the power system operator, such as frequency response services, since it provides a faster response and higher ramp rates than the conventional generation units.

6.5 THE VESS AS AN INTEGRAL PART OF THE VPP

Through the aggregation of various types of DERs, the VESS poses the characteristics of an ESS with high power and energy ratings. A VESS facilitates required flexibility for the VPP to shift electrical energy from one period of time to another, hence extending the VPP potential over widespread power system applications. A VESS can improve the reliability and quality of the power supply provided by the VPP. The VESS involvement increases the performance of the VPP and extends its capabilities that include, but are not limited to, the following:

- **Mitigate the fluctuation of renewable generation**
  A VESS could smooth the fluctuation of power generated by renewable generation within the VPP. A VESS deployment across a significant part of the VPP geographical area can eliminate many DG curtailments due to network constraints' violations. A VESS can alleviate renewable generation forecasting errors enabling an efficient and accurate service delivery by the VPP.
- **Enhance the quality of supply**
  The future VPP is anticipated to cope with essential supporting or balancing services, e.g. congestion management, black start capability and inertial response capability [19]. A VESS will assure that the VPP affirms these obligations. The future VPP is expected also to provide an uninterrupted power supply where the VESS retains the consistency in VPP operations. Additionally, the provided electrical service by the VPP will be disruption-free of voltage swells, sags and spikes. A VESS can also support the VPP to prevent blackouts and enhance ancillary services provided by the VPP [20].

6.6 THE POTENTIAL BENEFITS OF VESS IN POWER SYSTEMS

The benefits of the VESS may vary based on several factors such as controllers' design and performance, the targeted market as well as enabling technologies utilised and the VESS components involved. These benefits at different levels of the power system can be categorised as follows:

- **Benefits for VESS components owners**
  The components owners can obtain additional revenue through being a part of VESS, which arbitrages in the wholesale electricity market and/or provides ancillary services to power system operators. In addition, the advanced communication and control functionalities of VESS can help improve consumers' economic and environmental awareness for electricity consumption, which may result in better electricity-saving behaviours and bring diversified options for electricity costs and emission management.
- **Benefits for transmission and distribution systems**
  The VESS can reduce the overall power system losses, alleviate some of systems constraints and improve systems reliability. The VESS can defer the reinforcement of electrical networks without comprising network-assigned reliability levels.
- **Benefits for supply side of power systems**
  The VESS can reduce required generation during peak times, and hence investment in peaking units can be reduced. Additionally, as the VESS allows more renewable energy generation into the energy market, the influence of conventional generation companies on market prices may be reduced.
- **Benefits for VPP**
  The VESS can boost the capacity of VPP in participating in the energy market, potentially transforming a price-taker VPP into a large-scale generation entity and a price-maker [21]. Consequently, the VPP has a high influence in the electricity market that can adjust market prices to earn higher profits. The VESS will also increase the capability of VPP to provide ancillary services to power systems.

6.7 CONTROL SCHEMES OF VESS

The control scheme of a VESS can be central or distributed, depending mainly on the required information exchange among VESS components, spatial distribution of these components and the allocated budget involved. Central control schemes use sophisticated two-way communication systems at high-time resolutions that allow the VESS to furnish ancillary services such as frequency and voltage support and spinning reserve. For example, a VESS-centralised frequency controller can send a turning ON/OFF signal to home appliances, such as heat pumps, water heaters or refrigerators, after a frequency rise or dip event. Also, the near real-time VESS availability enables the accommodation of more distributed renewable generation that otherwise would be curtailed. The centralised controller can be managed by a VESS aggregator. The computation burden of the centralised control scheme continues to be a barrier, since numerous variables of VESS components need to be considered.

To address the problems associated with two-way communication systems, such as latency, packet loss and costs, decentralised controllers were investigated. For instance, a decentralised VESS frequency controller can manipulate the temperature set-points of air conditioners or refrigerators to vary in-line with the frequency deviations, hence altering their power consumption in response to the frequency deviations.

A hierarchical control scheme can include central and local controllers and utilise an amalgam of communication technologies to realise. A deep analysis of control requirements and capabilities is required to tailor the right set of these technologies.

Two applications were chosen to represent the potentials of the VESS in Sections 6.8 and 6.9. In the first application, the VESS is providing balancing services, i.e. frequency response, to the TSO. While in the second application, the VESS is supporting the voltage control in a distribution network with a high penetration of distributed renewable energy resources, hence assisting the DNO.

6.8 A FREQUENCY CONTROL SCHEME OF VESS

The frequency control scheme of a VESS was developed. The VESS can provide low, high and continuous frequency responses. In this application, the VESS coordinates domestic refrigerators and flywheel energy storage units to deliver a certain amount of frequency response at a lower cost compared with an equal capacity of using units of flywheel energy storage only [17].

6.8.1 Modelling of Components of the VESS

The thermodynamic model of refrigerators, which was adopted from [22], is utilised in this study. The model uses two first-order differential equations to relate the rate of change in the cavity and evaporator temperatures with time to parameters that describe the thermal characteristics of a refrigerator.

A simplified model of a FESS, which was developed in [23], is used in this study. The FESS is essentially an electrical machine coupled with a high inertia flywheel and is connected to the grid through back-to-back converters.

6.8.2 The Central Controller and Local Controllers of Refrigerators and Flywheel Energy Storage Units

Following a frequency deviation (Δf (Hz) in Figure 6.5), the required frequency response of the VESS (ΔP_{VESS_req} (MW) in Figure 6.5) is determined by the droop control with the droop coefficient (R_{VESS}) of the value of 1%. Hence, a 1% change in grid frequency would trigger a 100% change in the VESS power. First, local controllers of refrigerators respond to the frequency deviation. Then, FESS units eliminate the power mismatch between the change in refrigerators' power consumption and the power required from the VESS. Consequently, FESS units compensate for the uncertainty in the response of refrigerators. The required power from FESS units ($\sum \Delta l_{FESS\text{-}req}$ (MW) in Figure 6.5) is decided by a modified frequency value f' (Hz) through the droop setting (R_{FESS}). The local controllers of FESS units respond to the modified frequency. It is assumed that a fast two-way communication system is available for receiving the power of refrigerators and sending the modified frequency to FESS units.

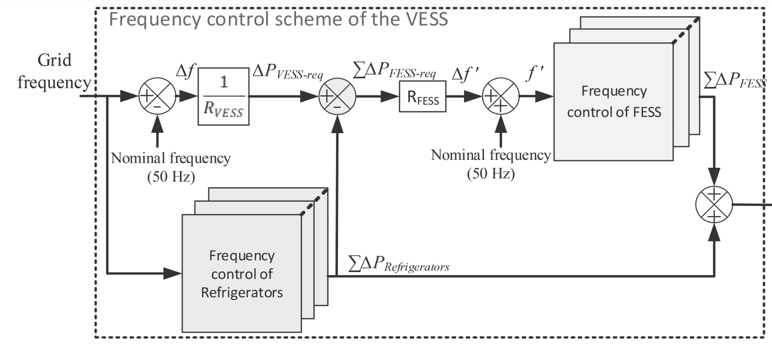

FIGURE 6.5 The central frequency controller of the VESS.

A local frequency controller is integrated, through a lookup table, to the internal temperature controller of a refrigerator, as shown in Figure 6.6 and Table 6.3. The temperature controller continuously measures the cavity temperature (T_{Ca}) (°C) and compares it with set-points (T_{low} and T_{high}) (°C). If the cavity temperature reaches T_{high}, the controller generates state signal (S_T) of 1, or it reaches T_{low}, the state signal generated (S_T) is 0. The frequency controller, based on T_{ca}, defines a pair of frequency set-points (i.e. F_{ON} and F_{OFF} (Hz)), which dynamically varies with the temperature T_{Ca}. It compares the measured frequency (f) to these set-points to determine the state signals (S_H and S_L). The range of F_{ON} is 50–50.5 Hz and the range of F_{OFF} is 49.5–50 Hz, which are consistent with the steady-state limits of grid frequency in the GB power system.

In the case of a population of refrigerators, a refrigerator having a lower temperature than others will have a higher F_{ON} and a higher F_{OFF} values as indicated in Figure 6.6. If f drops, refrigerators will start switching OFF from the refrigerator with the lowest T_{ca}, because it will take the longest time to reach the high-temperature limit. In contrast, refrigerators will start switching ON from the refrigerator with the highest T_{ca} when f rises above the nominal frequency value. The higher the frequency variation is, the larger number of refrigerators will be committed to respond. When a temperature-diversified population of refrigerators

TABLE 6.3
Lookup Table in Figure 6.6

Row	S_T	S_L	S_H	S_{final}
1	0	0	0	0
2	0	0	1	1
3	0	1	0	0
4	1	0	0	1
5	1	0	1	1
6	1	1	0	0

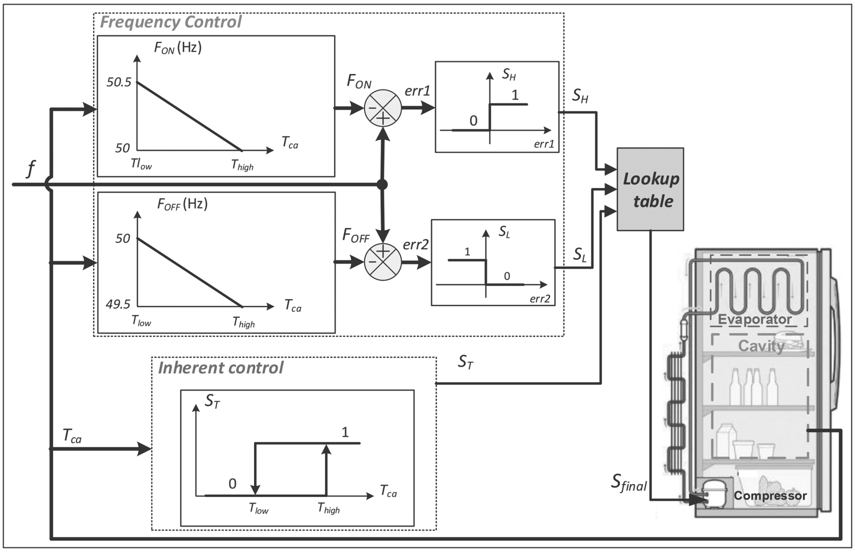

FIGURE 6.6 The integrated control of the refrigerator [17].

is considered, the number of refrigerators committed increases linearly with the increase in frequency variations.

The local frequency controller of the FESS consists of the coordinated control and the adaptive droop control as depicted in Figure 6.7. The coordinated control determines which unit to commit, while the adaptive droop control regulates the power output of the committed units. The coordinated control is similar to the local frequency control of refrigerators presented early. However, the temperature is replaced by the velocity (ω) (rad/sec) of the FESS unit, which also represents the state of charge (SoC) of the unit. The coordinated control, based on ω, defines a pair of frequency set-points (F_{Chrg} and $F_{Dischrg}$) and compares the grid frequency to these set-points to determine the state signals (S_{Chrg} and $S_{Dischrg}$). The coordinated control, through the OR logic gate and a switch shown in Figure 6.7, ensures that the number of FESS units committed is linearly increasing with the increase in frequency deviations.

The adaptive droop control value ($R_{adaptive}$) is inversely proportional to frequency deviations (Δf) as shown in Equations (6.1.a) and (6.1.b). Dictated by coordinated control, a small frequency deviation (Δf) triggers only a small number of FESS units to commit. Therefore, a droop value $R_{adaptive}$ greater than the conventional droop value R_{FESS} is required to increase the change of power output. When the frequency deviation increases and reaches the frequency deviation limits (Δf^{max}) (±0.5 Hz in the GB power system), all FESS units will be triggered to commit and $R_{adaptive}$ equals R_{FESS}. R_{FESS} is set to 1%, which indicates that a FESS unit will provide 100% power output change if frequency deviation is equal to or higher than 1% of the nominal frequency value.

$$R_{FESS} = \frac{\Delta f^{max}}{P_{FESS\_capacity}} \tag{6.1.a}$$

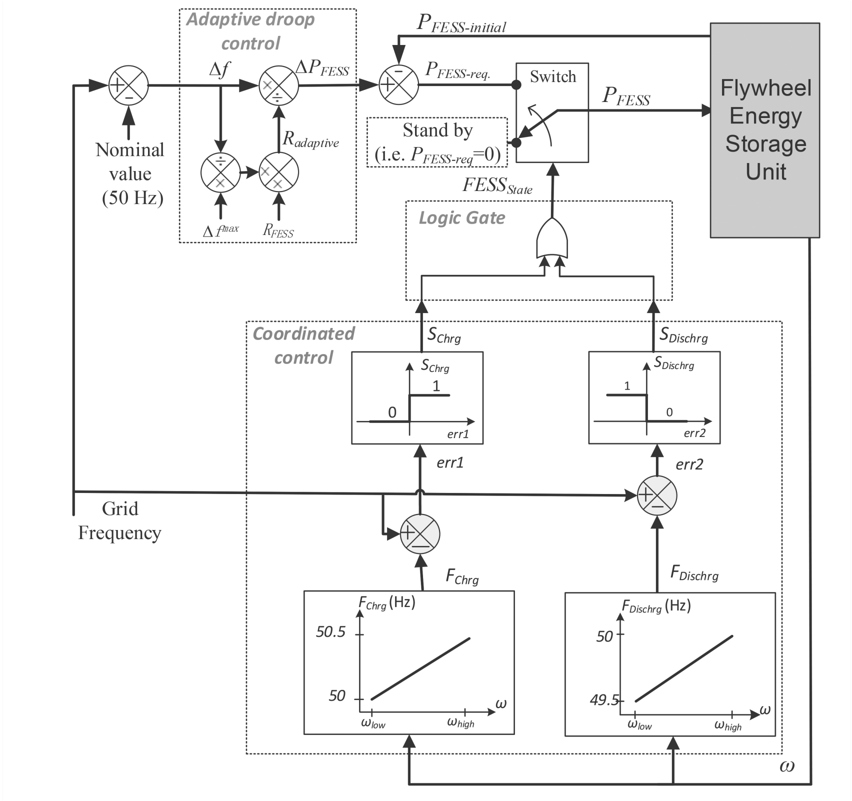

FIGURE 6.7 The frequency control of the FESS.

$$R_{adaptive} = \frac{\Delta f^{max}}{\Delta f} \times R_{FESS} \tag{6.1.b}$$

where $P_{FESS\_capacity}$ (MW) is the rated power capacity of the FESS unit.

6.8.3 CASE STUDY

To assess the performance of the VESS to provide low-frequency response services, it is connected to the simplified GB power system model adopted from [24, 25]. Further details can be found in [10]. Three scenarios were compared:

Scenario 1: No FESS/VESS.
Scenario 2: Only FESS (60 MW of FESS is used).
Scenario 3: VESS (a large number of refrigerators with the power reduction potential of 40–60 MW and 20 MW of FESS are used).

The availability of refrigerators to be switched OFF varies over the day from 13.2% to 18.5% [26]. Considering the participation of 3,220,000 refrigerators (0.1 kW for each), a maximum power reduction of 60 MW and a minimum power reduction of 40 MW is expected. It is worth noting that the availability of refrigerators to be switched ON over the day is 50%–56% [26], and hence, the power that can be increased ranges from 160 MW to 180 MW. This reveals that refrigerators have more potential to provide a response to the frequency rise than to the frequency drop. Each FESS unit has a power capacity of 50 kW and an energy capacity of 30 kWh, similar to the commercial FESS in [27]. Hence, the 20 MW of FESS consists of 400 units (**Scenario 3**) and 60 MW of FESS consists of 1200 units (**Scenario 2**).

Simulations were carried out by applying a loss of a generation of 1.8 GW to the GB power system. This case simulates the discharging phase of the VESS. Results are depicted in Figures 6.8 and 6.9. The frequency drop in Figure 6.9 is restricted by 60 MW of response (please see Figure 6.9a) from either FESS (Scenario 2) or VESS (Scenario 3). Since 60 MW of response is small in a 20-GW system, the frequency improvement is only 0.01 Hz, which is hardly noticeable. The capacity of FESS in the VESS (Scenario 3) is only one-third of that in Scenario 2, but VESS provided a similar amount of frequency response to that of FESS in Scenario 2. The reduced capacity of FESS in Scenario 3 will reduce the cost significantly compared to Scenario 2. An economic evaluation of the benefits of VESS for the provision of frequency response services (low, high and continuous responses) is presented in [17].

6.9 A VOLTAGE CONTROL SCHEME OF VESS

A voltage control scheme of the VESS was developed to support the distribution network voltage and hence allows more renewable generation in the distribution

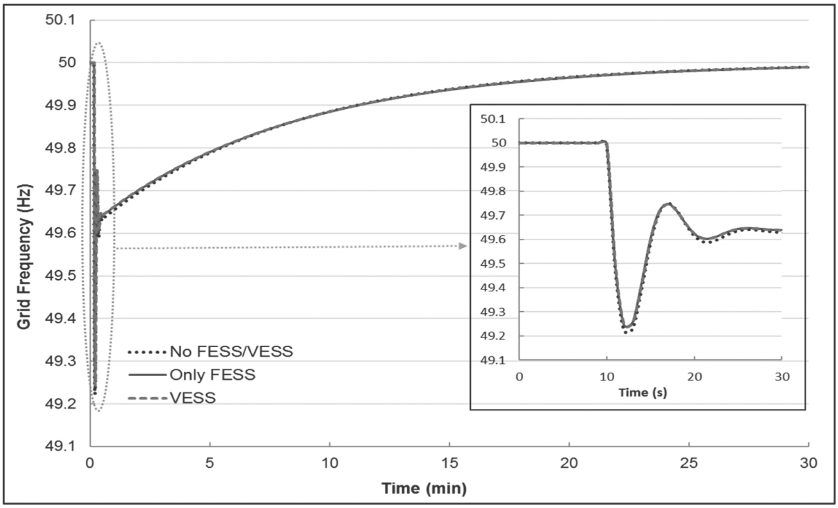

FIGURE 6.8 Variation of grid frequency after the loss of generation [17].

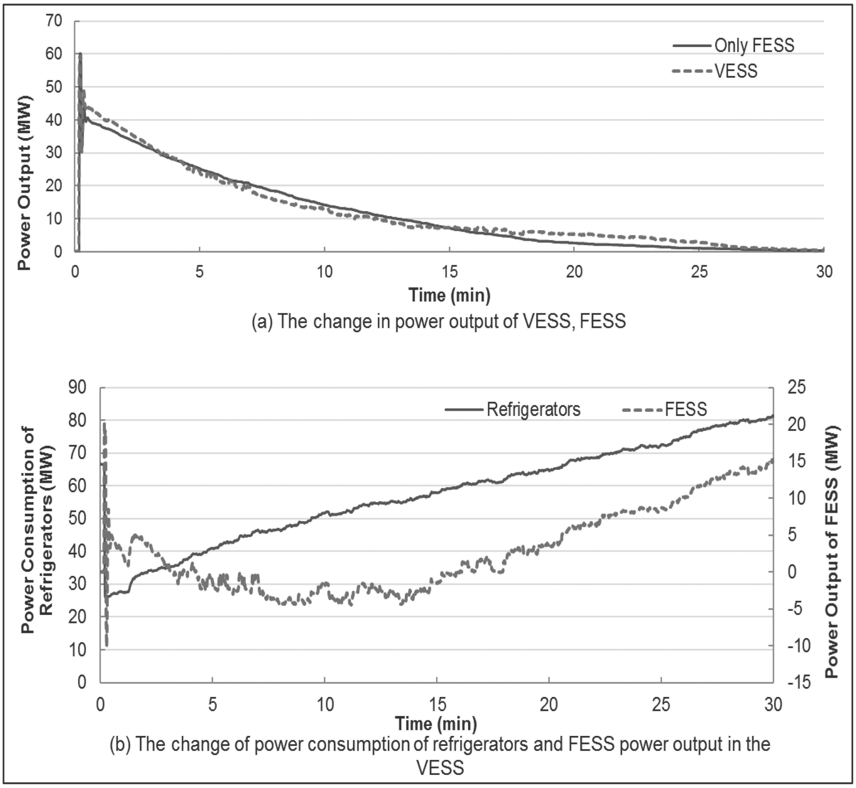

FIGURE 6.9 The change in power output/consumption of (a) the VESS against the FESS and (b) refrigerators and the FESS within the VESS [17].

network. Modelling of VESS components is presented, and then their voltage controllers are presented. In this application, the VESS is an aggregation of industrial bitumen tanks (BTs) and the BESS.

6.9.1 Modelling of Components of the VESS

A thermodynamic model of a BT adopted from [24] is used. The model depicts temperature variations of BT with time, which is captured by a single first-order differential equation. Each bitumen tank has an internal temperature controller which keeps the stored bitumen within a range of temperatures, i.e., T_{low} and T_{high} (°C).

A simplified model of a BESS developed in [23] is used. The model consists of a generic battery model and a simplified power electronics model.

6.9.2 DISTRIBUTED CONTROLLERS OF THE BITUMEN TANKS AND BATTERY ENERGY STORAGE SYSTEM

A local voltage controller was added to each BT's internal temperature controller [28], which has a similar structure to the frequency controller of refrigerators presented in Section 6.8.2. The voltage controller alters BT's power consumption based on local voltage measurements as shown in Figure 6.10. The temperature controller measures the bitumen temperature (T_{BT}) and generates state signals (S_T). The voltage controller measures the voltage (V) in (p.u.) of the busbar connecting BT and defines a pair of voltage set-points (V_{ON} and V_{OFF}) (p.u.) and compares V to these set-points to determine the state signals (S_{HV} and S_{LV}). The final switching signal (S_{final}) to the heater is then determined by a lookup table (see Table 6.3), which ensures the priority of the temperature control. Therefore, the extra voltage control will not undermine the thermal storage function of BTs.

The voltage controller of the BESS monitors, e.g. through remote terminal units (RTU), the most vulnerable busbars with respect to the voltage violation. These busbars are often the ones loaded heavily or connecting a large DG capacity. The controller initially selects, through the selection algorithm, the designated busbar (i), as

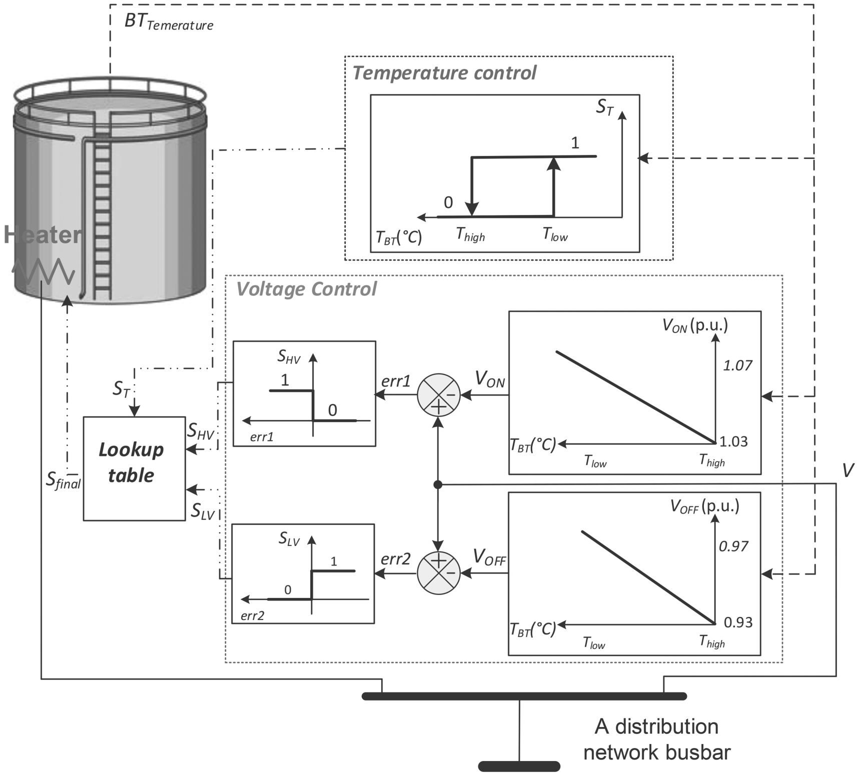

FIGURE 6.10 The integrated voltage and temperature controllers of the bitumen tank [28].

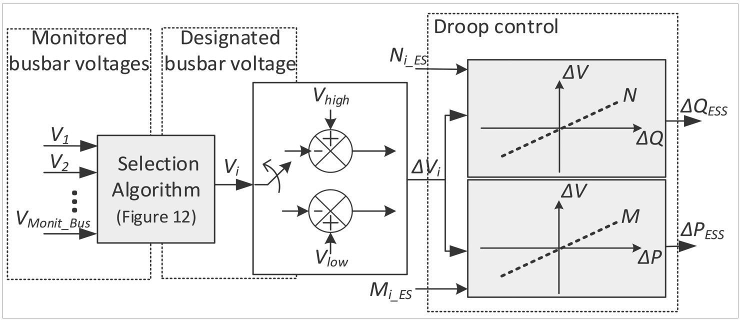

FIGURE 6.11 The voltage controller of the battery energy storage system.

shown in Figure 6.11. The high and the low voltage limits (i.e. V_{high} and V_{low}) were set to 1.06 and 0.94 p.u., respectively, based on [29]. The required changes in the active (ΔP_{ES} in p.u.) and the reactive powers (ΔQ_{ES} in p.u.) of the BESS were calculated using (6.2).

$$\Delta V_i = M_{i\_ES} \times \Delta P_{ES} + N_{i\_ES} \times \Delta Q_{ES} \tag{6.2}$$

where M_{i_ES} is the voltage sensitivity factor (in voltage p.u./active power p.u.), which relates the change in the active power of the BESS to the change in the voltage of busbar i and N_{i_ES} is the voltage sensitivity factor (in voltage p.u./reactive power p.u.), which relates the change in the reactive power of the BESS to the change in the voltage of busbar i. The calculation of voltage sensitivity factors is presented in [10].

The rule-based selection algorithm, depicted in Figure 6.12, is implemented as follows:

1. If all monitored busbar voltages are within limits, no designated busbar is assigned and the BESS takes no action.
2. Among all monitored busbars, select the two busbars with the largest voltage deviations. Since in the worst case, the network will suffer from a high voltage problem at a busbar and a low voltage at another.
3. If both selected busbar voltages violate limits in opposite directions, i.e. one above the high limit and the other is below the low limit, no designated busbar is assigned as well since reducing the voltage violation at one busbar may lead to a more severe voltage violation at the other busbar.
4. If both busbars have a similar direction of voltage deviations, i.e. voltages of both busbars are above/below a nominal value, the designated busbar is the busbar with the higher voltage violation. The BESS will then charge/discharge to bring the voltage of the designated busbar back to the voltage limit.
5. If the two busbars have opposite directions of voltage deviation, the designated busbar is the one not violating voltage limits. The BESS will charge/discharge to push the voltage of the designated busbar to the voltage limit, therefore reducing the other busbars have opposite direct

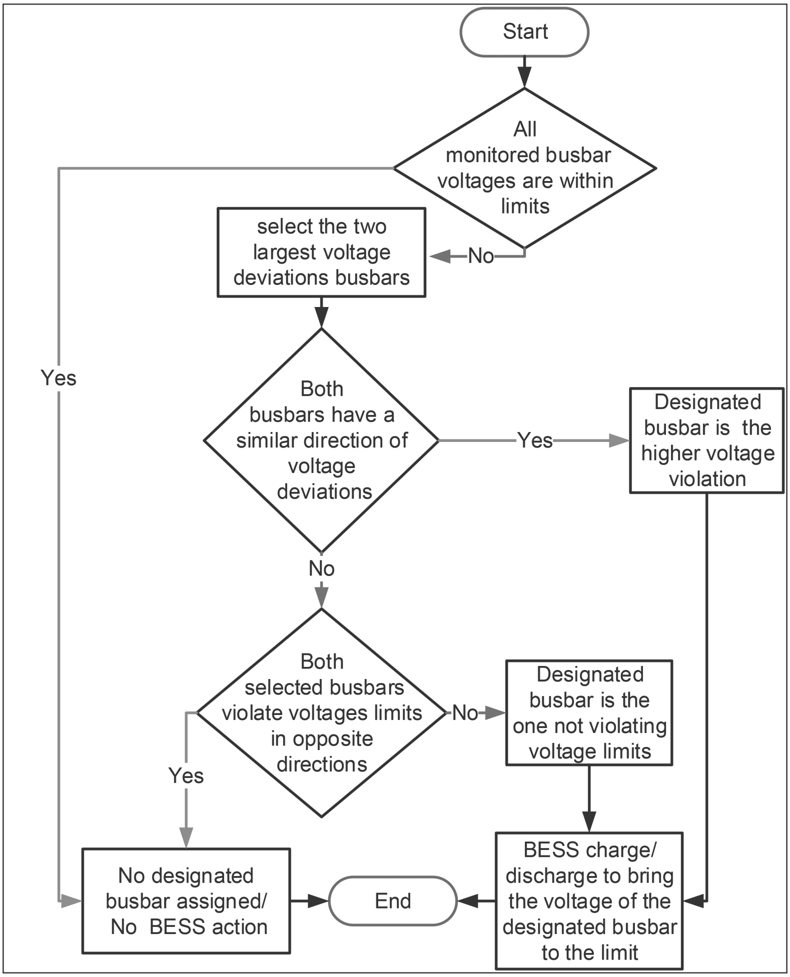

FIGURE 6.12 The designated busbar selection algorithm of the BESS voltage controller.

6.9.3 CASE STUDY

The performance of the proposed VESS voltage control scheme was evaluated using a simplified medium-voltage network, shown in Figure 6.13 [30]. The network supplies a peak load of 38.94 MVA. The network hosting capacity, defined as the total DG capacity under the minimum loading condition, was estimated in [28]. The network hosting capacity is 48.45 MW, which consists of 41.9 MW of wind farms and 6.55 MW of PV systems. The network voltage was only controlled by an on-load tap changing transformer (OLTC) and a voltage regulator (VR) transformer. The network data, half-hourly DG generation and load profiles, were obtained from [30].

For all the network load busbars, except the main busbar (busbar no.1), 30% of loads were assumed to be flexible, i.e. replaced by 9.8 MW, equivalent capacity of

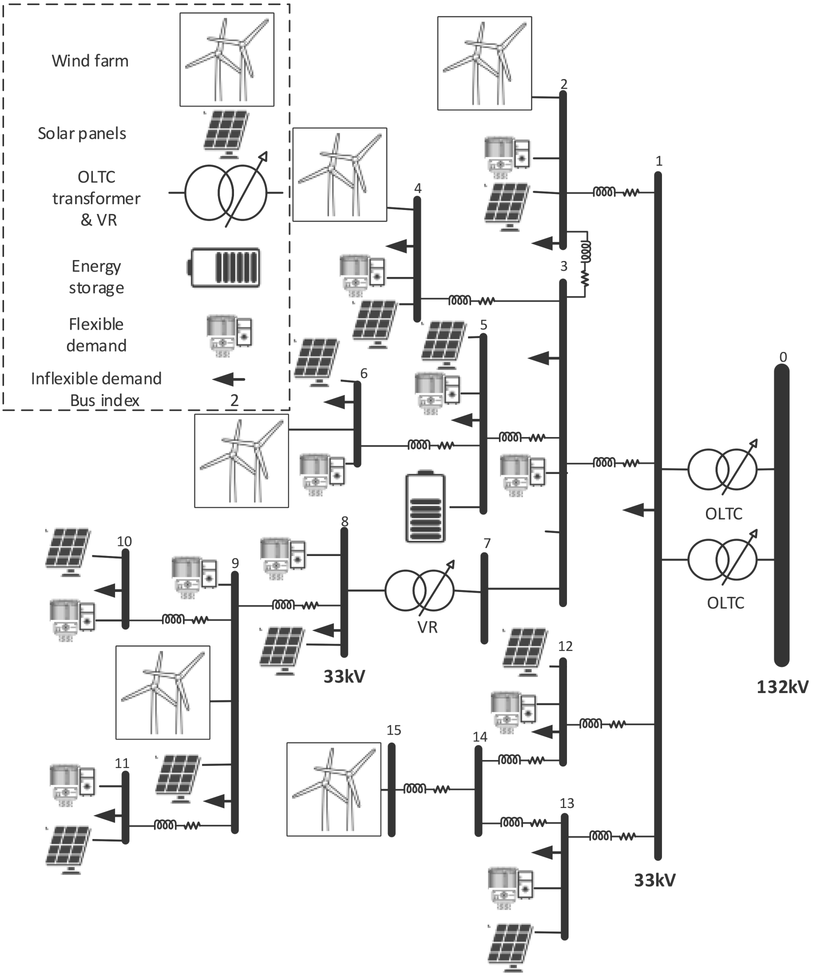

FIGURE 6.13 The distribution network used in the case study [28].

BTs. In addition to BTs, the VESS includes a 2.3-MW/1.4-MWh BESS at busbar no 5, which was installed to compensate for the flexible DR uncertainty. With the presence of flexible demand, the network hosting capacity for DG increased to 60.25 MW.

The VESS control scheme accounts for OLTC and VR voltage controllers to eliminate any controllers' conflicts or hunting between them. The time delay constraints for VESS elements and network transformers are detailed in Table 6.4.

The power flow analysis of 1-minute resolution was carried out to evaluate the proposed VESS control scheme performance over one spring day with high DG power output and low network demand. Results were compared with the base case in which no VESS was used. The half-hourly wind and solar generation profiles and total load of the base case are shown in Figure 6.14. The coincidence of high DG output and low demand led to voltage violations at several busbars in the first five hours of the

TABLE 6.4
VESS and Transformers Control Time Delay

Parameter	Time Delay (min)
τ_{DR}	1
τ_{ESS}	2
τ_{VR}	3
τ_{OLTC}	4

day. Figure 6.15 shows the response of the VESS, where BTs and mostly the reactive power of BESS were sufficient to mitigate the over-voltage caused by high DG. Figure 6.16 depicts the distribution of busbars voltages over the day, with the number of samples being 720 (i.e. 15 busbars over 48 time intervals). The proposed VESS control scheme reduces the number of actions of the OLTC and VR transformers by approximately 30% compared with the base case where no VESS was used [28], hence reducing their maintenance requirements and prolonging their lifespan.

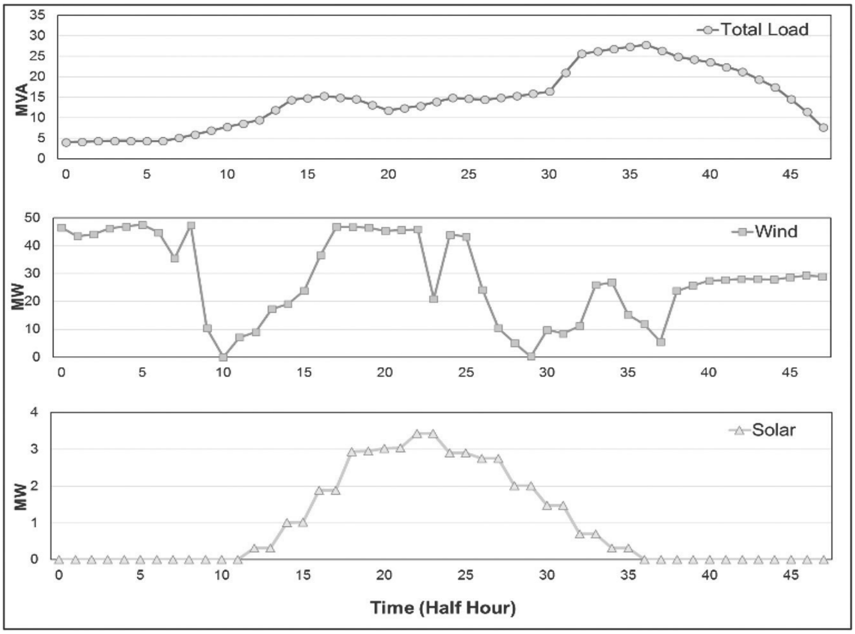

FIGURE 6.14 Wind and solar generation profiles and total load of the base case where no VESS exists in one spring day [28].

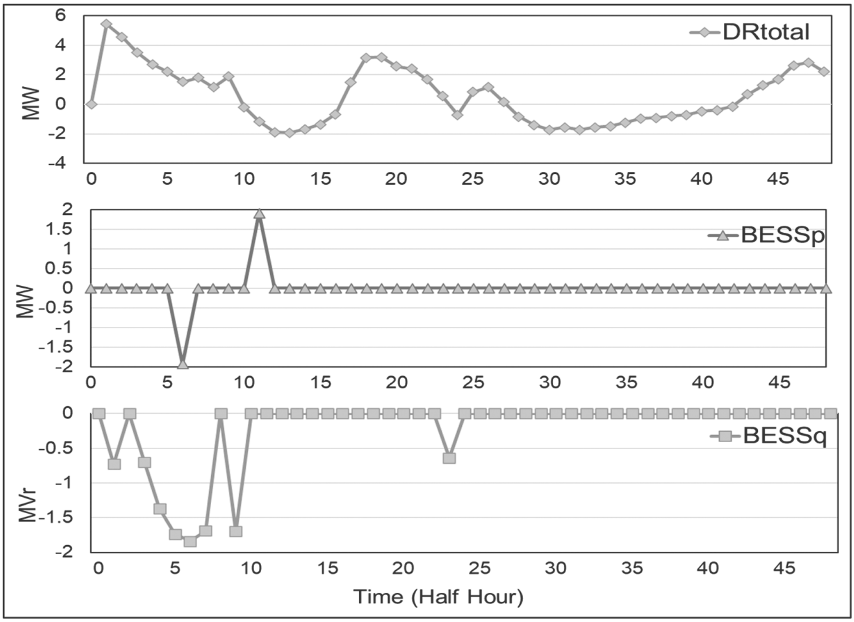

FIGURE 6.15 The response from different VESS components, where DRtotal is the aggregated response power from BTs and BESSp and BESSq are the active and reactive power outputs of BESS [28].

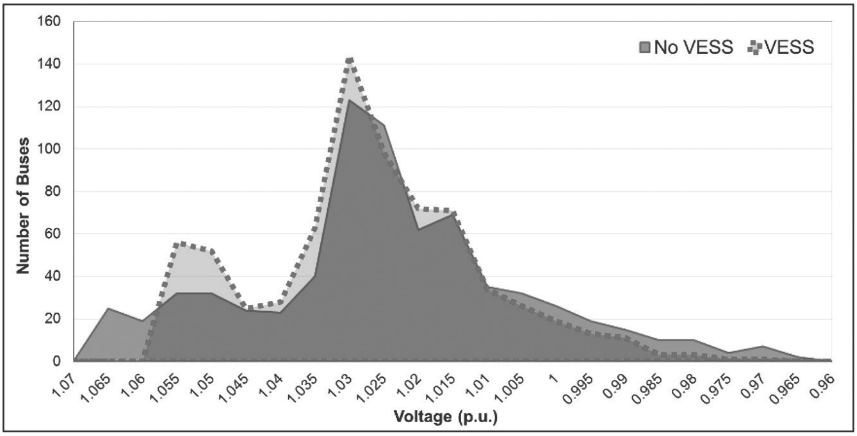

FIGURE 6.16 The distribution of voltages of all busbars over the day [28].

6.10 SUMMARY

In this chapter, a smart energy management paradigm, called a VESS, was presented. A VESS aggregates flexible demand units and small-capacity energy storage units into a single entity which functions similarly to a large-capacity conventional ESS.

An overview of components of a VESS was first introduced. DR programmes that utilise flexible demand in the power system were briefly reviewed. ESSs were classified. Some of enabling technologies for the VESS were briefly listed. Potential applications of VESS in power systems and its potential benefits were discussed.

A frequency control scheme of the VESS was designed. The control scheme provides low, high and continuous frequency response services to the TSO. The centralised control scheme coordinates a large number of domestic refrigerators and a small number of flywheel energy storage units.

A voltage control scheme of the VESS was also designed. This control scheme facilitates a larger penetration of distributed renewable energy generation by supporting the voltage control of distribution networks. The control scheme coordinates bitumen tanks and battery energy storage units by implementing different time delay settings for the voltage controllers.

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