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Flexibility services based on Connected and Interoperable Hybrid Energy Storage Systems

FlexCHESS

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D1.2 Report on FlexCHESS concept

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Report on FlexCHESS concept

Abbreviations

AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
ARC	Aggregators of Retail Customers
CAPEX	Capital Expenditure
CHESS	Connected Hybrid Energy Storage System
CHP	Combined Heat and Power
CSP	Curtailment Service Provider
DER	Distributed Energy Resource
DNO	Distribution Network Operator
DSO	Distribution System Operator
DG	Distributed Generation
DR	Demand Response
DRP	Demand Response Provider
DLT	Distributed Ledger Technology
DT	Digital Twin
ESS	Energy Storage Systems
EV	Electric Vehicle
FESS	Flywheel Energy Storage System
FlexCHESS	Flexibility services based on Connected and interoperable Hybrid Energy Storage System
GB	Great Britain
HP	Heat Pump
OLTC	On Load Tap Changing
OPEX	Operational Expenditure
PV	Photovoltaic
RES	Renewable Energy Source
SME	Small and Medium-sized Enterprise
SOC	State of Charge
ToU	Time-of-Use
TSO	Transmission System Operator

VESS	Virtual Energy Storage System
VPP	Virtual Power Plant
VR	Voltage Regulator
V2G	Vehicle-to-Grid

Executive Summary

FlexCHESS project is aimed to propose cutting-edge solutions based on Digital Twin (DT) concept, Virtual Energy Storage Systems (VESSs) and Distributed Ledger Technology (DLT) to revolutionise the existing practices in aggregating Connected Hybrid Energy Storage System (CHESS) for providing various ancillary services at the distribution and transmission network levels.

This deliverable report D1.2 presents the research results of Task 1.2 “Definition of FlexCHESS concepts” of the FlexCHESS project. This report first presents various concepts regarding FlexCHESS involved in the project, and then focuses on the key concepts regarding the quantification and exploitation of flexibility, as required in Task 1.2.

The key terminology in the project is first presented, including those at the whole project level, the physical system level and the tool level. The vision, value and mission of FlexCHESS are then described, followed by the technical framework, which interconnects various concepts in the FlexCHESS project. After that, a more detailed and comprehensive taxonomy of FlexCHESS is provided. Two vital concepts throughout the project, complementarity and interoperability, are also described and analysed in the context of flexibility quantification and exploitation.

Then the concepts regarding flexibility, which is the key focus of the project, are presented. Flexibility is of great significant for electric power systems with increasing penetration of variable Renewable Energy Resources (RESs) and soaring electricity demand mainly due to the electrification of transport and heat. Flexibility is also a research topic at the frontier. A number of variants of the concepts of flexibility have been reviewed, which are similar in nature although with different focuses and expressions. Generally, being flexible in terms of energy use means having the ability to shift energy use in time and space, or through changes in intensity or vector, for achieving a secure, reliable, and continuous energy supply.

The drivers of the research and development activities on flexibility are analysed, including the development of renewable energy and electric vehicles as well as flexible electricity pricing schemes and variable fuel prices. The technologies that can provide flexibility are also presented, including heat pumps (HPs), electric vehicles (EVs), combined heat and power (CHP) units, solar PV and wind generators as well as energy storage systems (ESSs). The temporal and spatial characteristics of flexibility are then analysed. The indicators characterising flexibility are further presented, including magnitude, ramp rate, ramping capability, response time, time availability, and costs.

For flexibility exploitation, the challenges are first analysed, and VESSs are proposed as the solution. A VESS aggregates distributed energy resources (DERs), functioning similarly to a large-capacity conventional ESS. VESSs can coordinate and utilise the complementary features of flexible demand units and ESSs – overcoming the uncertainties in flexible demand at the same time reducing the costs of using more expensive ESSs.

The potential applications of VESSs are presented, including facilitating the integration of distributed generation (DG) in distribution networks, reducing reserve margins, deferring transmission and distribution systems reinforcement, and providing other ancillary services. The benefits of VESSs are summarised for various parties, including VESS components owners, transmission and distribution systems, supply side of power systems, as well as Virtual Power Plants (VPP).

Finally, two example applications of VESSs are presented, i.e. frequency support and distribution network voltage support. The components, modelling and control for both cases are provided, with the simulation results presented. In the case study of frequency support, it is shown that VESSs combining flexible refrigerators and flywheel ESSs are able to achieve same level of frequency support with only one-third capacity of flywheel ESSs, reducing the overall costs. In the case study of voltage support, it is shown that with VESSs the voltage issues of the distribution network can be mitigated and the number of actions of On Load Tap Changing (OLTC) and Voltage Regulator (VR) transformers can be reduced by 30% extending the lifetime of the devices and thus saving the replacement costs.

1. Introduction

The large-scale integration of renewable energy sources (RESs) has introduced a new operating paradigm. RESs are characterised by uncertainty and volatility. Moreover, the overloading of transmission and distribution feeders has become more frequent. The curtailment of renewable power generation has thus increased, contradicting the goals for high shares of RES. A valuable solution to these challenges is the introduction of flexibility from flexible resources and loads. In this context, the FlexCHESS project proposes cutting-edge solutions based on Digital Twin (DT) concept, Virtual Energy Storage Systems (VESSs), and Distributed Ledger Technology (DLT) to revolutionise the existing practices. Based on the aggregation of Connected Hybrid Energy Storage Systems (CHESSs), FlexCHESS improves grid stability while increasing the profitability of its installations by guaranteeing various ancillary services at the distribution and transmission network levels. FlexCHESS will also ensure the highest level of interoperability of the proposed solutions and enhance the innovation capacity and competitiveness of Small and Medium-sized Enterprises (SMEs) and Startups in Europe by unlocking access to meaningful information and co-creating new business opportunities. This will be achieved by appropriate promoting open innovation and making smart technologies as an asset for the intelligent business. In order to validate and evaluate the proposed solutions, five pilot sites with diverse assets in different European countries are planned. The aggregation and optimisation of different resources will be extended to take into account not only electrical energy storage systems (ESSs), but also multi-ESSs. Thus, the FlexCHESS project will define different scenarios allowing to evaluate the performances and flexibility capability of CHESS. FlexCHESS project Consortium gathers 3 universities, 2 large companies, 3DSOs, 4 SMEs, and 2 NGOs.

This deliverable report D1.2 presents the research results of Task 1.2 “Definition of FlexCHESS concepts” of the FlexCHESS project. This report focuses on the concepts regarding the quantification and exploitation of flexibility. In Section 2, the concepts, drivers, and providers of flexibility are presented with the temporal and spatial characteristics followed. Then key indicators are presented for quantifying flexibility from different perspectives. In Section 3, the VESS is introduced to exploit the flexibility from large numbers of widely spread ESSs. Specifically, the challenges of exploiting flexibility are first presented, and then the solution, VESS, is described from the perspectives of concepts, components, and potential applications and benefits. Two example applications, i.e., frequency support and distribution network voltage support, are further presented. Finally, Section 4 concludes the report.

2. The concepts in the FlexCHESS project

2.1 Key terminology in the FlexCHESS project

Key terminology in the FlexCHESS project is first provided in Table 2-1 below before key concepts are discussed in the latter sub-sections.

Table 2-1 Key terminology in the FlexCHESS project

Terminology	Definition	Type
FlexCHESS	Concept of the project providing **Flex**ibility based on the **C**onnected **H**ybrid **E**nergy **S**torage **S**ystem	Concept
HESS	Hybrid and various energy storage systems (ESSs) and flexible loads (e.g., smart appliances)	Physical system: energy storage / flexible loads
CHESS-plug	Physical component (adapter) to adapt and connect HESS	Physical system: adapter / gateway
CHESS	Locally **C**onnected **H**ybrid **E**nergy **S**torage **S**ystem	FlexCHESS Tool: CHESS-plug + HESS
CHESS Node	Aggregation of distributed CHESSs based on Virtual Energy Storage Systems (**VESS**s)	FlexCHESS Tool
FlexPlatform	Digital layer of the FlexCHESS composed by the digital twin (**FlexShadow**), knowledge base and data driven services	FlexCHESS Tool: Digital layer

2.2 Vision, value, and mission of FlexCHESS

The **vision** of FlexCHESS is to revolutionise the existing paradigms of energy storage by developing a multi-level flexibility approach based on VESS that can store surplus energy through HESS and modify their behavior and architecture to support unpredictable growth and change of demand, climate and market. FlexCHESS will enhance the innovation storage capacity and competitiveness of the smart grids in Europe based on VESS-centric approaches to address uncertainties and weaknesses related to the extensive integration of variable renewable energies into the electricity market. This will be achieved by the appropriate promotion of open innovations and making the smart technologies as an asset for the intelligent business.

The **value** of FlexCHESS is to guarantee a strict green VESS and minimise the energy curtailment. This will be reached by ensuring the transparency and traceability of stored energy in parallel with information sharing while protecting private data related to each actor. Also, we embrace creativity and innovation to deliver flexibility services and the best practical outcomes.

The **mission** of FlexCHESS is to provide an easy-to-use platform configurable through a simplified interface and make the aggregation of different ESS technologies from various brands easier and accessible to the largest number of users.

2.3 Technical framework of FlexCHESS

FlexCHESS aims to provide innovative tools to facilitate the integration of renewable energy sources into existing grid systems while ensuring the stability of the energy system and flexibility of ancillary services (mainly scheduling / dispatch, balancing, reactive power, frequency and voltage control). FlexCHESS aims to develop three tools: Flex-Platform, FlexVESS and CHESS, as shown in Figure 2-1.

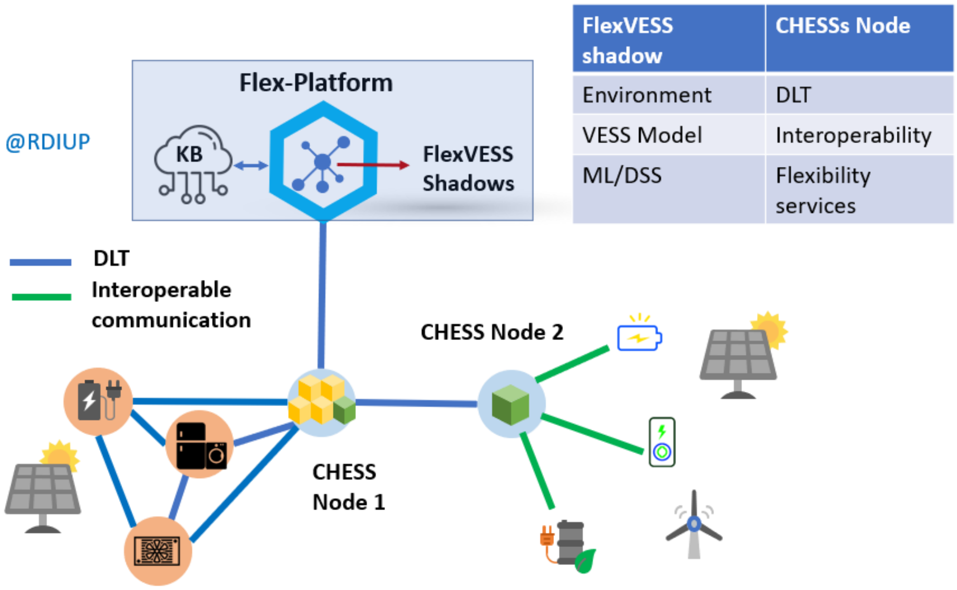


Figure 2-1 FlexCHESS tools

The FlexPlatform is a data and information service provider. It will collect data and information from real-time measurements of the physical systems (e.g., generation output, demand, voltage and current of the network), information on surrounding environment (e.g. price signals, weather info), and FlexShadow. It will further process such data and information using advanced software tools, e.g. machine learning, in order to provide an accurate and coherent data and information set for facilitating better decision making of the participants. It is not a data and service provider rather than a centralised operational centre. It will have a clear strategy on the data transparency and privacy.

Moreover, the PlexPlatform makes use of the digital twin concept which will combine the virtual and physical worlds together to make better decisions, reduce risks and perform forecasting. The digital twin comprises three main elements:

- The historical data collected from different platforms which allow to understand the past of each VESS, propose improvements and learn lessons from other experiences,
- The near real time data that permit to monitor and optimise the decision-making and share experiences with other FlexCHESSs.
- The future data generated from AI/data-mining and Machine Learning to forecasting potential factors and increase flexibility.

The workflow of FlexCHESS is shown in Figure 2-2, and mainly includes two parts:

1) Flexibility provision: The short-term forecasting module (including the sky camera) will predict all energy resources (such as power generation from renewables and power consumption) and work in parallel with the digital twin in order to assess the offer capability of the VESS through simulations. Then, based on data received from CHESSs, the flexibility service provision engine will generate bids and return setpoints for each CHESS. The smart energy management tool will control each asset in order to provide required services and return feedback to the cloud-base FlexPlatform.

2) Optimisation of VESS and CHESS: based on the received feedback, the digital twin will compare the real and digital behaviour to identify deviations and possible operating improvements. The smart decision support system, in interactions with the knowledge bases,

will recommend high-level optimisation of the CHESSs in order to reduce costs and/or carbon footprint and optimise the size of HESS compared to similar ones.

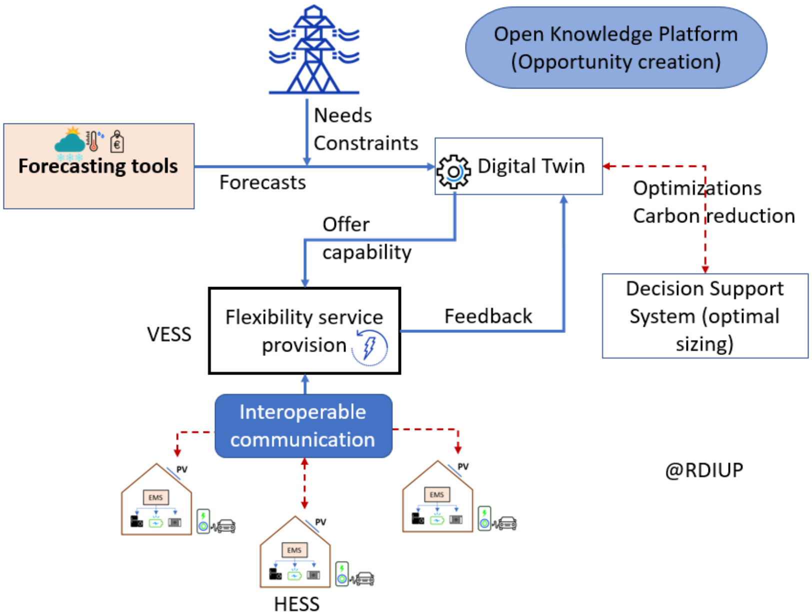


Figure 2-2 Simplified workflow of the FlexPlatform

2.4 Taxonomy of FlexCHESS

A taxonomy has been defined based on the Smart Grid Architecture Model (SGAM) to introduce next generation interoperable storage energy management to increase the performance of FlexCHESS, as shown in Figure 2-3.

2.5 Complementarity and interoperability

Complementarity and interoperability are two key concepts embedded throughout the whole project regarding the provision of flexibility services. Complementarity is the fundamental reason why connecting and aggregating many different types of ESSs is able to have non-linear increments in the benefits generated, realising the effect of “1+1>2”. The complementarity can be reflected by spatial complementarity when the power output of ESSs complements each other in different spaces or regions, temporal complementarity when their power output complements each other at different periods in the same region or space, as well as spatiotemporal complementarity combining the complementarity in both temporal and spatial dimensions [1]. The complementarity can be quantified via an index calculated by the product of sub-indexes measuring complementarity based on time, energy and amplitude [2], or another index averaging sub-indexes measuring the complementarity from short-term, long-term, and storage perspectives [3]. The complementarity of multiple types of ESSs can be utilised by the VESS approach presented in Section 4 of this report, and the resulting flexibility can be quantified by the indicators presented in Section 3 of this report.

Interoperability refers to the capability of multiple parties in exchanging and making use of data and information. Interoperability is thus vital to coordinating large numbers of ESSs, usually belonging to different owners and having different brands and data protocols, to provide various types of flexibility services required by multiple stakeholders. Interoperability will need to be achieved at all levels regarding flexibility service provision, from physical measurement equipment to control devices and further up to the digital twin level. Interoperability is essential to realised the flexibility described in this report.

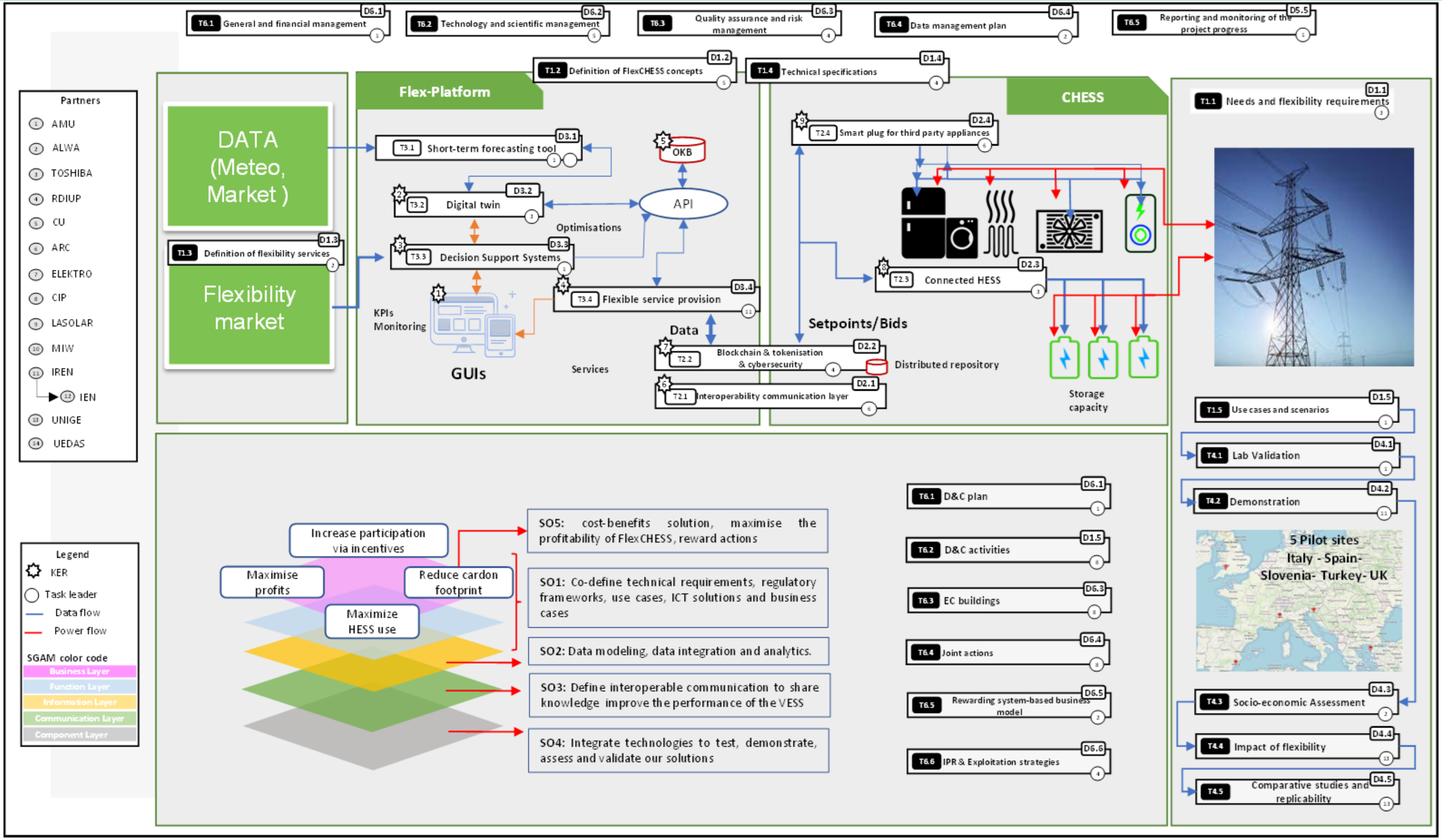


Figure 2-3 Taxonomy of FlexCHESS

3. Flexibility quantification

3.1 The concept of flexibility

In energy systems, the combination of challenges such as the need to integrate variable renewables and the emergence of digital innovation has intensified interest in flexibility. Being flexible in terms of energy use means having the ability to shift energy use in time and space or through changes in intensity or vector. This ability is determined by the combination of a wide variety of factors [4].

For the concept of flexibility, many scholars have given the definitions. Zade *et al*. [5] define the flexiability as “the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons”. The Union of the Electricity Industry—Eurelectric—defines flexibility in a more application-oriented way, as “the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system”. Ma *et al*. [6] define the flexibility as “the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons”. Paiho *et al*. [7] define the flexibility as “the ability of an energy system to adjust, with an acceptable ramp rate, and maintain its electricity generation/consumption inside a specified range within a given period in order to support the operation of the power grid”. Kleinschmidt *et al*. [8] define the flexibility as “the ability of controllable power system components to produce or absorb power at different rates, over various timescales, and under various power system conditions”. Therefore, there is a huge emphasis in the research community on managing flexibility in electricity systems. Babatunde *et al*. [9] define the flexibility as “the degree to which a power system can adjust the electricity demand or generation in reaction to both anticipated and unanticipated variability”. A techno-economic definition by International Energy Association [10] states that “Power system flexibility is the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales”.

All in all, the power system needs to be in balance, i.e. power supply and demand in the electric grid have to match at each point of time, and flexibility indicates the capacity of a power system to reliably sustain supply during transient and large imbalances. The energy systems are built in such a way that it has, up to a certain point, the capability to cope with uncertainty and variability in both demand and supply of power. From the electricity system point of view, flexibility relates closely to the grid frequency and voltage control, delivery uncertainty, variability, and power ramping rates [11].

3.2 Drivers of flexibility

Factors that drive research into the flexibility of power systems mainly include the uncertainties of renewable energy, electric vehicles (EVs), time-of-use (ToU) prices, and fuel prices. For example, forecasting of renewable energy generation is impacted by weather forecast uncertainty, and electricity prices are affected by both variations in load and renewable energy generation as well as by the actions of other participants in the electricity market.

3.2.1 Renewable energy

Energy production based on renewable energy often fluctuates due to seasonal or other weather conditions. On one hand, this supports decentralization of the energy systems, on the other hand, the outputs of variable RESs are not constant and therefore cause uncertainty.

The variability and unpredictability of renewable energy occur on different time scales: seconds, minutes, hours, days, months, seasons, and years. Potential mismatch can occur between the supply and the demand, or congestion in some transmission nodes of the grid, and therefore increases flexibility requirements of the entire energy system [12].

The rapid inclusion of a large share of renewable energy into the grid is a major factor known to drive investigation in power system flexibility [7]. The fluctuation affects the power plant mix, power plant dispatch sequence as well as the frequency. As such, power system flexibility is inevitable. The intermittent nature of the electricity generated from solar (solar thermal and photovoltaic) and wind energy technologies is caused by the variability features of the solar and wind resources and affects the distribution and transmission networks. The intermittent features of these resources are caused by changes in weather conditions and can reduce the capacity of wind turbines by 100% on calm days and up to 70% for solar-powered plants on cloudy days. These values are greater than that experienced due to the use of conventional generators and variability in load demand. As the penetration of variable RES within power systems increases, this problem becomes significant and more challenging to manage. Hence, a need for inclusion flexibility in the power system network arises [9].

3.2.2 Electric vehicles

Electric vehicles (EVs) are high-capacity loads, and their charging behavior has high level of uncertainty and produces a negative impact on the power system. Affected by the high uncertainties of weather, traffic, and driver behavior, the charging demand of EVs is difficult to forecast accurately. Moreover, due to many conditions that may have significant effects on the EV status, the actual data of aggregated EVs, especially arrival and departure times as well as trip energy consumption, change greatly from day to day and cannot be perfectly forecasted [13].

3.2.3 Time-of-use prices

Time-of-use (ToU) electricity tariffs are currently employed or considered for implementation in many jurisdictions around the world. In ToU modalities, a set of different tariffs for different hours of the day and/or seasons of the year are defined at the beginning of a given horizon, and then kept constant until its end. While designing ToU tariffs, one of the most significant sources of uncertainty to be considered relates to price-elasticities of demand. There is high uncertainty regarding price-elasticities of electricity demand, which are the parameters that describe how consumers respond to electricity prices [14].

3.2.4 Fuel prices

Fluctuations in conventional fuel prices and their availability especially for natural gas and coal, are also major sources of uncertainty during generation expansion planning. It is reported that the coal price is moderately stable, with an annual average increase of 2% while the price of natural gas is largely unpredictable. Natural gas is relatively the most expensive fuel in the mix, and its volatile prices cause a high level of uncertainty [9].

3.3 Enablers of flexibility

Digital technologies are the main way to facilitate the use of flexibility in power systems. Through the application of digital technologies, the temporal and spacial complementarity of flexibility can be better utilised. The commonly used digital technologies include blockchain, digital twin, advanced metering infrastructure (AMI), artificial intelligence (AI), etc.

1） Blockchain technology is an advanced database mechanism that allows transparent information sharing within power systems. Blockchain technology can assist multiple applications at the generation, transmission, distribution, and consumption stages in power systems to resolve relevant challenges.

2) Digital twins are systems of advanced sensing, communication, simulation, optimisation and control technologies, and can provide updating system states and prediction, based on which the flexibility of power systems can be greatly improved.

3) AMI enables two-way communication for meter reading and control signals sending at a higher frequency, thus being able to facilitating the utilisation of flexibility.

4) AI is intelligence—perceiving, synthesizing, and inferring information—demonstrated by machines, which has the potential to cut energy waste, lower energy costs, and facilitate and accelerate the use of clean renewable energy sources in power systems. At present, AI has been more and more applied in improving the flexibility of power systems.

3.4 Providers of flexibility

Large-scale flexibility products are widely used to stabilise the power system. On the supply side, system operators use measures such as redispatch and feed-in management. On the demand side, they use sheddable loads and industrial demand-side-management as grid ancillary services. While regulation and various market designs for energy trading already exist, academic and industrial research now focuses on introducing unique flexibility platforms. Such new platforms will allow residential consumers and prosumers to participate with their distributed energy resources (DER)—such as combined-heat-and-power units (CHP), electric vehicles (EV), residential heat pumps (HP), photovoltaic systems (PV), and battery storage units—as well as large industrial parties to offer flexibility [7].

3.4.1 Heat pumps

Heat pumps (HP) with thermal storage offer the possibility to decouple heat production and its associated electricity demand from the heat demand of a building over a certain time period. This offers the possibility to adjust operation to external needs to some extent [15]. Large HPs increase the flexibility of district heating systems and heat production, as they enable the use of electricity in heat production and increase flexibility between electricity production and consumption depending on the price of electricity [7]. HPs are capable of responding to load changes at a fast rate, due to which it is also considered an ideal flexibility resource. It also provides phase modulation, frequency modulation, and voltage regulation [16].

Moreover, electric heat pump systems are accompanied by heat storage for space heating. Different flexibility potentials are associated with such loads, such as the allowance of indoor temperature variation by the users within their specified thermal comfort level boundaries or the incorporation of some form of heat storage (e.g., hot water tanks) in the heating system, with the latter exhibiting a more significant potential and attracting the authors' interest due to its ability to preserve the desired level of service (i.e., temperature) delivered to the users [17].

3.4.2 Electric vehicles

EVs have been one of the key components in smart grid-related research involving flexibility with demand response or other similar concepts. If EVs are guided for charging in order and combined with demand response, these can be used as a flexibility improvement option with distributed energy storage devices [16]. Moreover, vehicle-to-grid (V2G) can provide several services to the power grid, such as ancillary services, peak load shaving, load leveling and support for renewable energy resources [7]. The EV demand flexibility potential is significant due to their inherent ability to store electrical energy in their batteries, their stationary character (parked for more than 90% of the time) and their low energy consumption requirements with respect to the significant energy and power capacities of their batteries [17].

3.4.3 CHP units

A CHP unit is a coal/gas-fired power unit, which has been widely used due to its high efficiency. Technical flexibility of the CHPs refers to the minimum load, startup time and ramp rate. The minimum load is the ability of CHP units to produce minimum power in order to reduce renewable energy curtailment and decrease financial loss during low energy price periods. The ramp rate is the ability to change the power output in order to realize the generation-load balance. Market incentives for delivering the quick ramp rates are the variable energy prices that the CHPs can follow quickly. The startup time is the ability to react to a sudden power imbalance like demand increase and outage of generation units. The technical flexibility can be represented by the operation region of heat and power output of the CHP system when the heat-to-power ratio is various. The adjustment of the ratio is realised by controlling the physical components inside the CHP unit [18].

3.4.4 PV/wind generators

Large-scale grid-integrated renewable energy influences security and stability of a power system network. Centralised wind power plants and solar power plants equipped with efficient controllable mechanisms provide good flexibility under certain conditions [16]. In the context of renewable energy generation scheduling and planning, the objective is to manage the daily net load cycle, the variations of which can be adequately examined on an hourly time scale. Very fast variations are smoothed out due to the inertia of the large rotating blades of variable speed wind turbines [19]. When considering a large area with geographically dispersed wind farms, the second and minute variations are mitigated by the smoothing effect of wind generation diversity. In addition, variations over longer time scales (days, months, seasons and years) are reflected by the aggregated effect of the hourly variations. Therefore, flexibility should be evaluated on an hourly basis [6].

3.4.5 Storage systems

Flexible energy storage systems have substantial inherent advantages in comparison with many currently employed systems due to improved versatility, performance and potentially lower cost [20]. Storage systems technologies are used in the power system to improve flexibility at large scales and increase the flexibility to utilise sources of energy that are not available at the same time as the demand [16]. All these technologies allow for storing supply surplus for later demand and thus provide flexibility by temporal unbundling of supply and demand, and thus a flexible share of storage systems can maximise the potential benefits for both parties [21].

3.4.6 Smart appliances

The smart appliances include smart washing machines, dishwashers, tumble dryers, electric hot water buffers, etc., which can offer residential flexibility. A better day-ahead electricity generation/consumption balance can be achieved using the flexibility offered by the smart appliances. The flexibility potential can be estimated as the extrapolated electricity demand from some selected residential smart appliances. The residential flexibility of smart appliances can be used to decrease voltage deviations in electricity distribution networks, caused by local power generation as well as increased consumption. Moreover, the lifetime of distribution transformers can be increased by using smart appliances to lower transformer temperature and sustained current peaks [22].

3.5 Temporal characteristics of flexibility

Since the flexibility of a system is determined by both the physical attributes of a system's resources and the operation of those resources, the resources cannot be deemed to be independent and the temporal correlation between the flexibility of resources must be preserved. The addition of each resource's time series of available flexibility to form a system flexibility time series results in a resource model which appropriately accounts for the interdependence between resources. The flexibility available from each resource can be obtained at each instance by examining historical or simulated production time series [23].

The production time series for each flexible resource is required since the flexibility available in either direction is limited by the maximum rated output and current production for upward flexibility, and between current production and the offline state for downward flexibility, assuming sufficiently long time horizons to reach these limits. By employing a production time series, the operator's adversity to risk from forecast errors is included in the resources' availability to ramp [23]. Moreover, the time horizons studied may be chosen based on criteria such as the magnitude of ramping events or the frequency of occurrence of monotonic ramps in each time horizon. Chosen time horizons may also coincide with the start-up times of common generation technology (e.g., combined cycle gas turbine) in a system, or an important operational time frame, such as a forecast horizon [23].

3.6 Spatial characteristics of flexibility

The spatial characteristic of flexibility refers to the comprehensive use of different flexibility resources between one or more regions, so the flexibility requirements of one region can be provided by another region. Interconnection of power grids of nearby regions will help to exchange power between these grids, which increases the supply demand balance, increasing flexibility. Interconnections of power grids and market transactions, dispatching modes can be adopted to improve the flexibility of power systems to some extent [16]. A main source of flexibility is grid exchange between regions. It appears that the highest levels of interconnections are found around areas rich in wind, rich in solar resources, or with extensive hydropower resources [24].

3.7 Indicators characterising flexibility

The flexibility requirement of a power system is quantified in terms of various metrics. These metrics describe the flexibility at operational timescales. A power system can be operated at various levels of flexibility estimated on selected timescales which vary from a few seconds to months, and all time intervals require different levels of flexibility [16].

3.7.1 Magnitude

Magnitude is the generation capacity required to respond to a ramp event on the supply side whereas, on the demand side, incremental and decremental flexibility requirements are dependent on the size of the net load ramp or outage [16]. Since different types of events lead to deviations between the forecast and actual values of the net load and thus require the deployment of flexibility resources. In specific, the difference between the net load at the beginning and the end of the time interval gives the magnitude of the deviation. If the magnitude is positive, this deviation requires up flexibility, that is, the ability of generators to pick up load or the ability of adjustable loads to reduce their consumption. On the other hand, a negative value means that down flexibility must be deployed, that is, controllable generators must reduce their output or adjustable loads must increase their consumption [25].

3.7.2 Ramp rate

Ramp rate means the capability to increase or decrease power and, sometimes, energy output after start-up, synchronization to the system, and to hold the technically required generation "set" points, for operation between minimum load and maximum continuous rating as it may be changed from time to time. Ramp rate measures how quickly a plant can change its output.

It is generally calculated as the capability of a unit between its minimum and maximum levels. It is expressed as percentage (of unit rating) per minute, and MW/min is the unit used to define ramp rate [26]. The capability of the reserve source which can provide positive and negative ramp rate is defined as the degree of meeting the variation of the load and renewable energy sources [27].

3.7.3 Ramping capability

Ramping capacity is characterised in terms of power capacity (MW), ramp rate (MW/min), that is, the ability to increase power and energy production with a certain rate, and ramp duration (min), that is, the ability to sustain ramping for a given duration [28]. Some resources can provide large amounts of ramping capacity over several hours, e.g. coal-fired plants, but cannot provide much ramping capacity in intra-hour time intervals. Smaller, fast acting resources can provide a higher share of the system flexibility in intra-hour intervals, but a smaller share over longer intervals [29].

3.7.4 Response time

The response time indicates how fast the system is expected to react to state deviations and restore the system to its normal state. The time window can be seconds, minutes, hours, days, and months depending on the purpose of study. A system may have different flexibility levels based on the selected response time. Shorter time windows focus on short-term operational flexibility, which indicates a system's timely response to emergencies in minutes or hours. Longer time windows focus on long-term planning, which shows a system's ability to cope with changes such as generation mix, regulatory policy, and electricity consumption pattern changes, in years. A power system may show more flexibility in longer periods while lacking it in shorter time frames. For example, a system might have sufficient capacity to cope with demand growth in a period of a year, but not enough to adapt to daily load fluctuations. Therefore, the time horizon has to be determined when we compare and evaluate system flexibility [30].

3.7.5 Time availability

It is important to understand the system flexibility over a range of time horizons, as data permits, and time availability play an important part in the evaluation of flexibility. Different flexibility resources have different flexibility in different time periods. For example, the flexibility of photovoltaic power generation only exists during the day, while the flexibility of wind power generation exists throughout the day. Therefore, it is of great significance to analyse the time availability of flexible resources for improving the supply and demand balance of power systems [23].

3.7.6 Costs

The costs for flexibility in power systems are related to the extra resources that are needed to realise and operate a more flexible power system. For example, information and communications infrastructure has to be upgraded and operated in a different way to support more advanced control needed to utilise flexibility. The corresponding costs can mainly be divided into two categories: capital expenditure (CAPEX), e.g., the investments to build new infrastructures or adapt existing ones, and operational expenditure (OPEX), which comprises all the increased costs for operating infrastructures due to flexibility provision [31].

3.7.7 Baseline

The baselines for flexibility in energy systems is the output of uncontrollable loads plus the original scheduled/dispatched controllable loads. Baselines are needed for quantifying how much flexibility is provided. System operators and flexibility providers need to agree upon such a baseline to define and verify flexibility activations [32].

4. Flexibility exploitation

4.1 Challenges of exploiting flexibility

The main barriers to exploiting the flexibility from the distributed energy resources, such as flexible commercial, industrial and residential demand, behind-the-meter energy storage systems and electric vehicles are presented in this section. Barriers to wider utilisation of the flexibility from the distributed energy resources can be classified into mainly four categories, i.e. economic, technical, social and regulatory.

- Economic challenges

A key economic barrier to broader participation in flexibility provision programs is predominately concerned about limited profitability and revenue uncertainty [33]. As financial incentives might not be sufficiently attractive, and variability associated with wholesale market prices, wear and tear of equipment and penalties for not participating during an event might all cause additional expenses [33]. Additionally, high costs of installation, management and maintenance are frequently indicated barriers [34]. Furthermore, The hidden costs associated with participation in flexibility markets, such as negotiation and enforcement transaction costs can also represent a barrier [35].

- Technical challenges

The main reported technical challenges were related to the complicated maintenance and installation of the devices, associated difficulties to operate and the availability and quality of the technical support [34]. The increase in the decentralisation and complexity of information systems and Internet of Things (IoT) reference models and architectures with a lack of standardisation on the interoperability of various components can pose technical challenges as well [35]. In addition, the equipment's ability to safely and reliably altered its power consumption or shut down and restarted without foreseen potential damages or violating manufacturers' specifications and warranties [33].

- Social challenges

The concern about participants' privacy and their sense of losing control of their equipment and constraints in the use of electricity at certain times were among the social and behavioural barriers [34]. The insufficient levels of credibility of the relevant parties, such as flexibility providers and buyers, and the level of trust between such parties can be also an important barrier [35]. Additionally, participants often value comfort over financial reward [33].

- Regulatory challenges

The regulatory challenges are often raised as a result of government policies or lack of them to support programs that exploit the flexibility from the distributed energy resources such as demand response schemes [33], [35].

4.2 The concept of Virtual Energy Storage Systems

The Virtual Energy Storage System (VESS) is defined as a collaboration between different controllable DERs to provide efficient services to power systems. DERs include flexible demand units and small-capacity energy storage units, however, other DERs such as Distributed Generation (DG) and multi-vector energy resources, e.g. CHP systems, can also be included in the VESS. A VESS, through virtually sharing DERs' storage potential, operates similarly to a large-capacity conventional energy storage system. The VESS concept addresses the uncertainty associated with the response from flexible demand by the coordination with energy storage systems.

A VESS is realised through an aggregator, allowing small-capacity flexible demand, energy storage systems and other DERSs to access the wholesale market and to 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.

The concept of VESS gained momentum in the literature recently. The concept is introduced to refer to a single flexible demand unit, i.e. residential air-conditioners [36], or an aggregation of flexible demand units, such as air-conditioning loads [37], and electric vehicles [38].

4.3 Components of a Virtual Energy Storage System

The two major components of VESSs, i.e. flexible demand units and energy storage systems, are presented in detail in this section.

- **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 prices changes or to incentives paid by power systems operators to improve system reliability [39].

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 demand response programs, while small flexible demand units are commonly aggregated by intermediaries, which are called demand response providers (DRPs), curtailment service providers (CSPs) or aggregators of retail customers (ARC) [40].

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 [41]. However, the share of domestic demand in demand response programs 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 [42]. Yet, a study for Great Britain (GB) revealed that the acceptance of demand response programs 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 DR programs [43].

Demand response programs are commonly classified into price-based and incentive-based programs based on how flexible demand is recruited. In the price-based demand response programs, consumers adjust their electricity consumption to changes in the electricity price. While incentive-based demand response programs are implemented through interruptible or curtailment contracts, in which consumers are paid to reduce or shift their electricity consumption. These demand response programs are deployed at different time scales within the power system. Sustaining the power system security and reliability is the main motivation for establishing incentive-based programs, while economic aspects drive the price-based programs. Typically, demand response in incentive-based programs is activated by events such as large frequency deviations, while changes in electricity prices often trigger demand response in price-based programs. Currently, flexible demand provides different services in several European countries and the USA, which include frequency regulation, congestion management and voltage regulation to Transmission System Operator (TSO) at the transmission system level and congestion management and voltage regulation to Distribution System Operator (DSO) at the distribution network level [44].

- **Energy storage systems**

The Energy Storage Systems (ESSs) are typically classified based on the stored energy form, into electrical, mechanical, electrochemical, and thermal energy storage systems, as shown in Figure 4-1 [45]. ESSs can be also categorized 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 super-capacitor ESS, flywheels ESS and superconducting magnetic ESS, which are often used for power management applications. Many types of battery ESSs have high energy and power densities, and hence, they might be suitable for both power and energy management applications.

Energy storage systems can provide a wide range of services to bulk power systems and microgrids. For example, these services can improve power quality and system stability and support the integration of renewable generation.

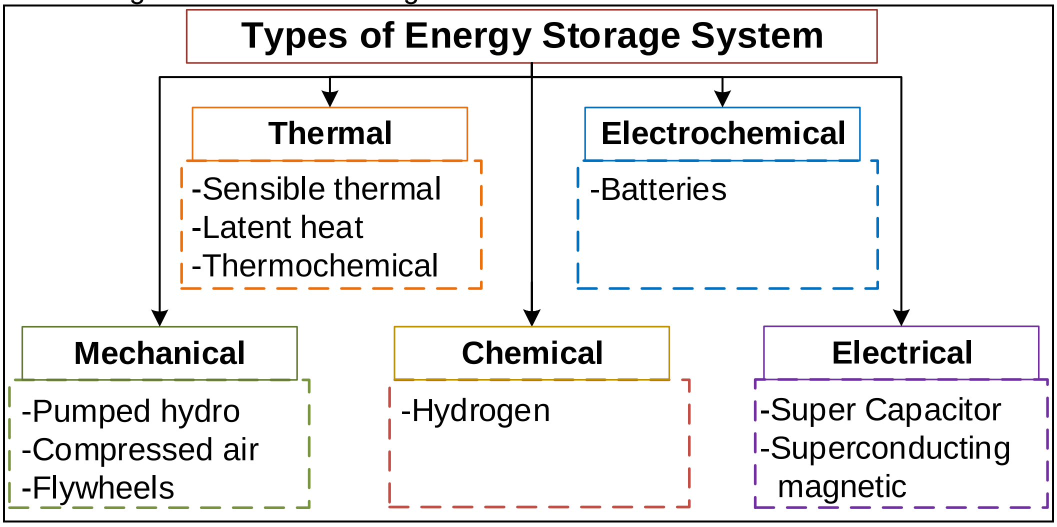


Figure 4-1. Energy storage systems used in the power system.

4.4 Potential applications and benefits of Virtual Energy Storage Systems

The 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 energy storage system 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.

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 utilized 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 emissions 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 enable the electrical networks upgrade deferral without comprising networks 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, and the influence of conventional generation companies on market prices may be reduced.

• Benefits for Virtual Power Plants (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 [46]. Consequently, the VPP has a high influence on 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.

4.5 Example applications of Virtual Energy Storage Systems

Two applications were chosen to establish the potential of the VESS. In the first application, the VESS is providing ancillary balancing services, i.e., frequency response, to the Transmission System Operator (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 Distribution Network Operator (DNO).

The control scheme of a VESS can be central, decentralised or hybrid, depending mainly on the required information exchange between VESS components, the 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 support. Additionally, 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. However, 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 voltage controller can manipulate the temperature set-points of industrial bitumen tanks to vary in line with voltage deviations.

A hierarchical or a hybrid 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.

4.5.1 A control scheme of a VESS for a system frequency support

The frequency control scheme of a VESS was developed. The VESS can provide low, high and continuous frequency responses to the power system. 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 [45].

- **Modelling of components of the VESS**

The thermodynamic model of refrigerators that was adopted from [47] is utilized 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 Flywheel Energy Storage System (FESS) which was developed in [48] 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.

- **The central controller and local controllers of refrigerators and flywheel energy storage units**

Following a frequency deviation, the required frequency response of VESS (ΔP_{VESS_req} (MW) in Figure 4-2) is determined by the droop control (R_{VESS}) with the droop coefficient 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 ($\sum \Delta P_{FESS\text{-}req}$ (MW) in Figure 4-2) is decided to 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.

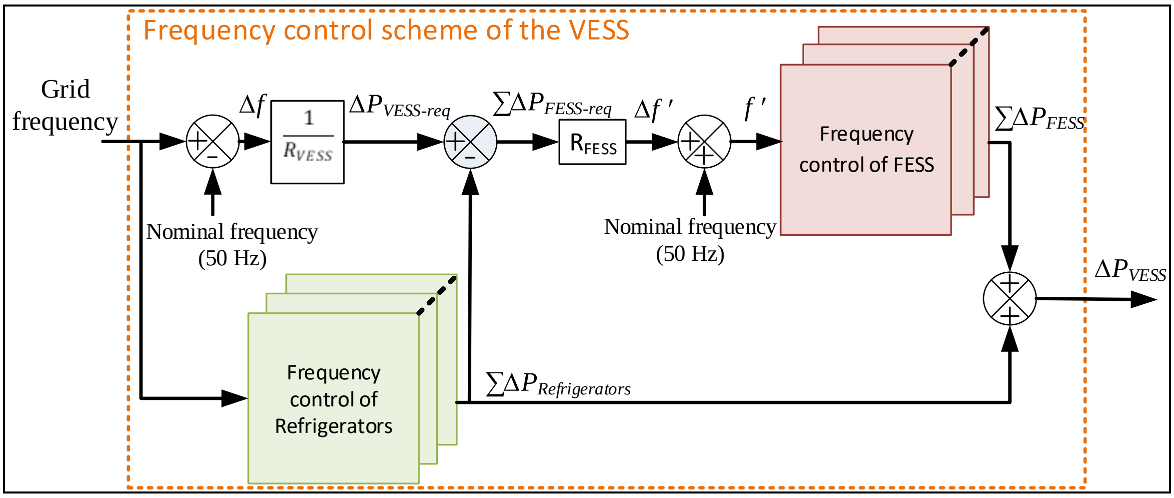


Figure 4-2. The central frequency controller of the VESS.

A local frequency controller is integrated, through a lookup table, into the internal temperature controller of a refrigerator as shown in Figure 4-3 and Table 4-1. The temperature controller continuously measures the cavity temperature (T_{Ca}) and compares it with set-points (T_{low}) and (T_{high}). If the cavity temperature reaches T_{high}, the controller generates state signal (S_T) equal to 1, or if it reaches T_{low}, the state signal generated (S_T) is 0. The frequency controller measures T_{ca} and defines a pair of frequency set-points (i.e., F_{ON} and F_{OFF}) 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 is consistent with the steady-state limits of grid frequency in the GB power system.

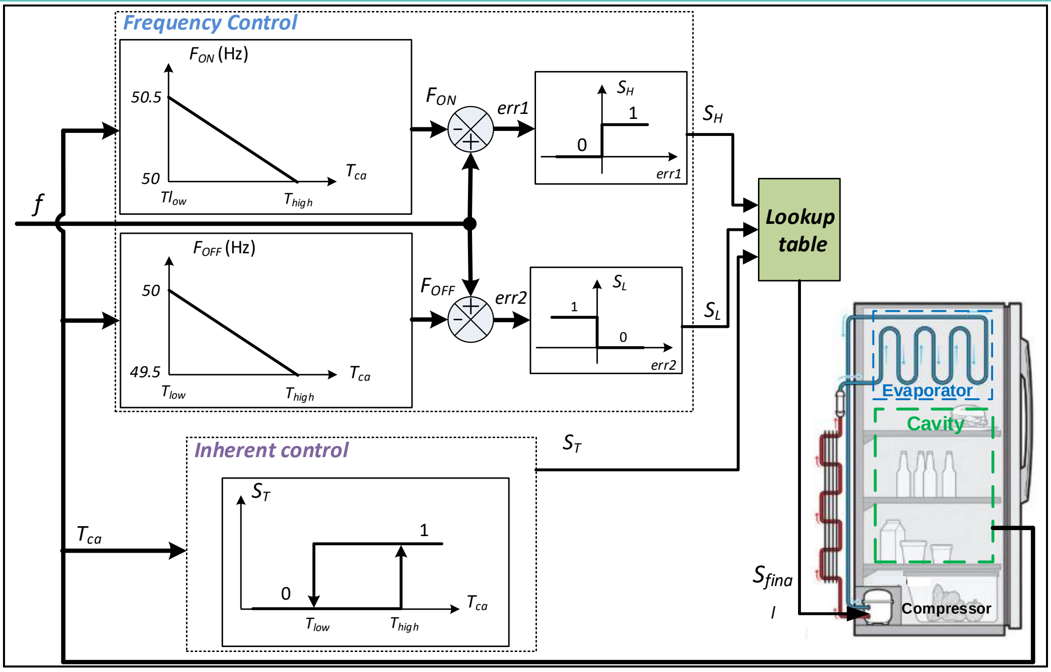


Figure 4-3. The integrated control of the refrigerator [49].

Table 4-1. Lookup table in Figure 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

In the case of a population of refrigerators, a refrigerator having a lower temperature than others will have a lower F_{ON} and a higher F_{OFF} values as indicated in Figure 4-3. 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 that will be committed to respond. When a temperature-diversified population of refrigerators 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 4-4. 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) of the FESS unit, which also represents the State of Charge (SoC) of the unit. The coordinated control measures ω and 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 4-4, ensures that the number of FESS units committed is linearly increasing with the increase in frequency deviations.

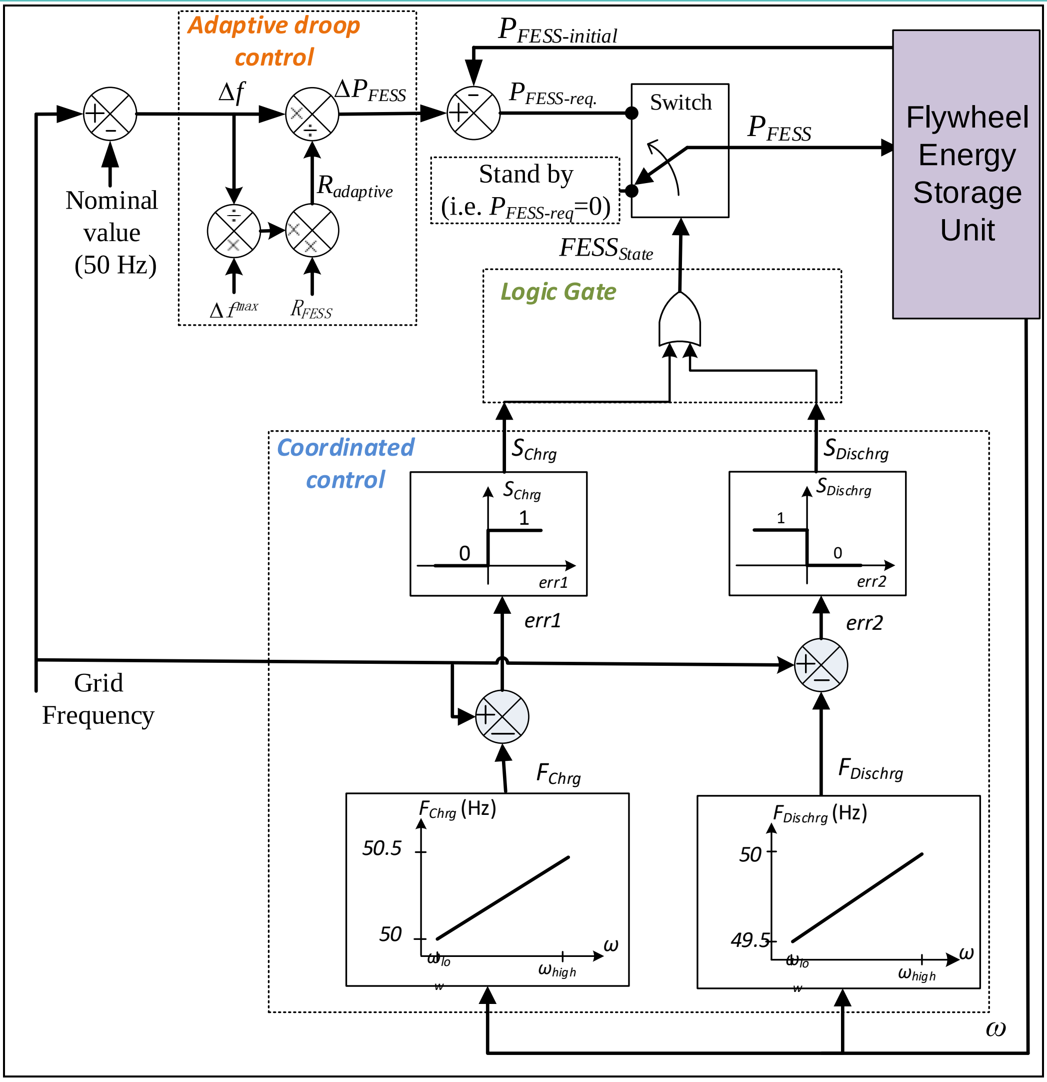


Figure 4-4. The frequency control of the FESS.

The adaptive droop control value ($R_{adaptive}$) is inversely proportional to frequency deviations (*df*) as shown in equations (1.a) and (1.b). Dictated by coordinated control, 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_{FESS} is required to increase the change of power output. When the frequency deviation increases and reaches the frequency deviation limits (df^{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.

$$R_{FESS} = \frac{\Delta f^{max}}{P_{FESS\_capacity}} \qquad (1.a)$$

$$R_{adaptive} = \frac{\Delta f^{max}}{\Delta f} \times R_{FESS} \qquad (1.b)$$

- **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 [49], [50]. Further details can be found in [41]. 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 a power reduction potential of 40 to 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% [19]. Considering the participation of 3,220,000 refrigerators (0.1 kW for each) a maximum power reduction of 60MW and a minimum power reduction of 40MW is expected. It is worth noting that the availability of refrigerators to be switched ON over the day is 50% to 56% [51], and hence, a maximum power increase of 180 MW to 160 MW is expected. 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 [52]. 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 4-5 and 4-6. The frequency drop in Figure 6 is restricted by 60 MW of response (please see **Figure 4-6.a**)) from either FESS (Scenario 2) or VESS (Scenario 3). Since 60MW of response is small in a 20 GW system, the frequency improvement of 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 [45].

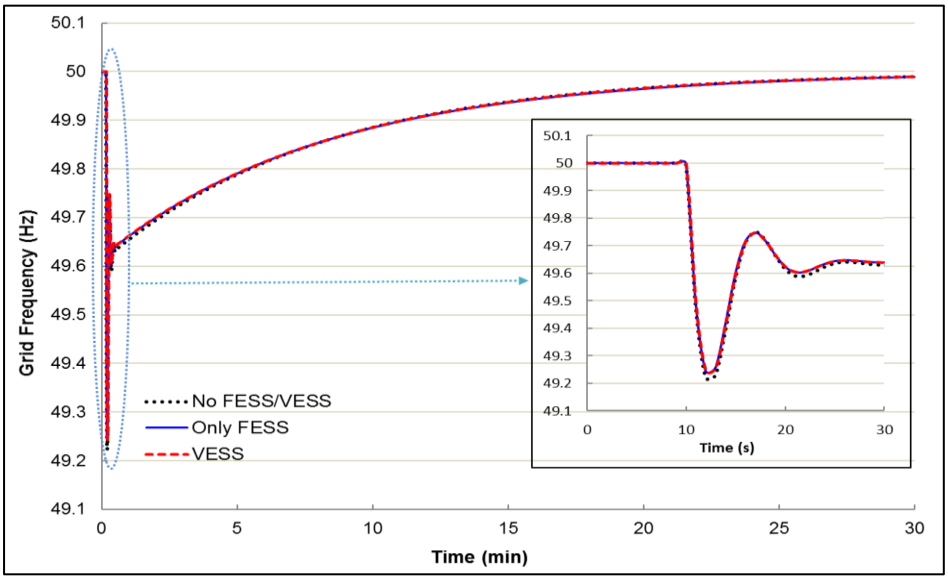
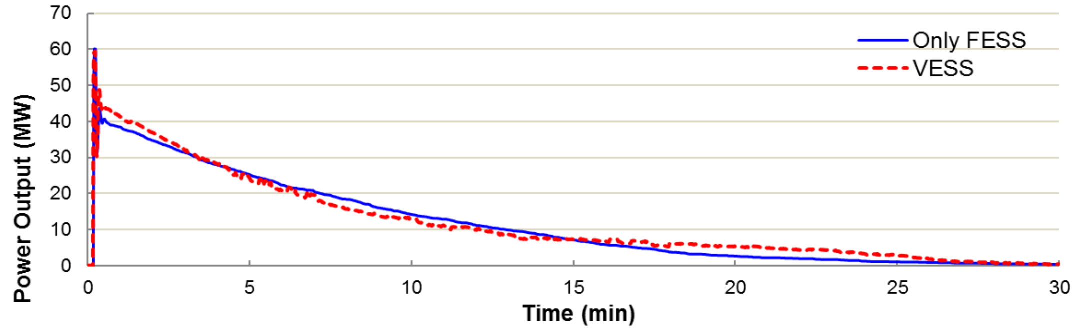
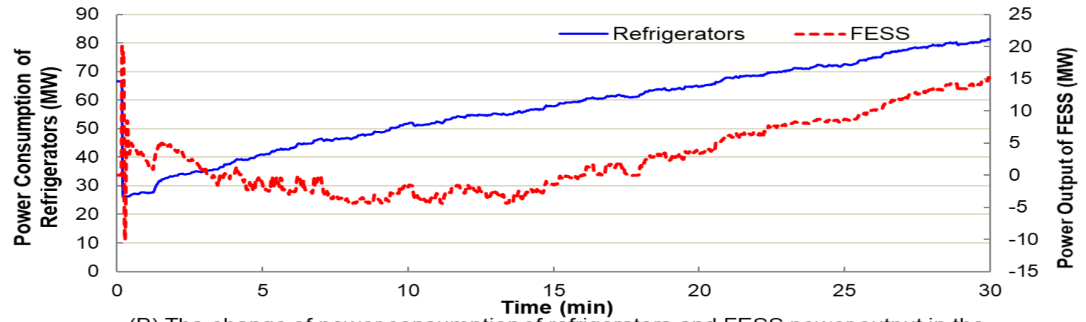


Figure 4-5. Variation of grid frequency after the loss of generation.



(A) The change in power output of VESS, FESS



(B) The change of power consumption of refrigerators and FESS power output in the VESS

Figure 4-6. The change in power output/consumption of (A) the VESS against the FESS and (B) refrigerators and the FESS within the VESS.

4.5.2 A control scheme of a VESS for a distribution network voltage support

The A voltage control scheme of the VESS was developed to support the distribution network voltage and hence allows more renewable generation in the distribution 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 (BT) and Battery Energy Storage Systems (BESS).

- **Modelling of components of the VESS**

A thermodynamic model of a BT adopted from [49] 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}.

A simplified model of BESS developed in [48] is used. The model consists of a generic battery model and a simplified power electronics model.

- Distributed controllers of the bitumen tanks and battery energy storage system.

The A local voltage controller was added to each BT's internal temperature controller [53], which has a similar structure to the frequency controller of refrigerators presented in Section 4.5.2. The voltage controller alters BT's power consumption based on local voltage measurements as shown in Figure 7. The temperature controller measures the bitumen temperature (T_{BT}) and generates state signals (S_T). The voltage controller measures the connection busbar voltage (V) and defines a pair of voltage set points (V_{ON} and V_{OFF}) 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 3), which ensures the priority of the temperature control. Therefore, the extra voltage control will not undermine the thermal storage function of BTs.

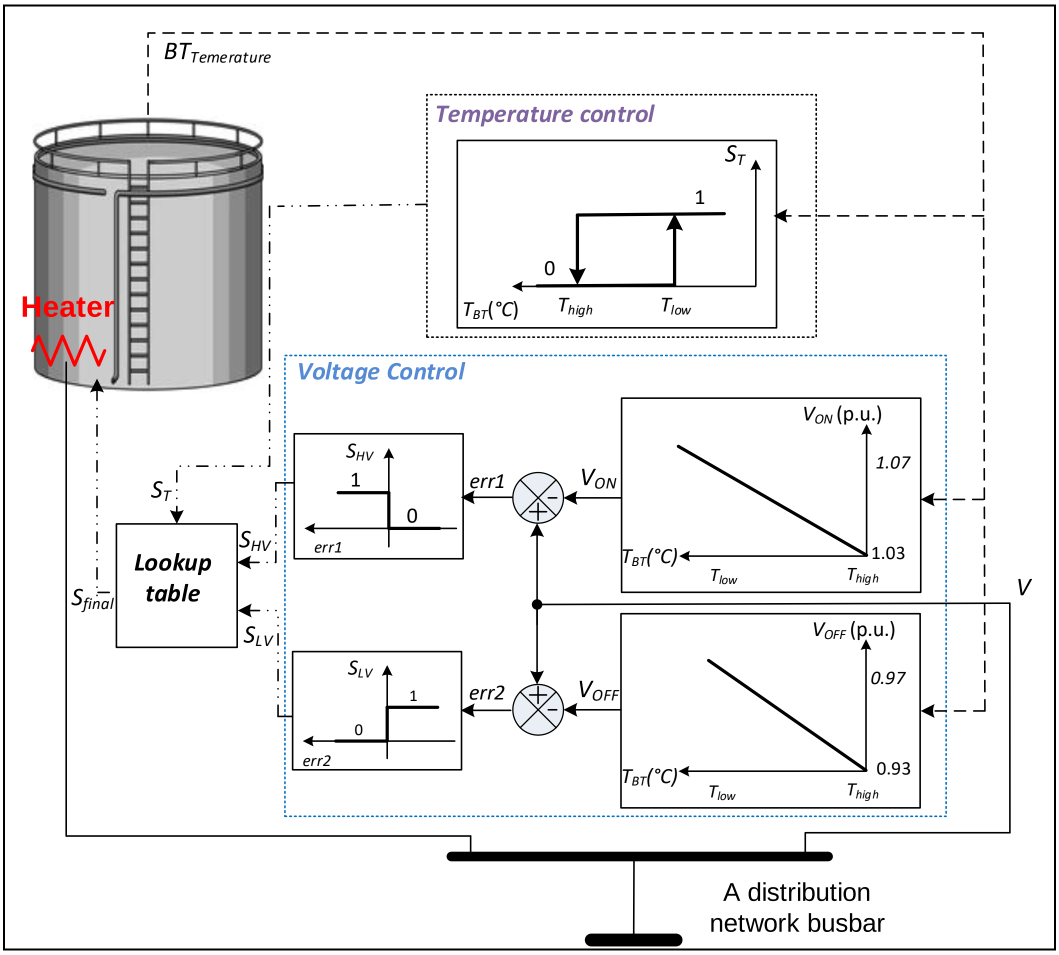


Figure 4-7. The integrated voltage and temperature controllers of the Bitumen tank.

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 Distributed Generation (DG) capacity. The controller initially selects, through the selection algorithm, the designated busbar (i), as shown in Figure 4-8. The high and the low voltage limits (i.e. V_{high} and V_{low}) were set to 1.06 p.u. and 0.94 p.u. based on [54]. The required changes in the active power (ΔP_{ES} in p.u.) and the reactive power (ΔQ_{ES} in p.u) of the BESS were calculated using (2).

$$\Delta V_i = M_{i\_ES} \times \Delta P_{ES} + N_{i\_ES} \times \Delta Q_{ES} \quad (2)$$

where M_{i_ES} is the voltage sensitivity factor (in voltage p.u./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./power p.u.), which relates the change in the reactive power of the battery energy storage system to the change in the voltage of busbar i. The calculation of voltage sensitivity factors is presented in [41].

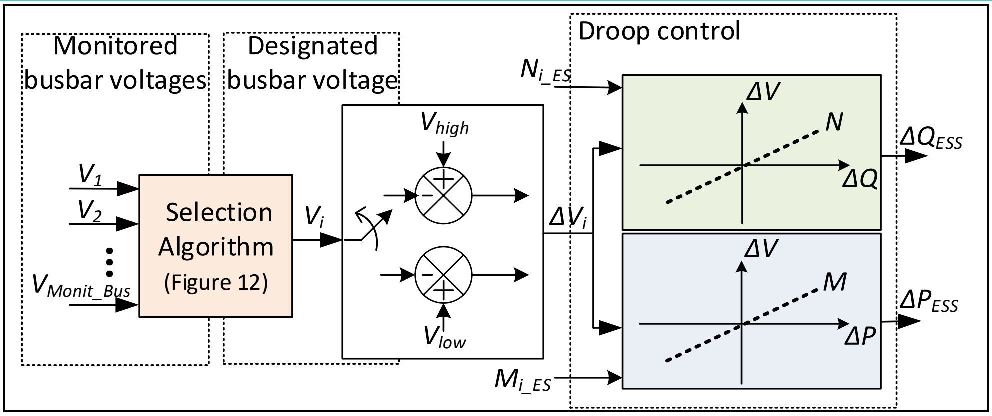


Figure 4-8. The voltage controller of the battery energy storage system.

The rule-based selection algorithm, depicted in Figure 4-9, 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 one busbar and a low voltage at another).
3. If both selected busbars 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 busbar's voltage violation.

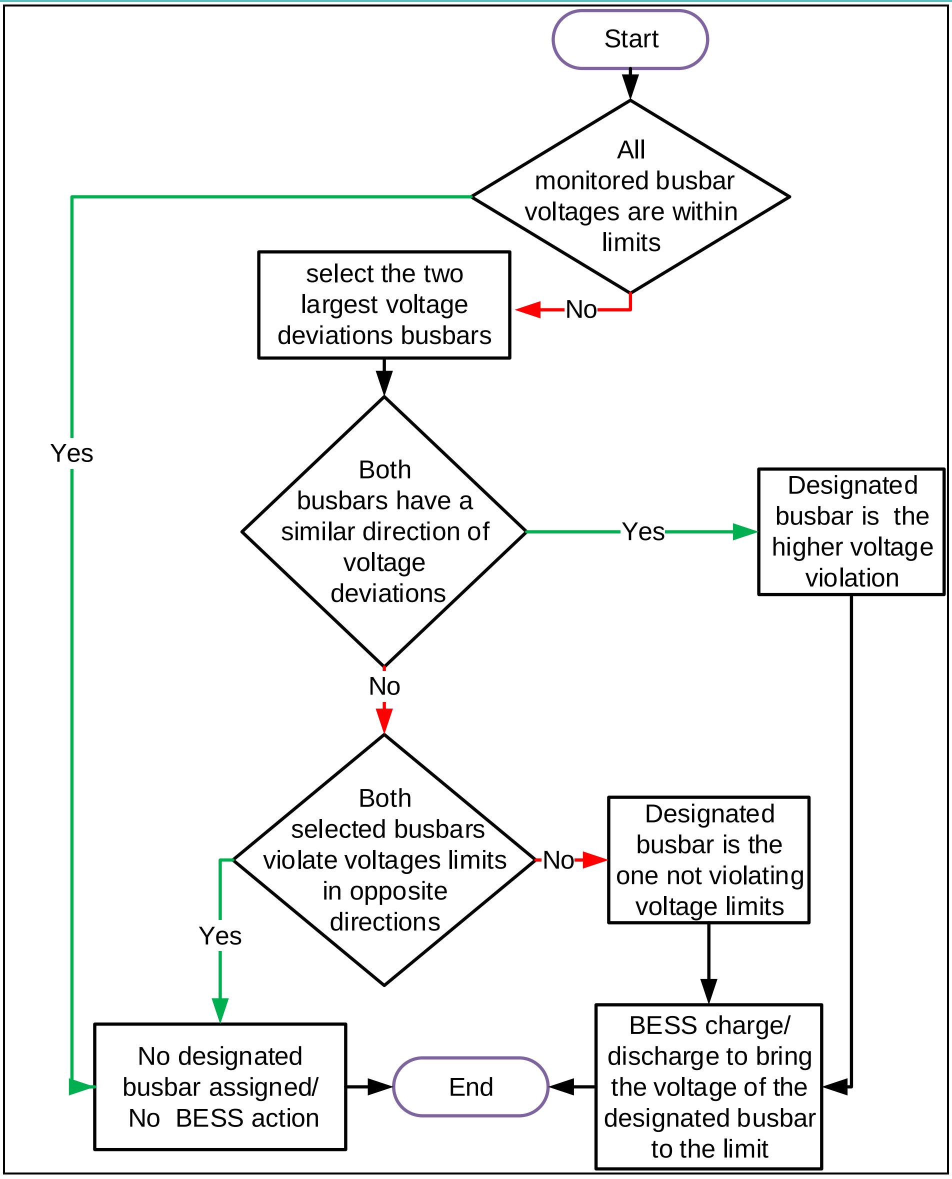


Figure 4-9. The designated busbar selection algorithm of the BESS voltage controller.

- **Case study**

The performance of the proposed VESS voltage control scheme was evaluated using a simplified medium-voltage network, shown in Figure 4-10 [55]. 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 [53]. The network hosting capacity is 48.45 MW, which consists of MW 41.9 MW of wind farms and 6.55 MW of PV systems. The network voltage was only controlled by On Load Tap Changing (OLTC) and Voltage Regulator (VR) transformers. The network data, half-hourly DG generation and load profiles were obtained from [55].

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 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 demand response uncertainty. With the presence of flexible demand, the network hosting capacity for DG increased to 60.25 MW.

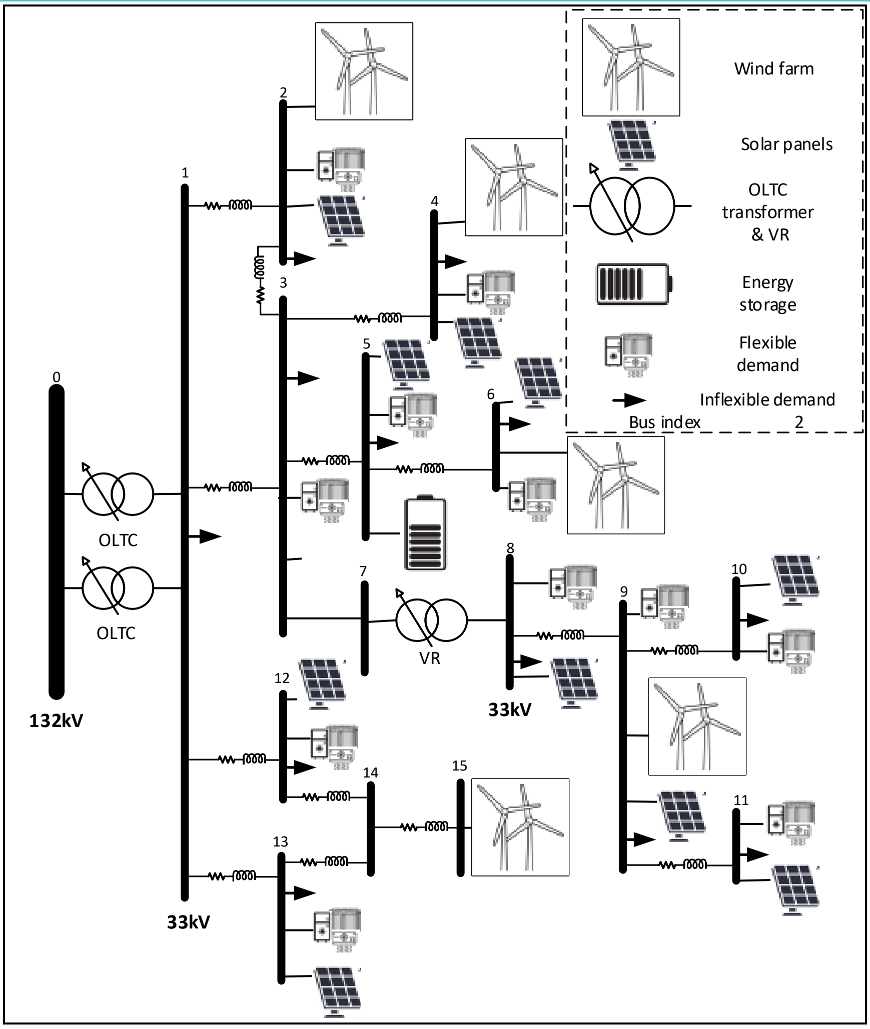


Figure 4-10. The distribution network used in the case study.

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 4-2.

Table 4-2. VESS and transformers control time delay

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

The power flow analysis of one-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 4-11. The coincidence of high DG output and low demand led to voltage violations at several busbars in the first five hours of the day. Figure 4-12 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 4-13 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 [53], hence reducing their maintenance requirements and prolonging their life span.

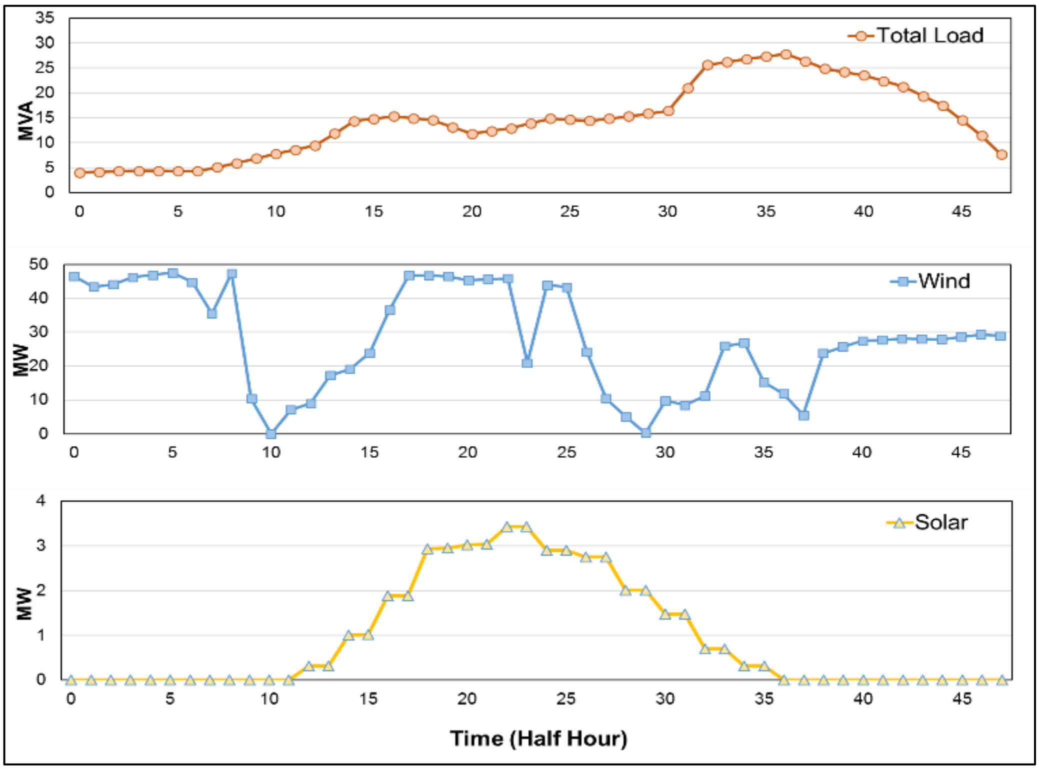


Figure 4-11. Wind and solar generation profiles and total load of the base case where in the case that no VESS exists in one spring day.

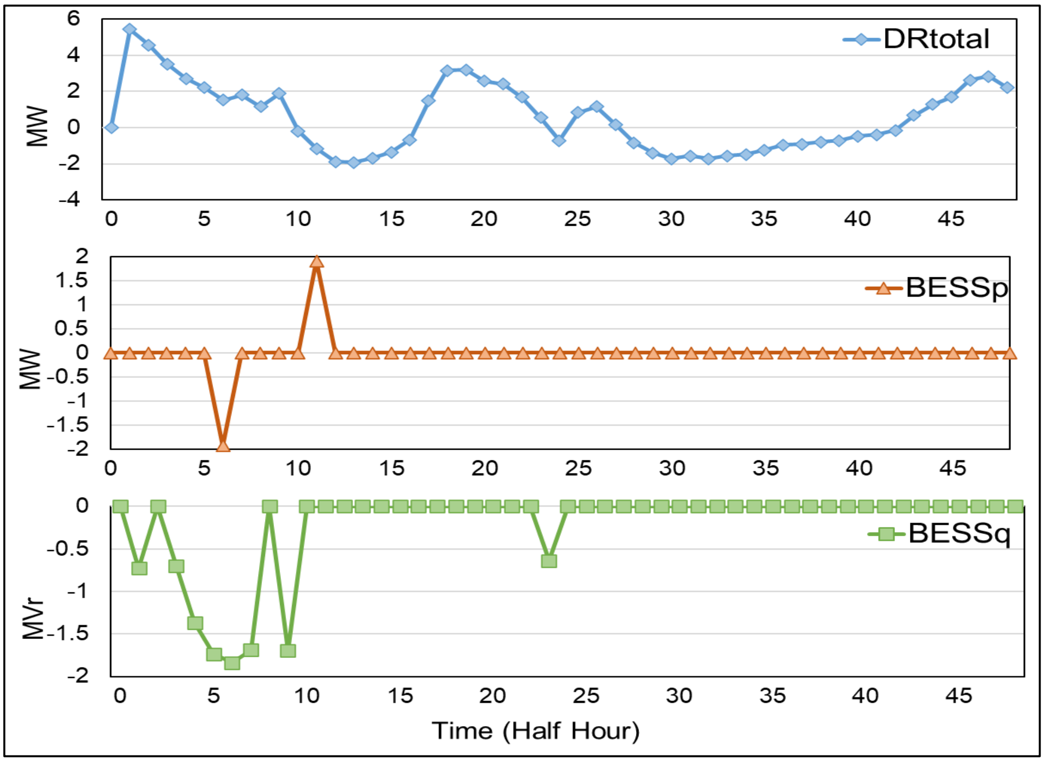


Figure 4-12. The response from different VESS components, where DRtotal is the aggregated response power from BTs and BESSp and BESSq are the active and reactive power outputs of BESS.

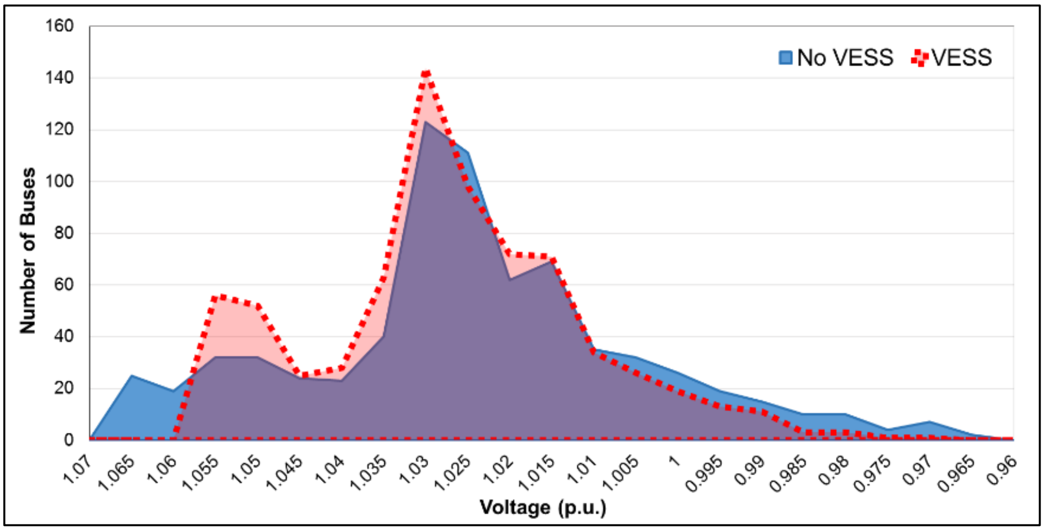


Figure 4-13. The distribution of busbars voltages over the day.

Conclusion

FlexCHESS is to revolutionise the existing paradigms of energy storage by developing a multi-level flexibility approach based on VESS that can store surplus energy through HESS and modify their behavior and architecture to support unpredictable growth and change of demand, climate and market. The key terminology and concepts is defined at the whole project level, the physical system level and the tool level, and their interaction is organised in a unified technical framework to make the FlexCHESS function. A more detailed and comprehensive taxonomy of FlexCHESS is defined based on the Smart Grid Architecture Model. Complementarity and interoperability are two vital concepts for the quantification and exploitation of flexibility.

Flexibility is of great importance for electric power systems with increasing variable RESs and soaring electric demand, where compatibility and interoperability are vital. Being flexible in terms of energy use means having the ability to shift energy use in time and space, or through changes in intensity or vector, for achieving secure, reliable and continuous energy supply.

The drivers of flexibility include the development of renewable energy and electric vehicles as well as flexible electricity pricing schemes and variable fuel prices. The providers of flexibility include HPs, EVs, CHP units, solar PV and wind generators as well as ESSs. Flexibility is with temporal and spatial characteristics. The indicators characterising flexibility include magnitude, ramp rate, ramping capability, response time, time availability and costs.

VESSs are proposed as the solution to exploit flexibility. A VESS aggregates distributed energy resources (DERs), functioning similarly to a large-capacity conventional ESS. VESSs can coordinate and utilise the complementary features of flexible demand units and ESSs – overcoming the uncertainties in flexible demand at the same time reducing the costs of using more expensive ESSs.

The potential applications of VESSs include facilitating the integration of distributed generation (DG) in distribution networks, reducing reserve margins, deferring transmission and distribution systems reinforcement, and providing other ancillary services. The VESSs can benefit various parties, including VESS components owners, transmission and distribution systems, supply side of power systems, as well as VPP.

Finally, two example applications of VESSs are presented, i.e. frequency support and distribution network voltage support. For frequency support, it is shown that VESSs combining flexible refrigerators and flywheel ESSs are able to achieve the same level of frequency support with only one-third capacity of flywheel ESSs, reducing the overall costs. For voltage support, it is shown that with VESSs the voltage issues of the distribution network can be mitigated and the number of actions of OLTC and VR transformers can be reduced by 30% extending the lifetime of the devices and thus saving the replacement costs.

Reference

[1] J. Jurasz, F. A. Canales, A. Kies, M. Guezgouz, and A. Beluco, "A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions," *Solar Energy*, vol. 195, pp. 703-724, 2020.

[2] A. Beluco, P. K. Souza, and A. Krenzinger, "A dimensionless index evaluating the time complementarity between solar and hydraulic energies," *Renewable Energy*, vol. 33, no. 10, pp. 2157-2165, 2008.

[3] H. Nasser and Dah, "11 Complementarity and flexibility indexes of an interoperable VPP," in *Virtual Power Plant Solution for Future Smart Energy Communities*, 1st ed., E. Heydarian-Forushani, H. H. Alhelou, S. B. Elghali, Ed. Boca Raton: CRC Press, 2022, pp. 209-220.

[4] G. Powells and M. J. Fell, "Flexibility capital and flexibility justice in smart energy systems," *Energy Research & Social Science*, vol. 54, pp. 56-59, 2019.

[5] M. Zade, Z. You, B. Kumaran Nalini, P. Tzscheutschler, and U. Wagner, "Quantifying the Flexibility of Electric Vehicles in Germany and California—A Case Study," *Energies*, vol. 13, no. 21, p. 5617, 2020.

[6] J. Ma, V. Silva, R. Belhomme, D. S. Kirschen, and L. F. Ochoa, "Evaluating and planning flexibility in sustainable power systems," in *2013 IEEE power & energy society general meeting*, 2013, pp. 1-11: IEEE.

[7] S. Paiho et al., "Increasing flexibility of Finnish energy systems—A review of potential technologies and means," *Sustainable cities and society*, vol. 43, pp. 509-523, 2018.

[8] V. Kleinschmidt, T. Hamacher, V. Perić, and M. R. Hesamzadeh, "Unlocking flexibility in multi-energy systems: A literature review," in *2020 17th International Conference on the European Energy Market (EEM)*, 2020, pp. 1-6: IEEE.

[9] O. M. Babatunde, J. L. Munda, and Y. Hamam, "Power system flexibility: A review," *Energy Reports*, vol. 6, pp. 101-106, 2020.

[10] I. E. Agency, *Status of Power System Transformation 2018*. 2018.

[11] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari, "Review of energy system flexibility measures to enable high levels of variable renewable electricity," *Renewable and sustainable energy reviews*, vol. 45, pp. 785-807, 2015.

[12] T. Q. Péan, J. Salom, and R. Costa-Castelló, "Review of control strategies for improving the energy flexibility provided by heat pump systems in buildings," *Journal of Process Control*, vol. 74, pp. 35-49, 2019.

[13] C. Wu, S. Jiang, S. Gao, Y. Liu, and H. Han, "Charging demand forecasting of electric vehicles considering uncertainties in a microgrid," *Energy*, vol. 247, p. 123475, 2022.

[14] R. de Sá Ferreira, L. A. Barroso, P. R. Lino, M. M. Carvalho, and P. Valenzuela, "Time-of-use tariff design under uncertainty in price-elasticities of electricity demand: A stochastic optimization approach," *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 2285-2295, 2013.

[15] B. Felten and C. Weber, "The value (s) of flexible heat pumps–Assessment of technical and economic conditions," *Applied Energy*, vol. 228, pp. 1292-1319, 2018.

[16] E. Kaushik, V. Prakash, O. P. Mahela, B. Khan, A. El-Shahat, and A. Y. Abdelaziz, "Comprehensive overview of power system flexibility during the scenario of high penetration of renewable energy in utility grid," *Energies*, vol. 15, no. 2, p. 516, 2022.
[17] D. Papadaskalopoulos, G. Strbac, P. Mancarella, M. Aunedi, and V. Stanojevic, "Decentralized participation of flexible demand in electricity markets—Part II: Application with electric vehicles and heat pump systems," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 3667-3674, 2013.
[18] J. Wang, S. You, Y. Zong, C. Træholt, Z. Y. Dong, and Y. Zhou, "Flexibility of combined heat and power plants: A review of technologies and operation strategies," *Applied energy*, vol. 252, p. 113445, 2019.
[19] E. Pierri, D. Hellkamp, S. Thiede, and C. Herrmann, "Enhancing energy flexibility through the integration of variable renewable energy in the process industry," *Procedia CIRP*, vol. 98, pp. 7-12, 2021.
[20] Y. Cheng and J. Liu, "Carbon nanomaterials for flexible energy storage," *Materials Research Letters*, vol. 1, no. 4, pp. 175-192, 2013.
[21] Z. Wang, C. Gu, and F. Li, "Flexible operation of shared energy storage at households to facilitate PV penetration," *Renewable energy*, vol. 116, pp. 438-446, 2018.
[22] R. D'hulst, W. Labeeuw, B. Beusen, S. Claessens, G. Deconinck, and K. Vanthournout, "Demand response flexibility and flexibility potential of residential smart appliances: Experiences from large pilot test in Belgium," *Applied Energy*, vol. 155, pp. 79-90, 2015.
[23] E. Lannoye, D. Flynn, and M. O'Malley, "Evaluation of power system flexibility," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 922-931, 2012.
[24] M. Child, C. Kemfert, D. Bogdanov, and C. Breyer, "Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe," *Renewable energy*, vol. 139, pp. 80-101, 2019.
[25] Y. Dvorkin, D. S. Kirschen, and M. A. Ortega‐Vazquez, "Assessing flexibility requirements in power systems," *IET Generation, Transmission & Distribution*, vol. 8, no. 11, pp. 1820-1830, 2014.
[26] B. M. Sanandaji, T. L. Vincent, and K. Poolla, "Ramping rate flexibility of residential HVAC loads," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 865-874, 2015.
[27] E. Kaushik, V. Prakash, O. P. Mahela, B. Khan, A. El-Shahat, and A. Y. Abdelaziz, "Comprehensive overview of power system flexibility during the scenario of high penetration of renewable energy in utility grid," *Energies*, vol. 15, no. 2, p. 516, 2022.
[28] Y. Dvorkin, D. S. Kirschen, and M. A. Ortega‐Vazquez, "Assessing flexibility requirements in power systems," *IET Generation, Transmission & Distribution*, vol. 8, no. 11, pp. 1820-1830, 2014.
[29] E. Lannoye, D. Flynn, and M. O'Malley, "The role of power system flexibility in generation planning," in *2011 IEEE Power and Energy Society General Meeting*, 2011, pp. 1-6: IEEE.
[30] J. Zhao, T. Zheng, and E. Litvinov, "A unified framework for defining and measuring flexibility in power system," *IEEE Transactions on power systems*, vol. 31, no. 1, pp. 339-347, 2015.
[31] W. Kellerer et al., "How to measure network flexibility? A proposal for evaluating softwarized networks," *IEEE Communications Magazine*, vol. 56, no. 10, pp. 186-192, 2018.
[32] C. Ziras, C. Heinrich, and H. W. Bindner, "Why baselines are not suited for local flexibility markets," *Renewable and Sustainable Energy Reviews*, vol. 135, p. 110357, 2021.
[33] N. Lashmar et al., "Motivations, barriers, and enablers for demand response programs: A commercial and industrial consumer perspective," *Energy Research & Social Science*, vol. 90, 102667, 2022.

[34] F. D’Ettorre et al., “Exploiting demand-side flexibility: State-of-the-art, open issues and social perspective,” *Renewable and Sustainable Energy Reviews*, vol. 165, 112605, 2022.

[35] N. Good et al., “Review and classification of barriers and enablers of demand response in the smart grid,” *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 57-72, 2017.

[36] D. Wang et al., "Smart coordination of virtual energy storage systems for distribution network management," *International Journal of Electrical Power & Energy Systems*, vol. 129, 106816, 2021.

[37] K. Xie, H. Hui, and Y. Ding, “Review of modeling and control strategy of thermostatically controlled loads for virtual energy storage system,” *Protection and Control of Modern Power Systems*, vol. 4, no. 1, pp. 1-13, 2019.

[38] X. Zhu, J. Yang, Y. Liu, C. Liu, B. Miao, and L. Chen, “Optimal scheduling method for a regional integrated energy system considering joint virtual energy storage,” *IEEE Access*, vol. 7, pp. 138260-138272, 2019.

[39] Q. Qdr, *Benefits of demand response in electricity markets and recommendations for achieving them*, US Dept. Energy, Washington, DC, USA, Tech. Rep, vol. 2006, 2006.

[40] P. Siano, "Demand response and smart grids—A survey," *Renewable and sustainable energy reviews*, vol. 30, pp. 461-478, 2014.

[41] S. Sami, *Virtual energy storage for frequency and voltage control*, Ph.D. thesis, Cardiff University, 2017.

[42] K. Ponds et al., "Aggregator of demand response for renewable integration and customer engagement: Strengths, weaknesses, opportunities, and threats," *Energies*, vol. 11, no. 9, 2391, 2018.

[43] National Grid, *Future energy scenarios*, Accessed: Mar, 2017.

[44] F. Sioshansi, *Variable Generation, Flexible Demand*. Academic Press, 2020.

[45] M. Cheng et al., “Benefits of using virtual energy storage system for power system frequency response," *Applied Energy*, vol. 194, pp. 376-385, 2016.

[46] G. Zhang et al., "Comprehensive review on structure and operation of virtual power plant in electrical system," *IET Generation, Transmission & Distribution*, vol. 13, no. 2, pp. 145-156, 2019.

[47] M. Cheng et al., "Primary frequency response in the Great Britain power system from dynamically controlled refrigerators," *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, 2013.

[48] S. S. Sami et al., "Modelling and control of multi-type grid-scale energy storage for power system frequency response," *IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia 2016)*, 2016.

[49] M. Cheng et al., "Power System Frequency Response From the Control of Bitumen Tanks," *IEEE Transactions on Power Systems*, vol. PP, pp. 1-10, 2015.

[50] B. Alexander, *Technical and commercial integration of distributed and renewable energy sources into existing electricity networks*, Ph.D. thesis, University of Manchester, 2006.

[51] M. Cheng et al., "Availability of load to provide frequency response in the great Britain power system," *2014 Power Systems Computation Conference*, pp. 1-7, 2014.

[52] Beacon Power Co, "Beacon Power Technology Brochure." [Online]. Available: http://beaconpower.com/resources/.

[53] S. Sami et al.,"A virtual energy storage system for voltage control of distribution networks," *CSEE Journal of Power and Energy Systems*, vol. 4, pp. 146-154, 2018.

[54] Statutory Instruments, *The electricity safety, quality and continuity regulations*, 2002.

[55] Distributed Generation, *Sustainable Electrical Energy Centre. United Kingdom Generic Distribution System (UK GDS)*, Previously Available: http://www. sedg. ac. uk, 2011.

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