A Review on Rapid Responsive Energy Storage Technologies for Frequency Regulation in Modern Power Systems

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Abstract

A paradigm shift in power generation technologies is happening all over the world. This results in replacement of conventional synchronous machines with inertia less power electronic interfaced renewable energy sources (RES). The replacement by intermittent RES, i.e., solar PV and wind turbines, has two fold effects on power systems: (i) reduction in inertia and (ii) intermittent generation lead to the degradation of the frequency stability. In modern power system, the frequency regulation (FR) has become one of the most crucial challenges compared to conventional system because the inertia is reduced and both generation and demand are stochastic. The fast responsive energy storage technologies, i.e., battery energy storage, supercapacitor storage technology, flywheel energy storage, and superconducting magnetic energy storage are recognized as viable sources to provide FR in power system with high penetration of RES. The important aspects that are required to understand the applications of rapid responsive energy storage technologies for FR are modeling, planning (sizing and location of storage), and operation (control of storage). This paper comprehensively reviews these important aspects to understand the applications of fast responsive storage technologies more effectively for FR services. In addition, based on the real world experiences this paper highlights the gaps and limitations in the state-of-the-art practices. Moreover, this study also provides recommendations and future directions for researchers working on the applications of storage technologies providing FR services.

Abbreviations

AEMO	Australian electricity market operator
AGPC	Adaptive generalized predictive control
ANFIS	Adaptive neuro fuzzy inference system
BES	Battery energy storage
CE	Continental Europe
DFS	Dynamic frequency support
DSM	Demand side management
ENTSO-E	European network of transmission system operators for electricity
ESS	Energy storage system
FCAS	Frequency control ancillary services
FCES	Fuel cell energy storage
FFR	Fast frequency response
FLC	Fuzzy logic control
FR	Frequency regulation
FES	Flywheel energy storage

GB	Great Britain
HESS	Hybrid energy storage system
IR	Inertial response
LFC	Load frequency control
MG	Microgrid
MPC	Model predictive control
NNAPC	Nonlinear neural adaptive predictive control
NREL	National renewable energy laboratory
PCS	Power conversion system
PD	Proportional derivative
PFR	Primary frequency regulation
PI	Proportional integral
PID	Proportional integral derivative
PV	Photovoltaic
RES	Renewable energy source
RoCoF	Rate of change of frequency
SAMPA	Set-membership affine projection algorithm
SCES	supercapacitor energy storage
SoC	State of charge
SMES	Superconducting magnetic energy storage
UFLS	Under frequency load shedding
WAM	Wide area monitoring
WT	Wind turbine

1 Introduction

Generation and transmission portfolios in power systems are changing rapidly due to the concerns over the potentially adverse effects of climate change, energy security, and sustainability [1, 2]. The inertial and dynamic characteristics of intermittent renewable energy sources (RESs), i.e. solar photovoltaic (PV) panels and wind turbines (WTs), are much different compared to the conventional synchronous machines based power generation systems. Unlike conventional generation, the RESs are connected to the grid via power electronic converters which decouple them from the host AC system [3, 4]. Moreover, the RESs normally operate at maximum power point tracking and when needed their power output cannot be increased [5]. Thus RESs plants inherently can neither provide the inertial response (IR) nor participate in frequency regulation (FR) services.

Power systems maintain frequency within the limits defined by grid codes by dynamically matching the generation and demand for secure operation. Large frequency excursions cause the tripping of loads and generators, which may lead to system collapse [6, 7, 8, 9]. The replacement of conventional generators with RESs at a large scale decrease the system inertia making system more vulnerable to larger frequency excursions. A system with smaller inertia has high rate of change of frequency (RoCoF), even a smaller generation-demand imbalance leads to large frequency nadir [10]. The intermittent generation, low inertia, and variations in demand make the FR a challenging task in the system having high share of RESs. Traditionally, load frequency control (LFC) placed at synchronous machine based generation plants provide FR.

Exploiting energy storage systems (ESSs) for FR services, i.e. IR, primary frequency regulation (PFR), and LFC, especially with a high penetration of intermittent RESs has recently attracted a lot of attention both in academia and in industry [12, 13]. ESS provides FR by dynamically injecting/absorbing power to/from the grid in response to decrease/increase in frequency. The ESS provides expeditious FR services that outperforms the services of available conventional networks assets. Various types of ESSs are available offering backup from fraction

Table 1: ENTSO-E network code: frequency quality parameters per synchronous area [11]

	GB	CE	NE	IRE
Standard frequency range	$\pm$0.2 Hz	$\pm$0.05 Hz	$\pm$0.1 Hz	$\pm$0.2 Hz
Maximum instantaneous frequency deviation	0.8 Hz	0.8 Hz	1.0 Hz	1.0 Hz
Maximum steady-state frequency deviation	0.5 Hz	0.2 Hz	0.5 Hz	0.5 Hz
Frequency recovery range	$\pm$0.5 Hz	not used	not used	$\pm$0.5 Hz
Time to recover frequency	60 sec	not used	not used	60 sec
Frequency restoration range	$\pm$0.2 Hz	not used	$\pm$0.1 Hz	$\pm$0.2 Hz
Time to restore frequency	600 sec	900 sec	900 sec	1200 sec

of second to hours with different characteristics, operational requirements, and limitations [14, 15]. This review is focused on the fast responsive ESSs, i.e., battery energy storage (BES), supercapacitor energy storage (SCES) storage, flywheel energy storage (FES) technology, superconducting magnetic energy storage (SMES), and their hybrid forms (BES-SCES, BES-SMES, and BES-FES). In this work, *supercapacitor* energy storage is used to refer to the electrochemical double-layer capacitor, which consists of two electrodes, one electrolyte and ion-permeable separator. No electrochemical reaction happens in the supercapacitor during the charging and discharging cycle, ions are used instead of electrons, as in batteries, and the form of stored energy is electrostatic. Other devices which shares properties of capacitors and/or batteries have been developed, i.e., pseudocapacitors, ultracapacitors and ultrabatteries. These, however, are still not fully developed technologies are not considered in this paper.

The main challenges in exploiting the ESSs for FR services are understanding mathematical models, dimensioning, and operation and control. In this review, the state-of-the-art is synthesized into three major sections: i) review of mathematical models, ii) FR using single storage technology (BES, FES, SMES, SCES), and iii) FR using hybrid energy storage system (HESS) (BES-SCES, BES-SMES, and BES-FES). The categories (ii) and (iii) are further divided into two sub categories: control and operation, and sizing. The contribution of this work lies in the fact that it comprehensively reviews all the aspects that are required to understand the FR services provided by ESSs. Moreover, it highlights the research gaps, limitations, and gives future directions.

The remainder of the paper is organized as follows. Section 2 briefly reviews various sources for FR available in modern power system. Overview of various energy storage technologies which are suitable for FR is given in Section 3. The review of mathematical model of ESSs is given in Section 4. Section 5, discusses the control and sizing strategies proposed for ESSs to provide FR. Summary and discussions of review are given in Section 6. Finally, the conclusion and future directions are given in Section 8.

2 FR in Power System

In power systems, frequency is the continuously changing variable which is influenced by the power generation and demand. A generation deficit results in frequency reduction while surplus generation causes an increase in the frequency. The frequency is kept in permissible limits for the stable operation of power systems. Different system operators have defined different set of frequency operating standards for normal and abnormal operations. The frequency operating standards set by European network of transmission system operators for electricity (ENTSO-E) are given in Table 1. The data given in Table 1 can be found in chapter 18, on page 1140 of [11]. There are four synchronous areas in Europe.

1) Great Britain (GB): alone forms synchronous area.

2) The continental Europe (CE): includes part or all of Austria, Bulgaria, Belgium, Bosnia, Herzegovina, Czech Republic, Croatia, western Denmark, France, Germany, Greece, Hungary, Luxembourg, Italy, Macedonia, Net--herlands, Montenegro, Poland, Romania, Portugal, Slovakia, Serbia, Spain, Slovenia, and Switzerland.

3) The inter-Nordic system (NE): constitutes transmission grids of Norway, Sweden, Denmark (eastern part), and Finland.

4) The all-island Irish system (IRE): includes Republic of Ireland and Northern Ireland is another synchronous area.

The frequency operation standards set by Australian Electricity Market Operator (AEMO) are given in Table 2 [16]. It can be observed form the Table 2 that the most of the time frequency is required to be kept within ± 0.15

Table 2: Frequency operating standards in Australia [16]

Condition	Containment	Stabilisation	Recovery
No contingency or load event	49.75-50.25 Hz 49.85-50.15 Hz*	49.85-50.15 Hz within 5 min	49.85-50.15 Hz within 5 min
Generation event or load event	49.50-50.50 Hz	49.85-50.15 Hz within 5 min	49.85-50.15 Hz within 5 min
Network event	49.00-51.00 Hz	49.50-50.50 Hz within 1 min	49.50-50.50 Hz within 5 min
Separation event	49.00-51.00 Hz	49.50-50.50 Hz within 2 min	49.50-50.50 Hz within 10 min

*: 99% of the time, load event: 50 MW, generation event: 50 MW

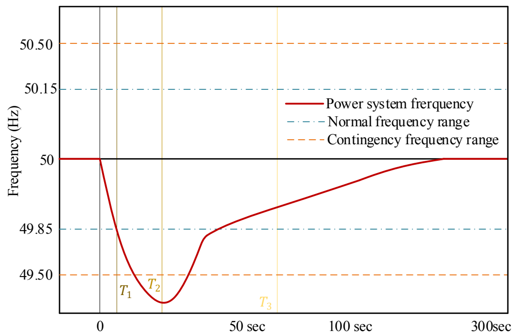

Figure 1: Contingency FCAS stages by AMEO.

Hz. The complete definitions of load, generation, network, and separation events can be found in the reference provided in [16]. Power systems need to be operated within the defined operating frequency standards. A deviation in frequency from the standard operating limits leads to disconnection of generators and demand which result in poor reliability and economic loss.

In AEMO contingency frequency control ancillary services (FCAS) are used to suppress large frequency variations caused by a sudden loss of large load or generation [17]. The contingency FCAS have six stages: 6 second raise (R6) and lower (L6), 60 second raise (R60) and lower (L60), and 5 minute raise (R5) and lower (L5). The Fig. 1, shows an example of the variation in frequency after loss of large generation and different stages of contingency FCAS. The generation loss event occurs at 0 sec resulting in rapid decline in frequency. The R6 contingency FCAS gets activated at T_1 when the frequency leaves the normal frequency operating range. The R6 contingency FCAS supports the system for 6 sec and then at T_2 (T_1+6) the R60 contingency get activated. The R60 contingency brings back the frequency within the normal frequency operating range. At T_3 (T_1+60) R5 contingency FCAS activates and restore the frequency to 50 Hz [17].

Fig. 2 shows a power system, with conventional generations, renewable power generation systems, energy storage systems, and controllable and uncontrollable loads. In modern power system, the system operators have multiple resources that can be procured for FR services, i.e., conventional synchronous machines based generation, ESS, demand side management (DSM), electric vehicles, and RESs. Active power of these resources is controlled to support grid frequency.

Conventional power generation systems employ synchronous machines with heavy rotating masses. In event of any difference in generation and demand the synchronous machines instantaneously slow-down/speed-up by injecting/absorbing the kinetic energy in/from the power system [18]. This instantaneous response is called IR which is the inherent characteristic of synchronous machine, requires no control. Controlled FR services can be obtained from conventional generation plants using the governor control which increases the power output of generator as per control signal [19, 20, 21]. The typical variation in frequency after the occurrence of an event and the necessary control actions taken to ameliorate its impact are shown in Fig. 3. The first stage is the inherent response of synchronous machines (i.e. IR) in which the synchronous machines oppose the reduction in frequency by releasing the kinetic energy stored in rotating masses. This stage is followed by the primary frequency

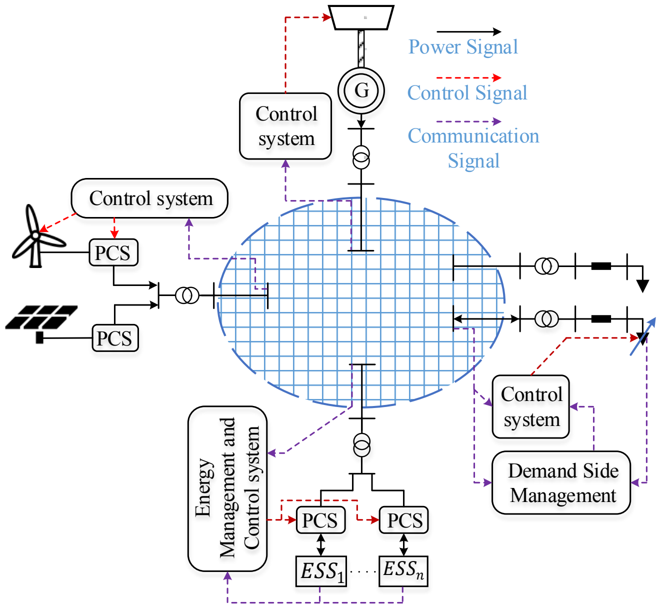

Figure 2: Power system with various FR resources.

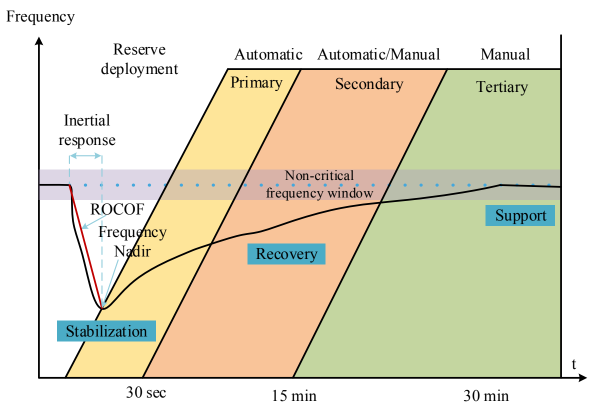

Figure 3: Frequency response stages by ENTSO-E.

control which stabilizes the frequency to a new steady state value. The next stage is the LFC where generally the proportional-integral (PI) controller used to recover the frequency to its nominal value [22, 23, 24].

Alternatively, the advancements in the power electronics have paved the way for RESs to participate in FR services. The most commonly utilized RESs are PV and WT. There are two main categories of WTs, variable speed and fixed speed. The fixed speed WT is directly coupled with the system. Therefore, it can provide IR [25], but it is very less compared to the IR of synchronous generators. While the variable speed WT and PV are completely decoupled from the grid frequency due to power electronic interface. Therefore, they cannot naturally provide FR services and require auxiliary power electronic controls. Deloading and inertia emulation are reported as two main controls used in WT for FR in power systems [26]. In deloading technique, the WT is operated lower than its rated capacity and its output is adjusted during the fault to provide FR [27, 28]. In inertia emulation, the kinetic energy stored in the blades of WT is used to provide IR [29, 30]. The deloading technique can also be applied to PV plants for FR services [31, 32].

Furthermore, the introduction of sophisticated communication network and smart switches allow loads to participate in FR services using demand side management (DSM). The main idea behind DSM for FR services is to make the controllable load sensitive to power frequency signal. FR using DSM can be divided into two categories: (i) load curtailment, (ii) load modulation. The load curtailment DSM scheme turns on/off the load to provide ancillary services [33, 34, 35]. The load modulation DSM modifies the consumption of load based on the variations

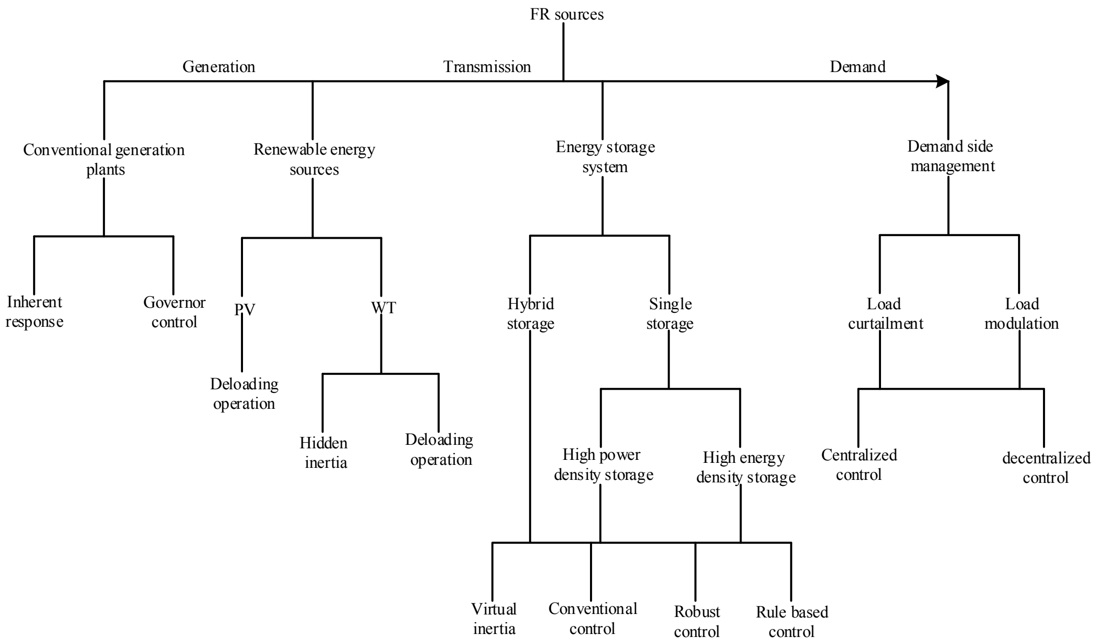

Figure 4: FR resources in modern power system.

in frequency [36, 37].

The ESS is one of the most favourable candidate to provide FR services (i.e. IR, PFR, LFC) because of its fast responsive time and flexibility of operation. Due to fast response time, ESS technologies can inject large amount of power into grid in a short time, which can be used as the virtual inertia [38, 39]. Similar to the fast conventional generation units which are kept on-line to provide PFR by increasing/decreasing their power output in under-frequency/over-frequency events, the ESS provides upward/downward regulation by injecting/absorbing power to/from the grid [40]. Many transmission system operators, including EirGrid in Ireland and ENTSO-E and AEMO are considering new services, such as the FFR (fast frequency response) which is not "inertial" but as it is provided by non-synchronous devices and hence, also possibly by storage systems. A summary of the operation of available FR resources is shown in Fig. 4. The conventional synchronous machine based power plants provide from the generation side, while the renewable energy sources and energy storage can be deployed for FR on generation or transmission side. The DSM is related to load side.

The operation of a grid connected BES providing PFR is shown in Fig. 5. The BES remains idle for the frequency excursions which are in between ± 0.02 Hz. The output of BES is increased linearly for the frequency deviations between ± 0.02 to ± 0.2 Hz. The power has to be supplied for 900 s, after which a break of 900 s

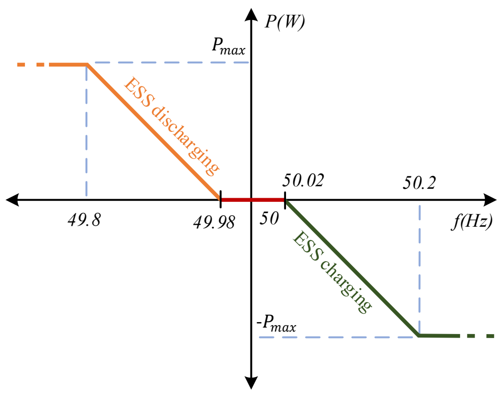

Figure 5: ESS deployment for PFR service.

Table 3: Real world energy storage facilities and their applications [43, 44, 45, 46]

Name/Location	Rating	Application
BES/Australia	30 MW/ 8 MWh	Fast frequency response
BES/USA	8 MW/ 2 MWh	Frequency regulation
BES/Germany	8.5 MW/ 8.5 MWh	Frequency control, spinning reserve
BES/Puerto Rico	20 MW/ 14 MWh	Frequency control, spinning reserve
BES/Japan	34 MW/ 244.8 MWh	Wind power fluctuation mitigation
BES/USA	10 MW/ 40 MWh	Spinning reserve, load leveling
BES/Ireland	2 MW/ 12 MWh	Wind power fluctuation mitigation
SCES/China	3 MW/ 17.2 kWh	Voltage sag mitigation
SCES/Spain	4 MW/ 5.6 kWh	Frequency stability
FES/USA	20 MW	Frequency regulation, power quality
FES/Japan	235 MVA	High power supply to nuclear fusion furnace
SMES/Japan	10 MW	System stability, power quality

is permitted for the ESS to get recharged [41]. The requirements for the deployment of ESS reserve, i.e. time of operation (900 s), linear deployment of reserve are mainly derived from the operation of fast responding convention generators [40]. The operation of other storage technologies providing PFR can be expected similar as given in Fig. 5. There are several types of energy storage technologies available and each of them offer different characteristics and operational requirements. Out of the currently available technologies BES, FES, SMES, and SCES are more suitable for FR services due to faster response time and flexible operation requirements [42]. Some examples of real world BES, SCES, FES, and SMES projects and their applications are given in Table 3. The mentioned projects were not primarily intended for frequency regulation. In fact, the BES projects in Japan and Ireland were designed to mitigate the fluctuations in the wind power plants. Since the variations of frequency occurred due to the mismatch between the power generation and demand, therefore, the poor load following may result in poor frequency regulation. Hence, minimizing the fluctuations in wind power output may indirectly improves the FR of the system. From the Table 3 it is worth noting that the BES is still the leading technology for FR services. There are three main aspects of ESS that need to be studied in relation to the FR services, i.e. control, sizing, and placement of ESS. A comprehensive review of these aspects is given in subsequent sections.

3 Characteristics of ESS used for FR Services

Several types of energy storage technologies are available with different characteristics, i.e., medium of storage used, response time, power density, energy density, life and efficiency [47, 48]. The primary focus of this study is to review applications of BES, SCES, SMES, and FES (which are considered as fast responsive energy storage technologies) in FR services.

3.1 Battery Energy Storage

The battery energy storage is considered as the oldest and most mature storage system which stores electrical energy in the form of chemical energy [48, 49]. A BES consists of number of individual cells connected in series and parallel [50]. Each cell has cathode and anode with an electrolyte [51]. During the charging/discharging of battery electrochemical reactions take place inside individual cells and battery absorbs/supplies power from/to grid [52]. Battery storage offers back up feasibility ranging from seconds to hours. Several types of batteries are available and each offers different characteristics [43]. In general, battery storage technology has high energy density, lower power density, and lesser cycle life. Batteries are suitable for applications that require long continuous discharge. However, the frequent charging/discharging of battery at very high rate degrades the battery life.

Among the many types of BES systems available it is difficult to state univocally that particular BES is better than others. Depending upon the application power and energy ratings, response time, operating temperature, and

Table 4: Normalized characteristics of BES technologies

Storage type	Life cycles	Energy density	Power density	Energy cost	Power cost	Technical maturity
Lead acid	0.125	0.040	0.300	0.214	0.250	Mature
Lithium-ion	1.000	0.190	1.000	0.714	1.000	Commercial
Sodium sulphur	0.333	0.195	0.200	0.286	0.750	Commercial
Metal air	0.125	1.000	0.100	0.107	0.086	Demo
Flow battery	1.000	0.020	0.166	0.429	0.523	Developing
Nickle cadmimum	0.250	0.060	0.150	1.000	0.500	Mature

ambient temperature, a unique decision can be taken for the corresponding case. However, a comparison has been made based on the power and energy characteristics of popular BES technologies. The normalized characteristics of popular battery storage technologies are given in Table 4. The data is extracted from [43, 53] and the references provide therein. It can be observed that the flow battery has longer cycle life, poor power, and energy density which limits its applications to large scale. The metal air battery has high energy density but poor power density and smaller cycle life. Lead acid battery has lower price but poor cycle life and energy density which limits its applications to FR services. It can be concluded that among all the mature and commercial technologies Li-Ion best suits for FR services. In addition Sodium Ion and Zinc Ion are emerging storage technologies. The sodium Ion has high energy density (e.g. 200-300Wh/kg) [54]. The main obstacles of utilizing the sodium Ion batteries for FR are low power density and poor cycle life. Currently research is going on to improve the power density and cycle life [55]. Zinc-ion has lower cost, environmentally friendly, and safe. The Zinc-ion batteries have low energy density (85Wh/kg) compared to Li-Ion batteries [56]. It can be concluded that among all the mature and commercial technologies Li-Ion best suits for FR services.

3.2 Supercapacitor Energy Storage

Supercapacitors are also known as electric double layer capacitors or ultracapacitors [58]. The SCES is composed of two electrodes which are separated by dielectric medium. The SCES stores electrical energy directly in electrostatic field between the electrodes rather than converting it to another form of energy, e.g., chemical energy in batteries or mechanical energy in case of FESs [59]. SCES is capable of very fast charge/discharge with high currents as it is independent of chemical reactions [60, 53]. SCES technology has higher power density, lower energy density, very large cycle life, and very fast response.

3.3 Flywheel Energy Storage

A FES is an electromechanical storage device which stores energy in the form of kinetic energy [61]. A FES energy storage has a rotating cylinder coupled with an electrical machine which acts as a motor and generator during charging and discharging [62]. The total energy of FES depends on the speed and mass of the rotating cylinder. During charging cycle the electric machine acts as a motor and speeds up the rotating cylinder and increases the stored energy. While during the discharging cycle the machine acts as generator which is driven by

Table 5: Energy, power, and cost comparison of BES, SCES, FES, and SMES [42, 43, 53, 57]

Storage type	Power density (W/kg)	Power density (MW/m^3)	Power cost ($/kW)	Energy density (Wh/kg)	Energy density (kWh/m^3)	Energy cost ($/kWh)	Cycle efficiency (%)	Life cycles (-)
Li-ion	150-500	0.4-2	686-4000	70-200	200-600	240-2500	90-97	up to 20000
SCES	1000-10000	0.4-10	100-400	0.5-5	4-10	500-15000	90-97	50000-1000000
FES	500-4000	1-2.5	150-400	10-50	20-100	1000-14000	90-95	20000+
SMES	500-2000	1-4	200-500	1-10	0.2-2.5	1000-10000	95-98	20000-100000

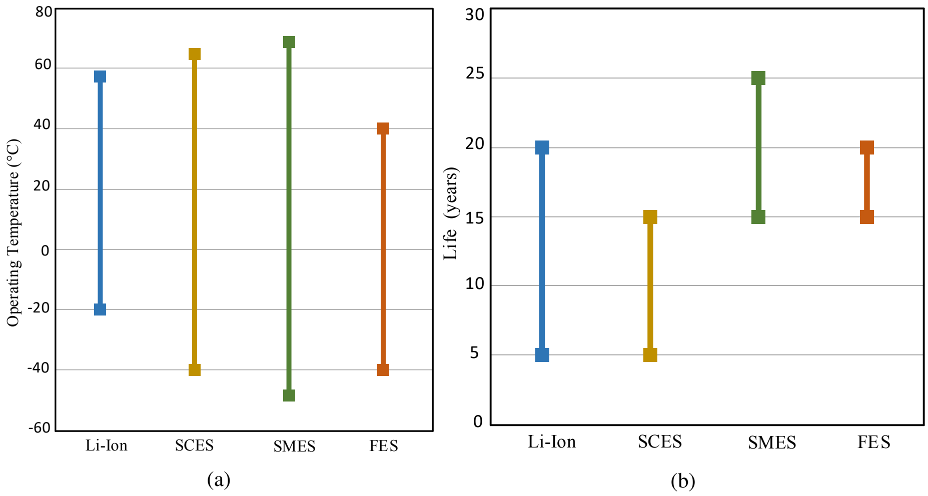

Figure 6: Comparison of BES, SCES, FES, and SMES: (a) Operating temperature, (b) Life in years [42].

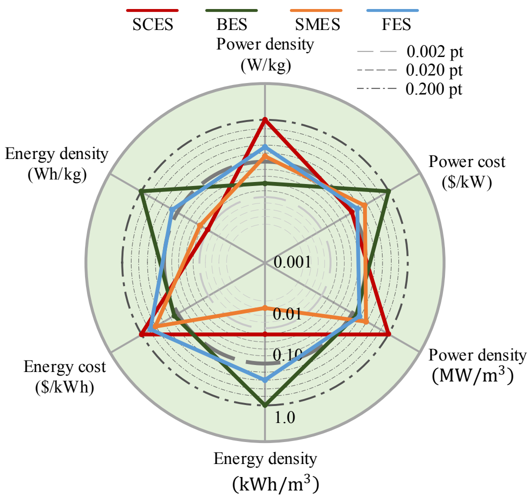

Figure 7: Normalized power and energy characteristics of BES, SCES, FES, and SMES.

the rotating cylinder [63, 64]. The FESs have fast response time, higher self discharge, high cycle life, low energy density, and high power density.

3.4 Superconducting Magnetic Energy Storage

SMES is an electromagnetic energy storage system that stores energy in the form of magnetic field [65]. A SMES consists of three major components: refrigeration system, superconducting coil, and power conditioning system [66]. During the charging cycle of SMES, the energy is stored in the magnetic field formed across the superconducting coil due to flow of current through it. The superconducting coil is kept cool below its superconducting critical temperature. The magnitude of stored energy depends on the magnitude of current and self-inductance of coil [67]. During the discharging of SMES, the stored energy is released to power grid via power conditioning unit. The SMES has higher cycle life, fast response, lower energy density, and higher power density.

3.5 Hybrid Energy Storage System

The high-power density, high energy density, longer cycle life, fast response, fast discharge rate, wider working temperature range, and lower cost are the desirable characteristics of an ESS. The power, energy, cost, number of life cycles, operating temperature range, and life span data of BES, SCES, FES, and SMES is given in Table 5

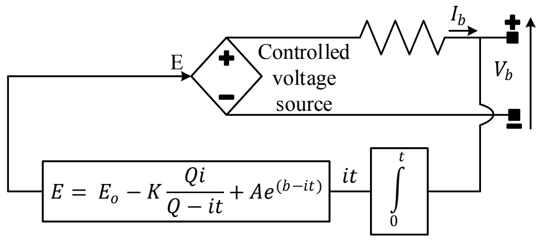

Figure 8: Non-linear dynamic model of BES.

and Fig. 6. From Table 5 and Fig. 6, it is evident that none of the storage technology exhibits the ideal storage characteristics. For example, BES has high energy density, but lower power density, smaller life cycles, and high cost associated with power capacity. While, the characteristics of SCES, SMES, and FES are almost similar, i.e. high-power density, lower cost associated with power capacity, and large cycle life with very small energy density and high cost associated with energy capacity. The normalized power and energy characteristics of various storage technologies given in Table 5 are further illustrated in Fig. 7. From the figure, it can be observed that the characteristics of the BES are complimentary to those of SCES, FES, and SMES technologies. A HESS can be formed by integrating two types of storage technologies that have complimentary characteristics. The feasibility, of BES-SCES, BES-SMES, and BES-FES, are reported in [68, 69, 70, 71, 72, 73] as HESS.

4 Overview of ESS Models for FR Studies

Several studies have investigated the effectiveness of ESS for FR. There are number factors such as storage type, charge/discharge rate, state of charge, and temperature that might affect the dynamic behaviour of the ESS. Thus, different models of ESSs that capture their dynamic behaviour relating to frequency response, have been proposed in literature for FR studies. This section briefly explain those models and limitations.

4.1 Dynamic models of BES

The first dynamic model of BES is proposed in [74, 75]. In this model, BES is represented by voltage source in series with parallel RC circuits. Although the proposed model correctly represents the external characteristics of a battery, but the model is incomplete as the values of resistance and capacitances are assumed to be constant. The equivalent model of battery and converter is proposed in [76]. The proposed model takes into account the battery characteristics, internal losses, and converter equivalent circuit. This model can easily incorporated for power system stability studies. In [77], an incremental BES model is proposed for LFC studies. The incremental model captures the dynamics of converter and battery storage. This proposed model is similar to the one developed in [76] except the fact that the reactive power is assumed zero. In [78, 79, 80, 81], BES is modeled as DC voltage source in series with the inverter for frequency stability studies.

A Non-linear model of BES (shown in Fig. 8) is proposed in [82]. In this model, the internal voltage is not fixed (which is considered as fixed in all previous models) and it depends on the charging/discharging current. In Fig. 8, E_o is the constant voltage of battery, E is the no load voltage, Q is the battery capacity, K is the polarization voltage, A is the exponential zone amplitude, I represents current, $\int idt$ is the actual battery charge, and b is the exponential zone time constant inverse. This model accurately represents the behaviour of various battery types. The parameters of the battery can be obtained from the discharge curve provided by the manufacturer [83]. Furthermore, the first order lag model (shown in Fig. 9a) and first order lag model with state of charge (shown in Fig. 9b) are most frequently used models for FR studies [84, 85, 86, 87, 88]. Although, the internal characteristics

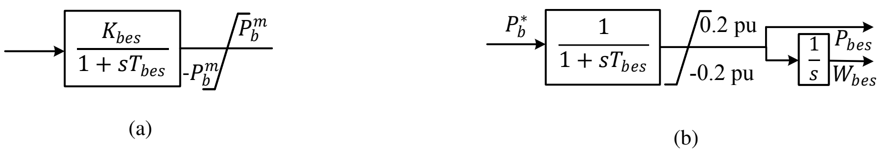

Figure 9: BES transfer function model: (a) lag compensator (b) lag compensator with state of charge.

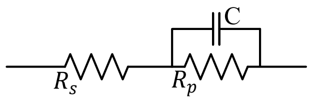

Figure 10: R-C model of SCES.

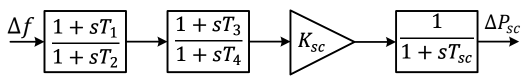

Figure 11: Transfer function model of SCES.

of BES are not considered in these models, they are widely used in dynamic studies due to representative control characteristics given by compensator. In Fig. 9a and Fig. 9b, T_{bes} is time constant of BES, K_{bes} is the gain, P_{bes} is the power output of BES, W_{bes} is energy of BES, and P_b^m is the MW rating of BES. In non-linear model obtaining accurate parameters is challenging [89], while lag models require only one parameter, time constant which can be obtained easily.

4.2 Dynamic Models of SCES, FES, and SMES

SCES based ESS consists of power conditioning system and supercapacitors stack. A RC circuit based model of SCES (shown in Fig. 10) is also used for FR services [90, 91, 92, 93]. In Fig. 10, R_s is the equivalent series resistance, C is the equivalent capacitance, and R_p is the parallel resistance to account for the leakage current. The leakage resistance is normally ignored for the short duration applications of SCES. The most frequently used model of SCES for FR studies is the first order lag model [94, 95, 96] as given in (1).

$$G_{sc} = \frac{K_{sc}}{1+sT_{sc}} \tag{1}$$

In (1), G_{sc} is the output of SCES, T_{sc} is time constant of SCES, and K_{sc} is the gain. The model of SCES energy storage proposed and used in [97, 98], is given in Fig. 11. The model employs two phase compensation blocks with time constants T_1, T_2, T_3, T_4, a gain block K_{sc}, and time constant of SCES (T_{sc}). It is worth noting that the limited work has been conducted in SCES modelling issues for power system dynamic studies.

A FES consists of three major parts; rotating cylinder, machine, and converter. The model of FES requires the modelling of all these three components. A comprehensive surface permanent magnet machine based model of FES is developed in [99]. In the proposed model, the rotating cylinder and rotor of machine are assumed as a single mass, while the converter is modelled as first order lag function with time constant of 0.5 ms. First order lag model (similar to the one given in (1)) of FES is used in number of studies studies for FR [100]. In [101], the dynamics of flywheel are represented using squirrel cage induction machine and converter. In [102], permanent magnetic synchronous motor is used to represent the FES. In [103], logic and control based dynamic model of FES used for FR (shown in Fig. 12). In [104, 105], the dynamics of machine and converters are ignored and FES unit is given by considering the dynamics of rotating cylinder. In [104], the dynamics of FES are represented using the equation of motion is used $T_f = -J_f \frac{d\omega_f}{dt}$, where T_f is electromagnetic torque, J_f is the total of moment of inertia of cylinder and machine, ω_f is the angular speed of rotating cylinder. In [106], A more realistic model of FES energy storage is proposed shown in Fig. 13. The proposed model considered the time constants of converter and measuring device. A number of studies have used detailed machine to represent FES for dynamic studies such as FR. But it is yet to find out the recommended models and parameters of FES for FR studies.

An SMES storage unit consists of superconducting coil and power electronic conversion system. The modelling of SMES requires the modelling of coil and the power electronic conversion unit. A transfer function based model of SMES is used in [107] (see Fig. 14). The voltage across the superconducting coil is controlled continuously as a function of frequency. Negative feedback of current deviation is used which allows the restoring of steady state value of SMES after the disturbance and make it able to respond to the next disturbance. In Fig. 14, K_o is the gain

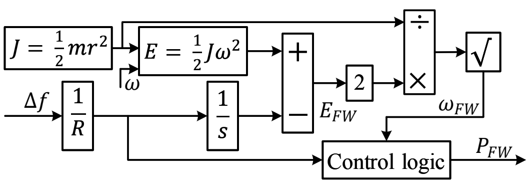

Figure 12: Dynamic model of FES.

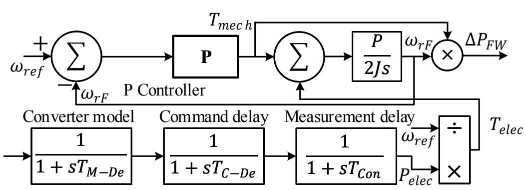

Figure 13: Transfer function representation of FES.

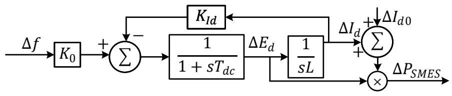

Figure 14: Dynamic model of SMES.

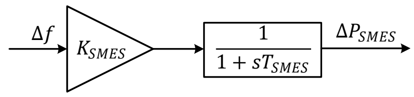

Figure 15: Simplified dynamic model of SMES.

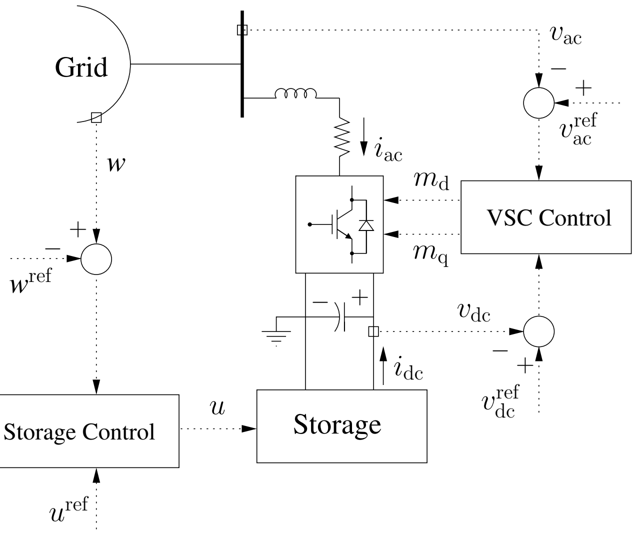

Figure 16: ESS connected to AC grid [114].

in kV/Hz, K_{Id} is the gain of feedback loop in kV/kA, T_{dc} is converter time delay in s Δf is frequency deviation, ΔE_d is the voltage across the coil, ΔI_d is the current, and ΔP_{SM} is the power output of SMES. A first order lag model (shown in Fig. 15) of SMES is used in [108, 109, 110, 111, 112, 113] for FR. In Fig. K_{SMES} is gain and T_{SMES} is time constant, Δf is the deviation in frequency, and ΔP is the deviation in power output of SMES unit. It is evident from the literature that most of the studies used transfer function based model of SMES for FR.

Figure 16 shows a generalized scheme of ESS connected to AC grid. The system employ a VSC converter and its control, and ESS and its control. The objective of the ESS is to control the measured quantity w, which can be frequency or power. The elements shown are common to all fast responsive storage technologies. As the models of the fast responsive storage technologies are discussed, here the model of VSC will be discussed. The VSC include transformer, which provides galvanic insulation, a condenser, which maintains the voltage level at the DC side, and bi-directional converter [115, 116, 117]. The converter converts the DC voltage to AC using appropriate control. The block diagram of the converter and inner current control loop is given in Fig. 17. The converter in $dq-$ frame

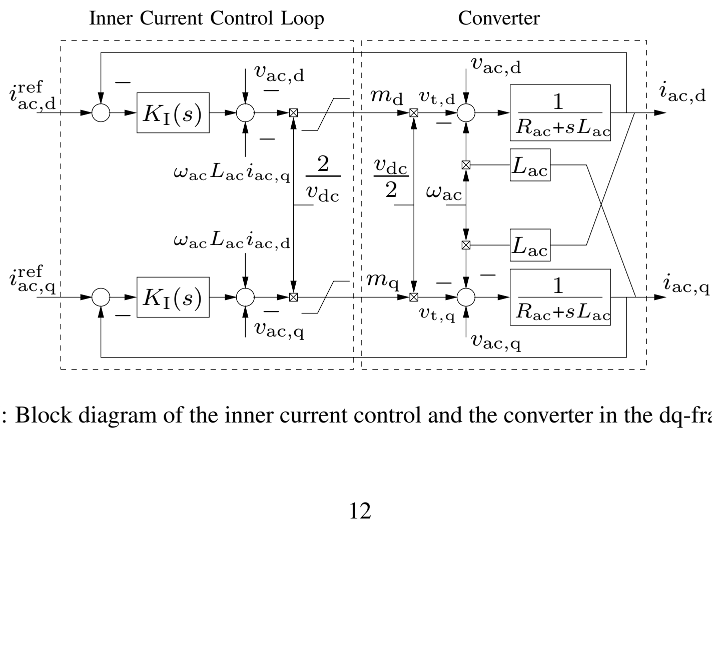

Figure 17: Block diagram of the inner current control and the converter in the dq-frame [114].

can be represented as following [114],

$$R_{ac}i_{ac,d} + L_{ac}\frac{di_{ac,d}}{dt} = \omega_{ac}L_{ac}i_{ac,d} + v_{ac,d} - v_{t,d} \tag{2}$$

$$R_{ac}i_{ac,q} + L_{ac}\frac{di_{ac,q}}{dt} = -\omega_{ac}L_{ac}i_{ac,q} + v_{ac,d} - v_{t,q} \tag{3}$$

where R_{ac}, and L_{ac} are aggregated resistance and inductance of the converter and transformer, $v_{t,d} = m_d v_{dc}/2$, $v_{t,q} = m_q v_{dc}/2$, ω_{ac} is the frequency, and v_{ac} is voltage.

5 FR using ESS

5.1 FR using single Storage

The ESS can be a single storage technology or a hybrid storage technology (combination of multiple storage technologies). This subsection reviews the control and sizing of single storage technology providing FR. While the sizing and control of HESS are reviewed in the Section 5.2.

5.1.1 Control and Operation

Different control strategies are proposed in the literature for a single storage to provide FR [118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129]. The control of ESS to provide FR can be classified into two categories; i.e., classical control (droop control, PID control) and advanced control (H_∞, fuzzy, neural, etc). In [130], the authors discussed a pioneering project for a BES to provide LFC in the isolated city grid of West-Berlin. A rule based control is used to operate the BES. It was found that a BES provides both operational and economical advantages for LFC and instantaneous reserve operation. In [131], the PFR service is provided by Li-Ion type BES. The power output of BES is controlled with classical control method. After providing the FR service, the SoC of BES is re-established every time when the frequency goes within the acceptable threshold (i.e., 49.98–50.02 Hz) or when the BES gets saturated (i.e., upper or lower limits of SoC are reached). A modified droop characteristics (conservative strategy) based control for power output of BES is proposed in [132, 133] with the following droop equation

$$K = K_{max} \times \begin{cases} SoC^2 & \Delta f \leq 0 \\ (SoC-1)^2 & \Delta f > 0 \end{cases} \tag{4}$$

In (5), K is control signal, K_{max} is the maximum value of droop, Δf is the deviation in frequency, and SoC is the available state of charge in the BES. This strategy pays more attention to SoC and allows storage output to be small when SoC is lesser. This is why the square of SoC is used which makes the control gain small for small values of SoC . Also, the term $SoC-1$ is negative and square is taken to make it positive. The relation between droop and SoC levels of battery is shown in Fig. 18. It can be observed that during the discharging of BES, the output is larger for higher values of SoC . During charging, the droop decreases quickly in the beginning and slows down with the increase in SoC . This type of control is more suitable for a system with multiple storage units operating in parallel. Another variable droop (radical strategy) based control strategy is proposed in [132, 134]

$$K = K_{max} \times \begin{cases} 1 - \left(\frac{SoC - SoC_{high}}{SoC_{min} - SoC_{high}}\right)^2 & \Delta f \leq 0 \\ 1 - \left(\frac{SoC - SoC_{low}}{SoC_{max} - SoC_{low}}\right)^2 & \Delta f > 0 \end{cases} \tag{5}$$

The SoC parameters, $SoC_{min} = 0.1$, $SoC_{max} = 0.9$, $SoC_{low} = 0.2$, and $SoC_{high} = 0.8$ are used to keep the value close to 0.5. Fig. 19 illustrates the variations in droop with change in SoC levels of BES.

In [135], a rule based control strategy is developed for BES providing PFR. The proposed strategy dynamically adjusts the SoC limits of based on the statistical analysis of frequency measurements. Moreover, the SoC of the BES is re-established at a moderate rate of current when the frequency returns within the allowable limit. A similar rule based strategy, that dynamically adjusts the SoC limits, for the operation of BES providing FR in an isolated power system is proposed in [136]. In [137], a control strategy is proposed to deploy BES for primary and secondary FR services. The proposed methodology takes into account the operational constraints of the BES, i.e., charge/discharge rate and SoC to provide reliable service. Instead of using two levels of SoC (SOC_{min} *and* SOC_{max}) different levels of SoC are defined and an adaptive SoC-feedback control is developed that maintains SoC at optimal level to extend the lifetime of the BES while providing the service reliably. The motivation of the proposed strategy is based on the fact SoC limits affects the life time of battery. For example, according to battery degradation model

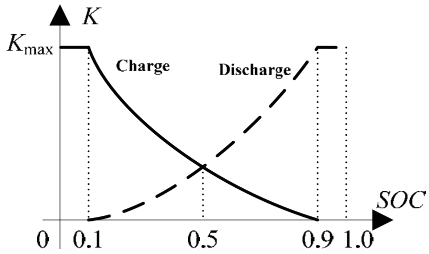

Figure 18: Conservative strategy [132].

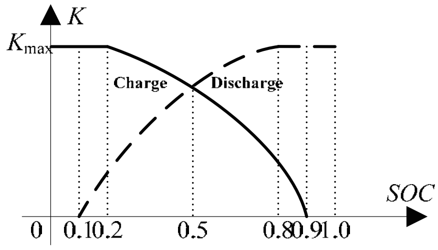

Figure 19: Radical strategy [132].

of National Renewable Energy Laboratory (NREL), the Li-Ion battery that operates in an SoC between 30%–50% has longer life compared to those that spend majority of their time between 70%–90% or 20%–40% [138]. The adaptability of SoC limits makes the strategy proposed in [135, 136, 137] suitable over methods given in [132, 134]. In [139], a strategy that combines inertia emulation function and traditional droop control is proposed which resulted in fast damping of the microgrid (MG) frequency oscillations. A two stage novel control strategy for ESS to participate in FR is proposed in [140]. In the first stage, wind power prediction information is used to adjust the power output of ESS. In the second stage, the power output of ESS is modified using frequency feedback to suppress the steady state error. Since, the output power of ESS is regulated ahead of the deviation in frequency with the proposed scheme, therefore, the speed of FR is improved with this method.

In [141], a SCES is used to emulate inertia to provide dynamic frequency support in power system. The operation of SCES is divided into three modes. The first mode is based on power/frequency droop, this control performs well during moderate transients. Although the first mode provides anticipated response without introducing unwanted disturbances on the operation of system but it has longer response time which may adversely effects the ability of the ESS to handle large events. To counter this problem, a derivative control is employed in the second operating mode. When the RoCoF falls below the threshold, the complete dynamic reserve is deployed immediately. This instantaneous deployment of reserve helps to handle the large disturbances. The third mode is charging mode which is switched on when frequency comes back in the non critical window. In [142], SCES is used to emulate inertia and improve FR. An adaptive generalized predictive control is proposed for SCES to provide primary and secondary frequency regulation [143]. In [144], it is showed that the inertial support provided by SCES can be improved using derivative-droop control instead of only derivative control.

In [145], a four-quadrant operation of SMES is proposed to reduce the frequency and voltage deviations in a wind-diesel system. The firing angle of SMES converter is controlled based on active and reactive power deficit. For continuous control, the SMES current is forced to return to its nominal value after handling an event to handle a new event. Set-membership affine projection algorithm (SMAPA) based adaptive control scheme for SMES is developed in [146]. The SMAPA based adaptive PI controller is used to control the active and reactive power output of SMES. In [147], an adaptive control scheme for SMES is proposed that encapsulates on-line identification with model predictive control (MPC). A reduced order model of the system is determined using recursive least-squares algorithm. Based on the reduced-order model of the system and discrete time model of SMES, an adaptive generalized predictive control (AGPC) is formulated. The proposed adaptive control scheme keeps the frequency deviations to minimum and keeps the operation of SMES within its operational constraints. In [148], a rule based control for SMES is developed to provide dynamic frequency regulation. The SMES gets activated based on the RoCoF of the system, if the RoCoF > 0.5 the SMES provides FR, otherwise, it remains in idle mode.

In [149], a control strategy is proposed for wind power generation system with FES based on fuzzy-PD controller to provide FR. A rule based control is used to provide FR using FES [150]. The control allows the FES to store energy (speed up) when generation is more, and discharge energy (slows down), when demand is more. In [151], fuzzy logic control (FLC) scheme is proposed for FES to smooth the active power output of wind generation. The control is divided into three levels; external, middle, and internal. The external level determine the power exchange between FES and DC bus. The middle level control dynamically tracks the reference signal provided by the external control level. While the internal level control generate the switching signals for voltage source inverter. In [152], FR in a standalone MG is provided by using FES. V/f control with FLC as an auxiliary controller is used to provide the required FR service. A droop control strategy is proposed for FES to provide FR in low voltage distribution networks [153]. The proposed controller calculates the required amount of power injected/absorbed to/from the system in event of frequency deviation and as a result slows-down/speeds-up the FES.

In addition to the control strategies mentioned above, H_∞ is also applied extensively to ESS for FR [154, 155, 156, 157, 158, 159]. In [155], a decentralized control technique for parallel operating BESs based on H_∞ control

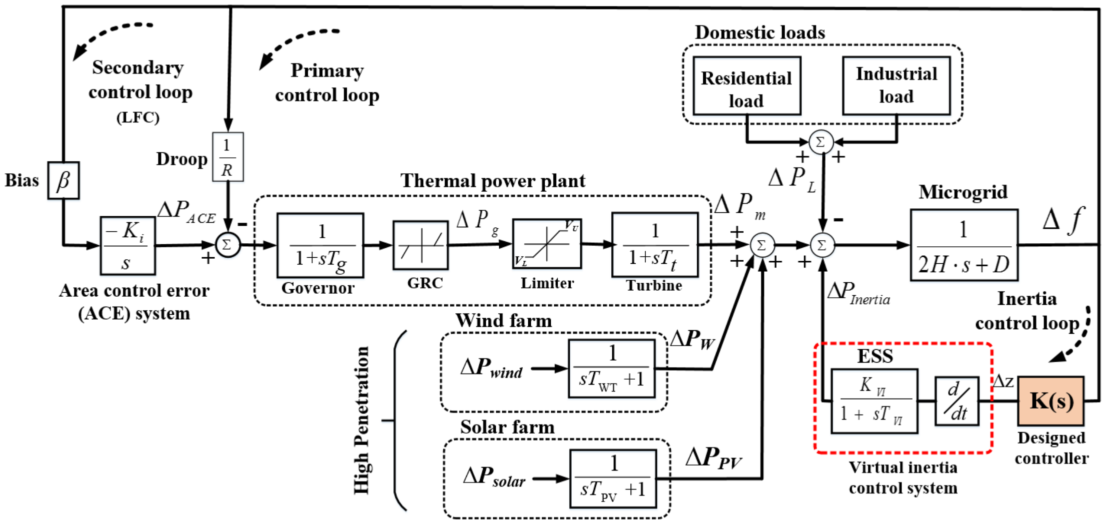

Figure 20: Dynamic model of the islanded microgrid considering high penetration of RESs [154].

control theory is proposed. A virtual inertia control of ESS (providing FR in standalone MG) is developed based on the robust H_∞ control scheme [154]. The dynamic model of the system used in [154] is shown in Fig. 20. The system has three control loops; inertial, primary, and secondary control loop. It can be seen from the figure that the ESS is represented by first order lag model, and placed in the inertial control loop to improve the inertial response of system. The derivative control is applied to emulate the inertia, and to determine the gain of derivative control H_∞ control is used. The primary control is based on the droop control which automatically adjust the output of thermal power plant after the disturbance. The secondary control loop, adjust the output of thermal power plant to bring the frequency back to nominal value. The RESs are also modelled as the first order lag models. The variation in frequency of the system is modelled as following

$$\Delta f = \frac{1}{2Hs + D}\left(\Delta P_m + \Delta P_W + \Delta P_{PV} + \Delta P_{inertia} - \Delta P_L\right) \tag{6}$$

In 6, Δf is the variations in frequency, H the is inertia constant of the system, D the is load damping factor, ΔP_m is the power output of thermal power plant, ΔP_W is the output power of wind turbine, ΔP_{PV} is the power output of PV system, ΔP_L is the load power, and $\Delta P_{Inertia}$ is the power output of ESS.

5.1.2 Sizing of ESS

In addition to control, the sizing of ESS providing FR is equally important. Some researchers have proposed methods to determine the size of ESS to provide FR [160]. The sizing of ESS is related to the determination of power supply capability (MW rating) and energy storage capacity (MWh rating). Typically, the sizing problem of ESS can be modelled as following:

$$obj : J = \sqrt{f(\mathbf{X})} \longrightarrow min \tag{7}$$

$$s.t. \begin{cases} \boldsymbol{g}_\ell(\boldsymbol{X}) = 0 & \ell = 1,2,\ldots,m \\ \boldsymbol{h}_\imath(\boldsymbol{X}) \leq 0 & \imath = 1,2,\ldots,q \end{cases} \tag{8}$$

In (7) and (8), J is the objective function which represents the cost of the ESS, $\boldsymbol{X}$ is the set of design variables which are the power and energy capacities of ESS, and $\boldsymbol{g}_\ell$ and $\boldsymbol{h}_\imath$ are equality and in-equality constraints. In [161], an analytical methodology based on the power spectrum density theory is proposed to determine the size of ESS in order to increase the penetration level of wind generation to expected level. In [136], an iterative methodology is developed for the sizing of BES to maximize the profit while providing PFR in an small isolated power system. An analytical methodology based on the frequency characteristics of power system is proposed for sizing of SCES to enhance the frequency stability [162]. In [127], an analytical methodology is developed for sizing of BES to provide and IR and PFR. The proposed methodology is based on equivalent inertia calculation of ESS. In [163], sizing of a BES providing PFR is done based on the investment cost. The sizing problem is formulated as

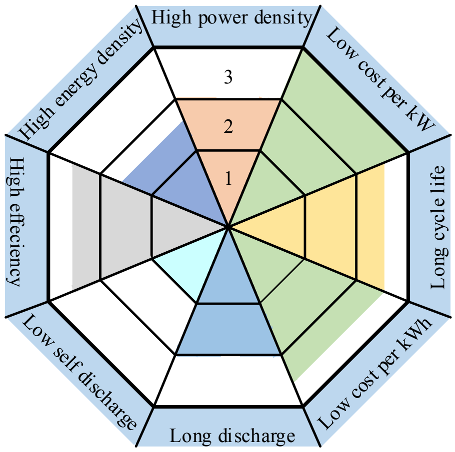

Figure 21: Different characteristics of ESSs for high power grid services(1–less important. 2–important. 3–very important).

standard cost minimization optimization problem and solved using metaheuristic optimization algorithm. From prior discussed work, it is worth noting that most of BES sizing methodologies are based on the deterministic approach and analytical approach.

5.2 FR using HESS

The importance of different characteristics of ESS to provide grid ancillary services (especially FR) are shown in Fig. 21 [42]. It is evident from the Fig. 21 that the characteristics of ESS that are more important are; low cost per kW, long cycle life, and low cost per kWh. The power density of battery is much smaller compared to its energy density. In a BES the power density needs to be sufficiently high to supply the peak load power demand. Although, the high power density batteries are also available in the market, their cost is much higher as compared to their lower power density counterparts. This problem can be solved by increasing the BES size which would be cost intensive for utilities. Also, if BES is cycled at very high C-rates, the life of the pack is adversely affected. This may also cause safety issues due to thermal runaway [164]. Moreover, while providing the dynamic frequency support service the BES undergoes very frequent, albeit partial, charge and discharge cycles, which causes battery degradation and this is a major practical problem faced by BES [165, 166]. Hence, it can be concluded that BES solely is not ideal to provide service which require high power for short time. Therefore, it is beneficial to combine a cheap and efficient high-power ESS with BES to be used as a buffer to handle the high surge currents economically and efficiently [167]. On the other hand, the power dense storage technologies, i.e. SCES, SMES, and FES have complementary characteristics to that of BES (given in Fig. 7). So, they are not suitable for the service require continuous power for longer period of time.

The concept of hybrid energy storage system (HESS) is proposed in [168] as potential solution to prior mentioned issues. A HESS can be formed by combining multiple storage technologies, i.e. BES-SCES, BES-SMES, BES-FES [169, 170, 171]. The HESS obtained by combining BES with SCES, SMES, and FES have the characteristics of an ideal ESS, i.e. high power density, high energy density, longer cycle life, lower cost associated to energy and power densities.

5.2.1 Control and Operation

The application of HESS in FR is investigated in a number of studies in literature [172, 173, 174, 175, 176]. The main challenge in HESS is the control of power output of the storage units. In [177], a control strategy based on FLC and low-pass filter is proposed for HESS, i.e., BES-SCES. A low-pass filter is employed to remove the high dynamic components from the BES demand signal. The FLC minimizes the peak current of BES while constantly considering the SoC of the SCES. Membership functions of the FLC are optimized using particle swarm optimization (PSO) algorithm to optimally achieve BES peak current reduction. In [178], SCES-fuel-cell (FC) are used to provide dynamic frequency support. The robust H_∞ design method is used in this work. In [179], a PID type neural network adaptive control for SCES-FC is proposed. The proposed adaptive control is developed using a feed-forward neural network based on a back-propagation training algorithm. In [180], rule based control for

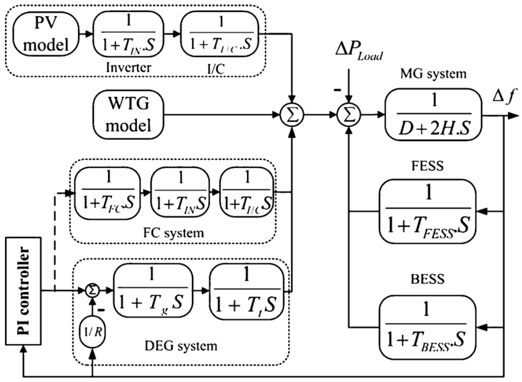

Figure 22: Frequency response model of MG with HESS [182].

power management of BES-SCES is developed. The SCES automatically responds to the fast-varying power surges using inertia emulation concept while the BES tackles the remaining parts of required demand and only responds to relatively long-term power fluctuations with slow dynamics. In [181], BES-SCES is employed to provide IR and PFR. The derivative control is employed for SCES to provide IR and droop control is designed for BES to provide PFR. From the reviewed work it is worth noting that the most of work studied the HESS for FR used advanced control techniques. In [182], BES-SCES-FCES are employed for FR in an isolated MG. The MG employs of PV system, wind farm, and conventional diesel generator for electric power generation. The frequency response model of MG is shown in Fig. 22. It can be seen that both BES and FES are modelled as first order lag functions with time constants T_{BESS} and T_{FESS}, respectively. BES and SCES have very small response time so they are placed in the inertial control loop while FC which has comparatively slower response time is placed in secondary frequency regulation loop. FLC and PSO algorithm are used for the on-line tuning of the PI controller for LFC. It should be worth noting that the most of the studies that are related to application of HESS for FR use similar simplified model of the system, i.e. ignoring exciter dynamics and considering frequency a globally uniform quantity.

5.2.2 Sizing of HESS

Sizing of HESS is important for economic and reliable FR services. A frequency based sizing methodology is developed in [183] to optimize the capacities of BES-SCES system in an isolated power system with high penetration of wind powered based generation. Based on the Fourier analysis of the power imbalance between generation and demand the low and high frequency power fluctuations are supplied to BES and SCES, respectively. In [181], a methodology based on the equivalent inertia calculations is proposed for the sizing of BES-SCES to provide IR and PFR. The SCES is used for IR service, and BES is used to provide PFR. The SCES and BES sizing issue is considered separately. The sizing of SCES only considered the IR while PFR is considered for sizing BES. In [184], the sizing of BES-SCES is done based on the cost minimization. The methodology takes into account the complementary characteristics of BES and SCES to maximize the profit. The sizing problem is formulated as a standard optimization problem and solved using metaheuristic optimization algorithm. In [185], capacity optimization problem of BES-SCES is modelled as follows:

$$TC_{hess} = g\left(\Delta f_{grid}^{max}\right) \,.\, \left(TC_b + TC_s\right) \tag{9}$$

where

$$TC_b = C_{pb} \,.\, P_{rated,b} + C_{eb} \,.\, E_{rated,b} \tag{10}$$

and

$$TC_s = C_{ps} \,.\, P_{rated,s} + C_{es} \,.\, E_{rated,s} \tag{11}$$

and

$$g\left(\Delta f_{grid}^{max}\right) = \begin{cases} 1, & \Delta f_{grid}^{max} \leq \Delta f_{grid}^{code} \\ M, & \Delta f_{grid}^{max} > \Delta f_{grid}^{code} \end{cases} \tag{12}$$

In (9), (10), (11), and (12), TC_{hess} is the total cost of HESS, TC_b is the total cost of BES, TC_s is the total cost of SCES, $P_{rated,b}$, and $P_{rated,s}$ are rated power capacities of BES and SCES, $E_{rated,b}$, and $E_{rated,s}$ are rated energy capacities of BES and SCES, C_{pb}, and C_{eb} are power and energy costs of BES, C_{ps}, and C_{es} are power and energy costs of SCES. The factor $g\left(\Delta f_{grid}^{max}\right)$ is included in the cost function, (9), to penalize the solution that doses not satisfy the grid code. As it can be seen from (12) that when the frequency deviation is more than the Δf_{grid}^{code}, then the $g\left(\Delta f_{grid}^{max}\right)$ is designated to M which is essentially a very large number. This optimization problem is solved using the differential evolution algorithm. From the reviewed literature it is evident that very few works have considered the sizing issue of HESS. The notable work has sized the faster storage technology for IR while slower one for PFR service.

In hybrid energy storage, both the sizing and operation are challenging tasks compared to single storage technology. As the hybrid storage system deploy more than one storage technologies, the sizing becomes more complicated. Moreover, a control algorithm for the appropriate dispatch of multiple storages while maintaining the constraints imposed by the system and storages is very challenging.

6 Summary and Discussions

The PV and WT have two distinct impacts on the frequency response of power systems, due to reduction in inertia and intermittent generation. If auxiliary control is not deployed for virtual inertia support or frequency regulation, the impact of PV and WT has a similar effect on system frequency characteristics due to inertia reduction.

Generally, the fluctuations in the power output of WT are more comparable to PV output. The WT is more stochastic compared to PV which is rather periodic. While the effect of clouds can be relatively fast, in general, the impact of PV on the system frequency can be assumed to be on a longer time scale than that of WT. Thus, special care must be taken while designing the control of battery energy storage to smoothen the power output of WT to avoid frequent partial charge discharge cycles (which are detrimental to battery cycle life). In the case of PV dominated systems, the chances of uneven charging/discharging of battery are less because of periodic nature of PV power output. Some strategies have been presented in [135, 169, 187, 188] to reduce the partial charge-discharge of battery storage. Mainly these methodologies suggest that instead of using a single battery bank, multiple parallel-connected battery banks can be used for unidirectional charging/discharging.

6.1 Selection of Control

A summary of different studies investigating the FR using ESS is given in Table 6. The table highlights the type of storage technology used, sizing methodology, control strategy, and application of study. Different control techniques have been applied ranging from the simple PI to robust H_∞ control. Most of works used the derivative control to provide synthetic inertia. The derivative control is fast and provide large output instantly to limit the RoCoF. But, it is susceptible to noise and may result in instability. In addition, during the frequency drop event, the output of derivative remains negative before the frequency nadir point while it becomes positive after the frequency nadir point (while frequency deviation is still negative). This may result in incorrect operation. Droop control has also been widely used for FR services. The droop control has no issue of instability and incorrect operation as of derivative control. But, the droop control cannot generate large power output immediately after the disturbance, while it increases the power output with the increment of frequency deviation. Hence, the droop control is not suitable for synthetic inertia. However, it is suitable for FR service. A combination of derivative and droop control may be suitable for both IR and PFR. The derivative-droop is capable of delivering large power immediately after the disturbance without incorrect operation of storage system. Rule based control has also been used extensively. Mostly the rule-based control is derived from the droop or derivative control. Some studies have also used the conventional PID control which is simple and easier to implement. The advanced control schemes have also been used in some studies. The advanced robust schemes give better performance but introduce complexity.

In the authors' opinion, a derivative-droop control with appropriate filters and gains is sufficient for IR and PFR. Moreover, the derivative-droop control is simplest and easy to implement. A better response from the derivative-droop control can also be achieved using the time varying gains instead of fixed gains.

6.2 Selection of ESS

As a rule of thumb, the high-power dense technologies are suitable for applications require large power for shorter time period. While, high energy dense storage technologies are more suitable for services that required continuous power for longer time period. The IR requires sudden large power to be injected/absorbed. Thus, the SCES, SMES, and FES are suitable for IR. Among the high-power dense storage technologies, SCES has lowest cost per kW. Hence, the SCES is best suited for IR services. The PFR services require continuous power for a longer time. For example, ENTSO-E requires the primary reserve to be deployed linearly and should remain connected into the system for 15 mins. Hence, the BES is most suitable candidate for PFR. Dynamic frequency support requires

Table 6: Summary of works

Reference	Storage	Dimensioning Methodology	Size (MWh–MW)	Control Strategy	Application
[189]	BES	Historic frequency data	1.24–2	Rule based	PFR
[190]	BES	Iterative algorithm	21.3–55	Rule based	Spinning reserve
[191]	BES	—	—	MPC	PFR
[192]	BES	Iterative	*–4	Rule based	PFR
[193]	FES	—	—	PI	IR
[194]	BES	Dynamic programming	0.1–1	Dynamic program	PFR
[195]	SCES	—	—	Rule based	DFS
[196]	SCES	—	—	Droop control	IR
[162]	SCES	Analytical	0.0059–4	Droop–derivative	DFS
[186]	SMES	—	—	PID	DFS
[184]	BES-SCES	Optimization algorithm	97–8.8, 2–6	Rule based	DFS
[197]	BES	Iterative approach	4–*	IR	
[198]	FES	—	—	PID	LFC
[199]	BES-SCES	Monte-carlo	—	Hysteretic loop	DFS
[200]	FES	—	—	Fuzzy-PI	DFS
[201]	BES-SCES	—	—	Rule based	DFS
[185]	BES-SCES	Differential evolution	500–450, 250–50	FLC	DFS
[202]	SCES	—	—	ANFS	LFC
[203]	SMES	—	—	Lead-lag	DFS
[204]	FCES-SCES	—	—	PI	DFS
[205]	BES	—	—	$\mu-$synthesis	DFS
[206]	BES-SCES	—	—	PI	DFS
[207]	SCES	—	—	FLC	LFC
[208]	SMES	—	—	NNAPC	LFC
[183]	BES-SCES	Fourier analysis	4130–514,126–190	—	DFS
[209]	FCES-FES	—	—	Rule based	DFS
[210]	BES	—	—	Droop control	DFS
[211]	BES-SMES	—	—	Dynamic droop	PFR
[212]	BES	—	—	Derivative control	IR
[213]	BES-SMES	—	—	Rule based control	PFR
[214]	BES	—	—	Rule based	PFR
[215]	BES-SCES	—	—	Rule based	DFS
[216]	SMES	—	—	Rule based	DFS
[217]	BES-SCES	—	—	H_∞ control	DFS
[218]	BES	—	—	Variable Droop	DFS
[219]	SCES	—	—	PIDN-FOPD	LFC
[220]	BES	—	—	FLC	DFS
[221]	BES	—	—	Derivative control	IR
[222]	BES	—	—	Droop–derivative	IR
[223]	BES	Iterative method	15–10	PI control	DFS
[224]	BES	—	—	Derivative control	IR
[225]	BES	—	—	Rule based	PFR
[226]	BES-SMES	—	—	H_∞ control	LFC
[227]	SCES	—	—	Droop–derivative	DFS

* Capacity is not specified

continuous charging/discharging which involves partial charge/ discharge events (detrimental to BES life). In addition, the required energy capacity can also be higher depending on the type of system. Thus, for dynamic frequency support hybrid storage is more suitable.

7 Research Gaps and Future Directions

Most of the studies are based on the following assumptions, i.e. (i) governor and exciter dynamics are completely decoupled, (ii) frequency is a global variable and remains uniform in all parts of power systems (iii) RoCoF is a global parameter. However, during the first few seconds after a large event the system dynamics result in multi-modal swings. Therefore, RoCoF and frequency vary at different locations of the system until the iner-area oscillations damped out. Fig. 23 shows the traces of frequency at various buses after the event occurred at 1 s. The frequency of the bus (blue trace) near to the event drops rapidly with high RoCoF. While the bus (orange trace) farthest from the disturbance does not see the effect of disturbance for approximately 3 s. It should be worth noting that the farthest bus (orange trace) is almost 1000 miles away from the location of the event. Similarly, Fig. 24 shows the traces of frequency for a large generation loss at the edge of US Eastern Interconnection. It can be seen that the farthest bus sees the event almost after 4 s. It should be worth noting that the time farthest bus sense the event the RoCoF sign is opposite to bus nearest bus. A non-uniform behavior of frequency and RoCoF in GB grid after the disturbance is also observed and shown in Fig. 25. It can be seen from the figure that the RoCoF varies significantly with location.

So, from the above discussion it can be concluded that during first few seconds after the disturbance, the frequency and RoCoF vary largely at different locations in the system. Therefore, the studies involving the applications of ESS for IR must not consider the frequency or RoCoF as uniform. Moreover, the controller designed based on the local RoCoF and frequency measurements might result in false triggering of IR reserve.

Another critical parameter for the FR by ESS is the total response time of ESS. The total response time of ESS unit must be less than that of UFLS relays. The total response time of ESS is sum of followings: measurement device time, event identifying device time, communication signal time, and storage activation time [228]. Most of the studies dealing with IR support have not considered these time delays. The size and operation of ESS depends greatly on these time delays and excluding them challenges may affect the accuracy of results.

The AC networks which are interconnected by means of HVDC links exhibit a natural decoupling in terms of both frequency and voltage. It is said that the AC networks are interconnected asynchronously. Considering the assumptions that the frequency remains uniform through out the system make the results less valid if the system has HVDC connection between different areas.

The following future directions are suggest based on the results from the real world examples and the identified the research gaps.

The important frequency stability indices, i.e., frequency nadir and RoCoF, depends highly on the magnitude of the reserve deployed before frequency nadir point is reached. Hence, during sizing and control design it is important to consider all the components that might cause delay in deployment of reserve. Therefore, more detailed models should be used. For example, along with the dynamics of storage device the inclusion of dynamics of the converter, measuring device, communication system can result in more realistic results.

The RoCoF based reserve activation might result in false triggering. Because, as discussed earlier, RoCoF is not uniform all over the system and becomes local variable for few seconds after the disturbance. As the IR

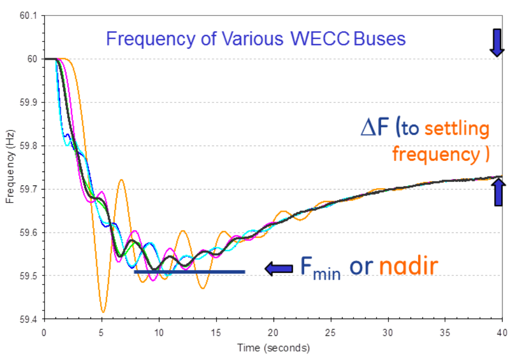

Figure 23: Bus frequencies for large disturbance in USA western grid [228].

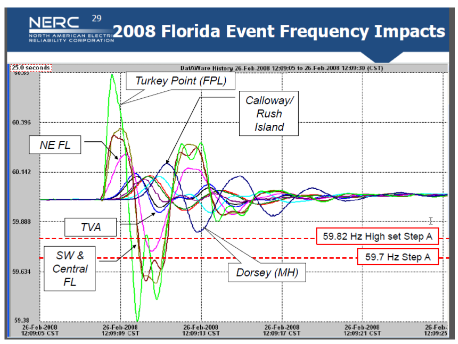

Figure 24: Geographic distribution of bus frequency for 2008 Florida, US event [228].

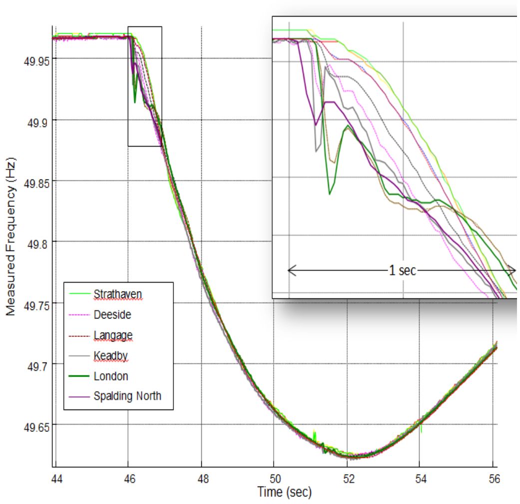

Figure 25: Variation in frequency of GB system at different geographical locations [229].

reserve should be deployed before the activation of RoCoF relays to prevent tripping, so, having one IR reserve and whose activation is based on local RoCoF might not help the system. A solution to this problem can be either the utilization wide area monitoring (WAM) control for the activation of IR reserve or location optimization of IR reserve. A synchrophasor based WAM system can help the more accurate activation IR reserve. Instead of using one IR reserve, multiple reserves appropriately sized and located, whose activation is based on the local signals can also result in better IR services in large system.

8 Conclusion

In this work, a comprehensive review of applications of fast responding energy storage technologies providing frequency regulation (FR) services in power systems is presented. The rapid responsive storage technologies include battery energy storage system (BES), supercapacitor storage storage (SCES) technology, flywheeel energy storage (FES), and super conducting magnetic energy storage (SMES). The basic characteristics of fast responsive energy storage technologies and their mathematical models used for FR studies are discussed and compared. In addition, the motivations behind the hybrid energy storage technologies are discussed in detail and different possible hybrid combinations are presented i.e. BES-SCES, BES-FES, and BES-SCES. The two most important aspects that are related to the applications of fast responsive energy storage technologies for FR services i.e. control and sizing are discussed in detail for both single and hybrid storage technologies. In addition, based on the results from the real world examples, the research gaps has also been identified.

References

[1] U. Akram, M. Khalid, and S. Shafiq, “Optimal sizing of a wind/solar/battery hybrid grid-connected microgrid system,” *IET Renewable Power Generation*, vol. 12, no. 1, pp. 72–80, 2017.

[2] M. Q. Raza, M. Nadarajah, and C. Ekanayake, “On recent advances in pv output power forecast,” *Solar Energy*, vol. 136, pp. 125–144, 2016.

[3] R. Doherty, A. Mullane, G. Nolan, D. J. Burke, A. Bryson, and M. O’Malley, “An assessment of the impact of wind generation on system frequency control,” *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 452–460, 2009.

[4] J. M. Carrasco, G. L. Franquelo, J. T. Bialasiewicz, E. Galván, R. C. P. Guisado, P. M. Á. Martín, J. I. León, and M. N. Alfonso, “Power-electronic systems for the grid integration of renewable energy sources: a survey,” *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1002–1016, 2006.

[5] Y.-z. Sun, Z.-s. Zhang, G.-j. Li, and J. Lin, "Review on frequency control of power systems with wind power penetration," in *International Conference on Power System Technology*. IEEE, 2010, pp. 1–8.

[6] R. Yan, T. K. Saha, F. Bai, and H. Gu, "The anatomy of the 2016 South Australia blackout: a catastrophic event in a high renewable network," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5374–5388, 2018.

[7] M. A. Kabir, M. M. H. Sajeeb, M. N. Islam, and A. H. Chowdhury, "Frequency transient analysis of countrywide blackout of Bangladesh power system on 1st November, 2014," in *International Conference on Advances in Electrical Engineering*. IEEE, 2015, pp. 267–270.

[8] H. H. Alhelou, M. E. Hamedani-Golshan, T. C. Njenda, and P. Siano, "A survey on power system blackout and cascading events: research motivations and challenges," *Energies*, vol. 12, no. 4, pp. 1–28, 2019.

[9] Y.-K. Wu, S. M. Chang, and Y.-L. Hu, "Literature review of power system blackouts," *Energy Procedia*, vol. 141, pp. 428–431, 2017.

[10] T. Kerdphol, F. S. Rahman, M. Watanabe, Y. Mitani, D. Turschner, and H.-P. Beck, "Enhanced virtual inertia control based on derivative technique to emulate simultaneous inertia and damping properties for microgrid frequency regulation," *IEEE Access*, vol. 7, pp. 14 422–14 433, 2019.

[11] F. Milano and Á. O. Manjavacas, *Converter-Interfaced Energy Storage Systems*. Cambridge, UK: Cambridge University Press, 2019.

[12] P. Denholm, J. Jorgenson, M. Hummon, T. Jenkin, D. Palchak, B. Kirby, O. Ma, and M. O'Malley, "Value of energy storage for grid applications," National Renewable Energy Lab. (NREL), Golden, CO (United States), Tech. Rep., 2013.

[13] J. W. Shim, G. Verbič, N. Zhang, and K. Hur, "Harmonious integration of faster-acting energy storage systems into frequency control reserves in power grid with high renewable generation," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6193–6205, 2018.

[14] D. Akinyele and R. Rayudu, "Review of energy storage technologies for sustainable power networks," *Sustainable Energy Technologies and Assessments*, vol. 8, pp. 74–91, 2014.

[15] B. Zakeri and S. Syri, "Electrical energy storage systems: a comparative life cycle cost analysis," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 569–596, 2015.

[16] "The frequency operating standard-AEMC." [Online]. Available: $https://www.aemc.gov.au/sites/default/files/content/c2716a96-e099-441d-9e46-8ac05d36f5a7/REL0065-The-Frequency-Operating-Standard-stage-one-final-for-publi.pdf$, Accessed on June 15th 2019

[17] H. Gu, R. Yan, and T. K. Saha, "Minimum synchronous inertia requirement of renewable power systems," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1533–1543, 2017.

[18] F. Díaz-González, M. Hau, A. Sumper, and O. Gomis-Bellmunt, "Participation of wind power plants in system frequency control: review of grid code requirements and control methods," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 551–564, 2014.

[19] G. A. Chown and R. C. Hartman, "Design and experience with a fuzzy logic controller for automatic generation control (AGC)," *IEEE Transactions on Power Systems*, vol. 13, no. 3, pp. 965–970, 1998.

[20] N. Jaleeli, L. S. VanSlyck, D. N. Ewart, L. H. Fink, and A. G. Hoffmann, "Understanding automatic generation control," *IEEE Transactions on Power Systems*, vol. 7, no. 3, pp. 1106–1122, 1992.

[21] A. N. Venkat, I. A. Hiskens, J. B. Rawlings, and S. J. Wright, "Distributed MPC strategies with application to power system automatic generation control," *IEEE Transactions on Control Systems Technology*, vol. 16, no. 6, pp. 1192–1206, 2008.

[22] C. Chang and W. Fu, "Area load frequency control using fuzzy gain scheduling of PI controllers," *Electric Power Systems Research*, vol. 42, no. 2, pp. 145–152, 1997.

[23] J. Talaq and F. Al-Basri, "Adaptive fuzzy gain scheduling for load frequency control," *IEEE Transactions on Power Systems*, vol. 14, no. 1, pp. 145–150, 1999.

[24] D. Rerkpreedapong, A. Hasanovic, and A. Feliachi, "Robust load frequency control using genetic algorithms and linear matrix inequalities," *IEEE Transactions on Power Systems*, vol. 18, no. 2, pp. 855–861, 2003.

[25] E. Muljadi, V. Gevorgian, M. Singh, and S. Santoso, *Understanding inertial and frequency response of wind power plants*. IEEE, 2012.

[26] M. Dreidy, H. Mokhlis, and S. Mekhilef, "Inertia response and frequency control techniques for renewable energy sources: a review," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 144–155, 2017.

[27] K. Vidyanandan and N. Senroy, "Primary frequency regulation by deloaded wind turbines using variable droop," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 837–846, 2013.

[28] Y. Wang, J. Meng, X. Zhang, and L. Xu, "Control of PMSG-based wind turbines for system inertial response and power oscillation damping," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, pp. 565–574, 2015.

[29] H. Knudsen, J. N. Nielsen, and T. Ackermann, "Introduction to the modeling of wind turbines," in *Wind Power in Power Systems*. Wiley Online Library, 2005, pp. 525–585.

[30] Y.-z. Sun, Z.-s. Zhang, G.-j. Li, and J. Lin, "Review on frequency control of power systems with wind power penetration," in *International Conference on Power System Technology*. IEEE, 2010, pp. 1–8.

[31] P. Zarina, S. Mishra, and P. Sekhar, "Deriving inertial response from a non-inertial PV system for frequency regulation," in *International Conference on Power Electronics, Drives and Energy Systems*. IEEE, 2012, pp. 1–5.

[32] C. Rahmann and A. Castillo, "Fast frequency response capability of photovoltaic power plants: The necessity of new grid requirements and definitions," *Energies*, vol. 7, no. 10, pp. 6306–6322, 2014.

[33] W. Zhang, J. Lian, C.-Y. Chang, and K. Kalsi, "Aggregated modeling and control of air conditioning loads for demand response," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4655–4664, 2013.

[34] J. Hu, J. Cao, J. M. Guerrero, T. Yong, and J. Yu, "Improving frequency stability based on distributed control of multiple load aggregators," *IEEE Transactions on Smart Grid*, vol. 8, no. 4, pp. 1553–1567, 2017.

[35] S. A. Pourmousavi and M. H. Nehrir, "Real-time central demand response for primary frequency regulation in microgrids," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1988–1996, 2012.

[36] Y. Lin, P. Barooah, S. Meyn, and T. Middelkoop, "Experimental evaluation of frequency regulation from commercial building hvac systems," *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 776–783, 2015.

[37] H. Hao, T. Middelkoop, P. Barooah, and S. Meyn, "How demand response from commercial buildings will provide the regulation needs of the grid," in *50th Annual Allerton Conference on Communication, Control, and Computing*. IEEE, 2012, pp. 1908–1913.

[38] E. Spahic, D. Varma, G. Beck, G. Kuhn, and V. Hild, "Impact of reduced system inertia on stable power system operation and an overview of possible solutions," in *Power and Energy Society General Meeting*. IEEE, 2016, pp. 1–5.

[39] F. A. Inthamoussou, J. Pegueroles-Queralt, and F. D. Bianchi, "Control of a supercapacitor energy storage system for microgrid applications," *IEEE Transactions on Energy Conversion*, vol. 28, no. 3, pp. 690–697, 2013.

[40] D.-I. Stroe, V. Knap, M. Swierczynski, A.-I. Stroe, and R. Teodorescu, "Operation of a grid–connected lithium–ion battery energy storage system for primary frequency regulation: a battery lifetime perspective," *IEEE Transactions on Industry Applications*, vol. 53, no. 1, pp. 430–438, 2017.

[41] ENTSO-E, "Survey on ancillary services procurement, balancing market design 2014," *Brussels, Belgium*, 2015.

[42] M. Farhadi and O. Mohammed, "Energy storage technologies for high–power applications," *IEEE Transactions on Industry Applications*, vol. 52, no. 3, pp. 1953–1961, 2016.

[43] X. Luo, J. Wang, M. Dooner, and J. Clarke, "Overview of current development in electrical energy storage technologies and the application potential in power system operation," *Applied energy*, vol. 137, pp. 511–536, 2015.

[44] "Ultracapacitors: transforming the grid." [Online]. Available: $https://www.maxwell.com/images/documents/PowerGrid_CaseStudies_3001287_EN_1.pdf$, Accessed on June 15th 2019

[45] J. Arseneaux, "20 mw flywheel frequency regulation plant," Hazle Spindle LLC, Hazleton, PA (United States), Tech. Rep., 2015.

[46] [Online]. Available: $https://www.escri-sa.com.au/about/$, Accessed on June 15th 2019

[47] M. Aneke and M. Wang, "Energy storage technologies and real life applications–a state of the art review," *Applied Energy*, vol. 179, pp. 350–377, 2016.

[48] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: a critical review," *Progress in Natural Science*, vol. 19, no. 3, pp. 291–312, 2009.

[49] J. Baker and A. Collinson, "Electrical energy storage at the turn of the millennium," *Power Engineering Journal*, vol. 13, no. 3, pp. 107–112, 1999.

[50] L. Cai, N. F. Thornhill, S. Kuenzel, and B. C. Pal, "A test model of a power grid with battery energy storage and wide-area monitoring," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 380–390, 2019.

[51] J. Song, Y. Wang, and C. C. Wan, "Review of gel–type polymer electrolytes for lithium-ion batteries," *Journal of Power Sources*, vol. 77, no. 2, pp. 183–197, 1999.

[52] A. R. Sparacino, G. F. Reed, R. J. Kerestes, B. M. Grainger, and Z. T. Smith, "Survey of battery energy storage systems and modeling techniques," in *Power and Energy Society General Meeting*. IEEE, 2012, pp. 1–8.

[53] F. Nadeem, S. S. Hussain, P. K. Tiwari, A. K. Goswami, and T. S. Ustun, "Comparative review of energy storage systems, their roles, and impacts on future power systems," *IEEE Access*, vol. 7, pp. 4555–4585, 2019.

[54] X. Pu, H. Wang, D. Zhao, H. Yang, X. Ai, S. Cao, Z. Chen, and Y. Cao, "Recent progress in rechargeable sodium-ion batteries: toward high-power applications," *Small*, p. 1805427, 2019.

[55] X. Pu, H. Wang, T. Yuan, S. Cao, S. Liu, L. Xu, H. Yang, X. Ai, Z. Chen, and Y. Cao, "$Na_4Fe_3(PO_4)_2P_2O_7$/C nanospheres as low-cost, high-performance cathode material for sodium-ion batteries," *Energy Storage Materials*, 2019.

[56] J. Ming, J. Guo, C. Xia, W. Wang, and H. N. Alshareef, "Zinc-ion batteries: Materials, mechanisms, and applications," *Materials Science and Engineering: R: Reports*, vol. 135, pp. 58–84, 2019.

[57] S. A. P. Kani, P. Wild, and T. K. Saha, "Improving predictability of renewable generation through optimal battery sizing," *IEEE Transactions on Sustainable Energy*, 2018.

[58] I. S. Ike, I. Sigalas, S. Iyuke, and K. I. Ozoemena, "RETRACTED: An overview of mathematical modeling of electrochemical supercapacitors/ultracapacitors," *Journal of Power Sources*, vol. 273, pp. 264–277, 2015.

[59] K. Sahay and B. Dwivedi, "Supercapacitors energy storage system for power quality improvement: an overview," *J. Energy Sources*, vol. 10, no. 10, pp. 1–8, 2009.

[60] R. Mishra and R. Saxena, "Comprehensive review of control schemes for battery and super-capacitor energy storage system," in *International Conference on Power Systems*. IEEE, 2017, pp. 702–707.

[61] H. Liu and J. Jiang, "Flywheel energy storage–an upswing technology for energy sustainability," *Energy and Buildings*, vol. 39, no. 5, pp. 599–604, 2007.

[62] R. Hebner, J. Beno, and A. Walls, "Flywheel batteries come around again," *IEEE spectrum*, vol. 39, no. 4, pp. 46–51, 2002.

[63] A. K. Arani, H. Karami, G. Gharehpetian, and M. Hejazi, "Review of flywheel energy storage systems structures and applications in power systems and microgrids," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 9–18, 2017.

[64] F. Díaz-González, A. Sumper, O. Gomis-Bellmunt, and F. D. Bianchi, "Energy management of flywheel-based energy storage device for wind power smoothing," *Applied Energy*, vol. 110, pp. 207–219, 2013.

[65] H. Zhao, Q. Wu, S. Hu, H. Xu, and C. N. Rasmussen, "Review of energy storage system for wind power integration support," *Applied Energy*, vol. 137, pp. 545–553, 2015.

[66] M. H. Ali, B. Wu, and R. A. Dougal, "An overview of SMES applications in power and energy systems," *IEEE Transactions on Sustainable Energy*, vol. 1, no. 1, pp. 38–47, 2010.

[67] W. Yuan, *Second-generation high-temperature superconducting coils and their applications for energy storage*. Springer Science & Business Media, 2011.

[68] L. Kouchachvili, W. Yaïci, and E. Entchev, "Hybrid battery/supercapacitor energy storage system for the electric vehicles," *Journal of Power Sources*, vol. 374, pp. 237–248, 2018.

[69] Q. Zhang, W. Deng, and G. Li, "Stochastic control of predictive power management for battery/supercapacitor hybrid energy storage systems of electric vehicles," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 7, pp. 3023–3030, 2018.

[70] J. Hou, J. Sun, and H. Hofmann, "Control development and performance evaluation for battery/flywheel hybrid energy storage solutions to mitigate load fluctuations in all-electric ship propulsion systems," *Applied energy*, vol. 212, pp. 919–930, 2018.

[71] R. Hemmati and H. Saboori, "Emergence of hybrid energy storage systems in renewable energy and transport applications–a review," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 11–23, 2016.

[72] N. Bizon, "Effective mitigation of the load pulses by controlling the battery/SMES hybrid energy storage system," *Applied Energy*, vol. 229, pp. 459–473, 2018.

[73] J. Li, M. Zhang, Q. Yang, Z. Zhang, and W. Yuan, "SMES/battery hybrid energy storage system for electric buses," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 4, pp. 1–5, 2016.

[74] J. Beck, D. Carroll, G. Gareis, P. Krause, and C. Ong, "A computer study of battery energy storage and power conversion equipment operation," *IEEE Transactions on Power Apparatus and Systems*, vol. 95, no. 4, pp. 1064–1072, 1976.

[75] Z. M. Salameh, M. A. Casacca, and W. A. Lynch, "A mathematical model for lead-acid batteries," *IEEE Transactions on Energy Conversion*, vol. 7, no. 1, pp. 93–98, 1992.

[76] C.-F. Lu, C.-C. Liu, and C.-J. Wu, "Dynamic modelling of battery energy storage system and application to power system stability," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 142, no. 4, pp. 429–435, 1995.

[77] S. Aditya and D. Das, "Application of battery energy storage system to load frequency control of an isolated power system," *International Journal of Energy Eesearch*, vol. 23, no. 3, pp. 247–258, 1999.

[78] D. Kottick and M. Blau, "Operational and economic benefits of battery energy storage plants," *International Journal of Electrical Power & Energy Systems*, vol. 15, no. 6, pp. 345–349, 1993.

[79] M. R. Aghamohammadi and H. Abdolahinia, "A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded microgrid," *International Journal of Electrical Power & Energy Systems*, vol. 54, pp. 325–333, 2014.

[80] R. Sebastian and J. Quesada, "Distributed control system for frequency control in a isolated wind system," *Renewable Energy*, vol. 31, no. 3, pp. 285–305, 2006.

[81] I. Serban and C. Marinescu, "A solution for frequency control in islanded three-phase micro-grids supplied by renewable energy sources," in *International Conference on Optimization of Electrical and Electronic Equipment*. IEEE, 2008, pp. 327–332.

[82] O. Tremblay, L.-A. Dessaint, and A.-I. Dekkiche, "A generic battery model for the dynamic simulation of hybrid electric vehicles," in *Vehicle Power and Propulsion Conference*. IEEE, 2007, pp. 284–289.

[83] R. Sebastián, "Smooth transition from wind only to wind diesel mode in an autonomous wind diesel system with a battery-based energy storage system," *Renewable Energy*, vol. 33, no. 3, pp. 454–466, 2008.

[84] I. Chidambaram and B. Paramasivam, "Optimized load-frequency simulation in restructured power system with redox flow batteries and interline power flow controller," *International Journal of Electrical Power & Energy Systems*, vol. 50, pp. 9–24, 2013.

[85] M. Toge, Y. Kurita, and S. Iwamoto, “Supplementary load frequency control with storage battery operation considering SOC under large-scale wind power penetration,” in *Power & Energy Society General Meeting*. IEEE, 2013, pp. 1–5.

[86] D. Kottick and M. Blau, “Operational and economic benefits of battery energy storage plants,” *International Journal of Electrical Power & Energy Systems*, vol. 15, no. 6, pp. 345–349, 1993.

[87] E. Abbasi, H. Ameli, K. Strunz, and N. Duc, “Optimized operation, planning, and frequency control of hybrid generation-storage systems in isolated networks,” in *Innovative Smart Grid Technologies Europe*. IEEE, 2012, pp. 1–8.

[88] D. C. Das, A. Roy, and N. Sinha, “GA based frequency controller for solar thermal–diesel–wind hybrid energy generation/energy storage system,” *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 262–279, 2012.

[89] A. Adrees, H. Andami, and J. V. Milanović, “Comparison of dynamic models of battery energy storage for frequency regulation in power system,” in *Mediterranean Electrotechnical Conference*. IEEE, 2016, pp. 1–6.

[90] V. Gevorgian, E. Muljadi, Y. Luo, M. Mohanpurkar, R. Hovsapian, and V. Koritarov, “Supercapacitor to provide ancillary services,” in *Energy Conversion Congress and Exposition*. IEEE, 2017, pp. 1030–1036.

[91] R. Nema and A. Trivedi, “Load frequency control of a small isolated power station by using supercapacitor based energy storage system,” *International Journal of Advanced Research in Computer Engineering & Technology*, vol. 1, no. 10, 2012.

[92] S. Kabir, A. Al Amin, M. Anayatullah, B. K. Saha, and T. Aziz, “Impact of supercapacitor placement in renewable integrated microgrid to minimize post-fault frequency fluctuation,” in *International Conference on Electrical Engineering and Information & Communication Technology*. IEEE, 2014, pp. 1–5.

[93] X. del Toro García, C. de la Cruz, P. Roncero-Sánchez, and A. Parreño, “A small-scale hybrid energy storage system for modeling and control validation purposes,” in *Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2015, pp. 003 702–003 707.

[94] P. K. Ray, S. R. Mohanty, and N. Kishor, “Dynamic modeling and control of renewable energy based hybrid system for large band wind speed variation,” in *Innovative Smart Grid Technologies Conference Europe*. IEEE, 2010, pp. 1–6.

[95] M. H. Fini and M. E. H. Golshan, “Determining optimal virtual inertia and frequency control parameters to preserve the frequency stability in islanded microgrids with high penetration of renewables,” *Electric Power Systems Research*, vol. 154, pp. 13–22, 2018.

[96] P. Ray, S. Mohanty, and N. Kishor, “Small-signal analysis of autonomous hybrid distributed generation systems in presence of ultracapacitor and tie-line operation,” *Journal of Electrical engineering*, vol. 61, no. 4, pp. 205–214, 2010.

[97] M. Ponnusamy, B. Banakara, S. S. Dash, and M. Veerasamy, “Design of integral controller for load frequency control of static synchronous series compensator and capacitive energy source based multi area system consisting of diverse sources of generation employing imperialistic competition algorithm,” *International Journal of Electrical Power & Energy Systems*, vol. 73, pp. 863–871, 2015.

[98] S. Dhundhara and Y. P. Verma, “Capacitive energy storage with optimized controller for frequency regulation in realistic multisource deregulated power system,” *Energy*, vol. 147, pp. 1108–1128, 2018.

[99] H. Silva-Saravia, H. Pulgar-Painemal, and J. M. Mauricio, “Flywheel energy storage model, control and location for improving stability: the Chilean case,” *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3111–3119, 2017.

[100] J. P. Lee and H. G. Kim, “Design of load frequency controller for flywheel energy storage system,” in *International Conference on Electrical Machines and Systems*. IEEE, 2013, pp. 381–384.

[101] D. Peralta, C. Cañizares, and K. Bhattacharya, “Practical modeling of flywheel energy storage for primary frequency control in power grids,” in *Power & Energy Society General Meeting*. IEEE, 2018, pp. 1–5.

[102] J. Yao, M. Yu, W. Gao, and X. Zeng, "Frequency regulation control strategy for PMSG wind–power generation system with flywheel energy storage unit," *IET Renewable Power Generation*, vol. 11, no. 8, pp. 1082–1093, 2016.

[103] K. Vidyanandan and N. Senroy, "Frequency regulation in a wind–diesel powered microgrid using flywheels and fuel cells," *IET Generation, Transmission & Distribution*, vol. 10, no. 3, pp. 780–788, 2016.

[104] W. Hui and T. Wen, "Load frequency control of power systems with wind turbine through flywheels," in *Chinese Control and Decision Conference*. IEEE, 2015, pp. 3495–3499.

[105] Y. Zhang, Y. Xu, H. Guo, X. Zhang, C. Guo, and H. Chen, "A hybrid energy storage system with optimized operating strategy for mitigating wind power fluctuations," *Renewable Energy*, vol. 125, pp. 121–132, 2018.

[106] A. Abazari, H. Monsef, and B. Wu, "Coordination strategies of distributed energy resources including FESS, DEG, FC and WTG in load frequency control (LFC) scheme of hybrid isolated micro–grid," *International Journal of Electrical Power & Energy Systems*, vol. 109, pp. 535–547, 2019.

[107] M. Elsisi, M. Soliman, M. Aboelela, and W. Mansour, "Optimal design of model predictive control with superconducting magnetic energy storage for load frequency control of nonlinear hydrothermal power system using bat inspired algorithm," *Journal of Energy Storage*, vol. 12, pp. 311–318, 2017.

[108] K. Sudha and R. V. Santhi, "Load frequency control of an interconnected reheat thermal system using type-2 fuzzy system including SMES units," *International Journal of Electrical Power & Energy Systems*, vol. 43, no. 1, pp. 1383–1392, 2012.

[109] S. Padhan, R. K. Sahu, and S. Panda, "Automatic generation control with thyristor controlled series compensator including superconducting magnetic energy storage units," *Ain Shams Engineering Journal*, vol. 5, no. 3, pp. 759–774, 2014.

[110] P. C. Pradhan, R. K. Sahu, and S. Panda, "Firefly algorithm optimized fuzzy PID controller for AGC of multi-area multi–source power systems with UPFC and SMES," *Engineering Science and Technology, an International Journal*, vol. 19, no. 1, pp. 338–354, 2016.

[111] S. Pothiya, I. Ngamroo, and W. Kongprawechnon, "Design of optimal fuzzy logic–based PID controller using Multiple Tabu Search algorithm for AGC including SMES units," in *International Power Engineering Conference*. IEEE, 2007, pp. 838–843.

[112] R. V. Santhi, K. Sudha, and S. P. Devi, "Robust load frequency control of multi–area interconnected system including SMES units using Type-2 Fuzzy controller," in *International Conference on Fuzzy Systems*. IEEE, 2013, pp. 1–7.

[113] I. Ngamroo, Y. Mitani, and K. Tsuji, "Application of SMES coordinated with solid–state phase shifter to load frequency control," *IEEE Transactions on Applied Superconductivity*, vol. 9, no. 2, pp. 322–325, 1999.

[114] A. Ortega and F. Milano, "Generalized model of VSC-based energy storage systems for transient stability analysis," *IEEE transactions on Power Systems*, vol. 31, no. 5, pp. 3369–3380, 2015.

[115] N. Chaudhuri, B. Chaudhuri, R. Majumder, and A. Yazdani, *Multi–terminal direct-current grids: Modeling, analysis, and control*. John Wiley & Sons, 2014.

[116] N. R. Chaudhuri, R. Majumder, B. Chaudhuri, and J. Pan, "Stability analysis of VSC MTDC grids connected to multimachine AC systems," *IEEE Transactions on Power Delivery*, vol. 26, no. 4, pp. 2774–2784, 2011.

[117] J. Beerten, S. Cole, and R. Belmans, "Modeling of multi-terminal VSC HVDC systems with distributed DC voltage control," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 34–42, 2013.

[118] Z. Wu, D. W. Gao, H. Zhang, S. Yan, and X. Wang, "Coordinated control strategy of battery energy storage system and PMSG-WTG to enhance system frequency regulation capability," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 3, pp. 1330–1343, 2017.

[119] H. Zhao, M. Hong, W. Lin, and K. A. Loparo, "Voltage and frequency regulation of microgrid with battery energy storage systems," *IEEE Transactions on Smart Grid*, 2017.

[120] J. W. Choi, S. Y. Heo, and M. K. Kim, "Hybrid operation strategy of wind energy storage system for power grid frequency regulation," *IET Generation, Transmission & Distribution*, vol. 10, no. 3, pp. 736–749, 2016.

[121] S. Zhang, Y. Mishra, and M. Shahidehpour, "Fuzzy–logic based frequency controller for wind farms augmented with energy storage systems," *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1595–1603, 2016.

[122] M. Cheng, S. S. Sami, and J. Wu, "Benefits of using virtual energy storage system for power system frequency response," *Applied Energy*, vol. 194, pp. 376–385, 2017.

[123] M. L. Lazarewicz and A. Rojas, "Grid frequency regulation by recycling electrical energy in flywheels," in *Power Engineering Society General Meeting*. IEEE, 2004, pp. 2038–2042.

[124] R. Sebastián, "Application of a battery energy storage for frequency regulation and peak shaving in a wind diesel power system," *IET Generation, Transmission & Distribution*, vol. 10, no. 3, pp. 764–770, 2016.

[125] M. Khalid and A. Savkin, "An optimal operation of wind energy storage system for frequency control based on model predictive control," *Renewable Energy*, vol. 48, pp. 127–132, 2012.

[126] T. Goya, E. Omine, Y. Kinjyo, T. Senjyu, A. Yona, N. Urasaki, and T. Funabashi, "Frequency control in isolated island by using parallel operated battery systems applying H_∞ control theory based on droop characteristics," *IET Renewable Power Generation*, vol. 5, no. 2, pp. 160–166, 2011.

[127] V. Knap, S. K. Chaudhary, D.-I. Stroe, M. Swierczynski, B.-I. Craciun, and R. Teodorescu, "Sizing of an energy storage system for grid inertial response and primary frequency reserve," *IEEE Transactions on Power Systems*, vol. 31, no. 5, pp. 3447–3456, 2016.

[128] D. Kottick, M. Blau, and D. Edelstein, "Battery energy storage for frequency regulation in an island power system," *IEEE Transactions on Energy Conversion*, vol. 8, no. 3, pp. 455–459, 1993.

[129] E. Rakhshani and P. Rodriguez, "Inertia emulation in AC/DC interconnected power systems using derivative technique considering frequency measurement effects," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3338–3351, 2017.

[130] H.-J. Kunisch, K. Kramer, and H. Dominik, "Battery energy storage another option for load–frequency–control and instantaneous reserve," *IEEE Transactions on Energy Conversion*, no. 3, pp. 41–46, 1986.

[131] M. Świerczyński, D. I. Stroe, A. I. Stan, and R. Teodorescu, "Primary frequency regulation with Li-ion battery energy storage system: a case study for denmark," in *ECCE Asia Downunder*. IEEE, 2013, pp. 487–492.

[132] X. Li, Y. Huang, J. Huang, S. Tan, M. Wang, T. Xu, and X. Cheng, "Modeling and control strategy of battery energy storage system for primary frequency regulation," in *International Conference on Power System Technology*. IEEE, 2014, pp. 543–549.

[133] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, L. Huang, and R. Teodorescu, "SoC-based droop method for distributed energy storage in DC microgrid applications," in *International Symposium on Industrial Electronics*. IEEE, 2012, pp. 1640–1645.

[134] Y. Ota, H. Taniguchi, T. Nakajima, K. M. Liyanage, J. Baba, and A. Yokoyama, "Autonomous distributed V2G (vehicle–to–grid) considering charging request and battery condition," in *Innovative Smart Grid Technologies Conference Europe*. IEEE, 2010, pp. 1–6.

[135] A. Oudalov, D. Chartouni, and C. Ohler, "Optimizing a battery energy storage system for primary frequency control," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 1259–1266, 2007.

[136] P. Mercier, R. Cherkaoui, and A. Oudalov, "Optimizing a battery energy storage system for frequency control application in an isolated power system," *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1469–1477, 2009.

[137] J. Tan and Y. Zhang, "Coordinated control strategy of a battery energy storage system to support a wind power plant providing multi–timescale frequency ancillary services," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 3, pp. 1140–1153, 2017.

[138] A. Hoke, A. Brissette, D. Maksimović, D. Kelly, A. Pratt, and D. Boundy, "Maximizing lithium ion vehicle battery life through optimized partial charging," in *Innovative Smart Grid Technologies Conference*. IEEE, 2013, pp. 1–5.

[139] I. Serban and C. Marinescu, “Control strategy of three-phase battery energy storage systems for frequency support in microgrids and with uninterrupted supply of local loads,” *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 5010–5020, 2014.

[140] L. Wu, W. Gao, Z. Cui, and X. Kou, “A novel frequency regulation strategy with the application of energy storage system for large scale wind power integration,” in *Annual Green Technologies Conference*. IEEE, 2015, pp. 221–226.

[141] G. Delille, B. François, and G. Malarange, “Dynamic frequency control support: a virtual inertia provided by distributed energy storage to isolated power systems,” in *Innovative Smart Grid Technologies Conference Europe*. IEEE, 2010, pp. 1–8.

[142] N. Kakimoto, S. Takayama, H. Satoh, and K. Nakamura, “Power modulation of photovoltaic generator for frequency control of power system,” *IEEE Transactions on Energy Conversion*, vol. 24, no. 4, pp. 943–949, 2009.

[143] M. Mufti, S. Iqbal, S. Lone, and Q.-u. Ain, “Supervisory adaptive predictive control scheme for supercapacitor energy storage system,” *IEEE Systems Journal*, vol. 9, no. 3, pp. 1020–1030, 2015.

[144] U. Akram, N. Mithulananthan, and R. Shah, “Improving synthetic inertial response of supercapacitor using supplementary control signal,” in *International Conference on Power and Energy Systems*. IEEE, 2019.

[145] M. Y. Zargar, M. U.-D. Mufti, and S. A. Lone, “Modelling and performance assessment of a standalone hybrid wind-diesel-superconducting magnetic energy storage system using four-quadrant operation of superconducting magnetic energy storage,” *Wind Engineering*, vol. 42, no. 5, pp. 496–509, 2018.

[146] H. M. Hasanien, “A set-membership affine projection algorithm-based adaptive-controlled SMES units for wind farms output power smoothing,” *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4, pp. 1226–1233, 2014.

[147] M. Y. Zargar, M. U.-D. Mufti, and S. A. Lone, “Adaptive predictive control of a small capacity SMES unit for improved frequency control of a wind-diesel power system,” *IET Renewable Power Generation*, vol. 11, no. 14, pp. 1832–1840, 2017.

[148] M. N. Musarrat, M. R. Islam, K. M. Muttaqi, and D. Sutanto, “Enhanced frequency support from a PMSG-based wind energy conversion system integrated with a high temperature SMES in standalone power supply systems,” *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 2, pp. 1–6, 2019.

[149] J. Yao, M. Yu, W. Gao, and X. Zeng, “Frequency regulation control strategy for PMSG wind-power generation system with flywheel energy storage unit,” *IET Renewable Power Generation*, vol. 11, no. 8, pp. 1082–1093, 2016.

[150] B. Meriem and K. Katia, “A new design of flywheel energy storage system based on a double star asynchronous machine associated to wind energy,” in *International Renewable Energy Congress*. IEEE, 2017, pp. 1–6.

[151] G. Suvire and P. Mercado, “Active power control of a flywheel energy storage system for wind energy applications,” *IET Renewable Power Generation*, vol. 6, no. 1, pp. 9–16, 2012.

[152] A. K. Arani, B. Zaker, and G. Gharehpetian, “A control strategy for flywheel energy storage system for frequency stability improvement in islanded microgrid,” *Iranian Journal Electrical and Electronic Engineering*, vol. 13, pp. 10–21, 2017.

[153] S. Karrari, M. Noe, and J. Geisbuesch, “High-speed flywheel energy storage system (FESS) for voltage and frequency support in low voltage distribution networks,” in *International Conference on Intelligent Energy and Power Systems*. IEEE, 2018, pp. 176–182.

[154] T. Kerdphol, F. S. Rahman, Y. Mitani, M. Watanabe, and S. Küfeoğlu, “Robust virtual inertia control of an islanded microgrid considering high penetration of renewable energy,” *IEEE Access*, vol. 6, pp. 625–636, 2018.

[155] T. Senjyu, E. Omine, M. Tokudome, Y. Yonaha, T. Goya, A. Yona, and T. Funabashi, “Frequency control strategy for parallel operated battery systems based on droop characteristics by applying H_∞ control theory,” in *In Transmission & Distribution Conference & Exposition: Asia and Pacific*. IEEE, 2009, pp. 1–4.

[156] D. Zhu and G. Hug-Glanzmann, "Robust control design for integration of energy storage into frequency regulation," in *Innovative Smart Grid Technologies Europe*. IEEE, 2012, pp. 1–8.

[157] A. M. Howlader, Y. Izumi, A. Uehara, N. Urasaki, T. Senjyu, and A. Y. Saber, "A robust H_∞ controller based frequency control approach using the wind-battery coordination strategy in a small power system," *International Journal of Electrical Power & Energy Systems*, vol. 58, pp. 190–198, 2014.

[158] D. Zhu and G. Hug-Glanzmann, "Coordination of storage and generation in power system frequency control using an H_∞ approach," *IET Generation, Transmission & Distribution*, vol. 7, no. 11, pp. 1263–1271, 2013.

[159] J. Mongkoltanatas, D. Riu, and X. LePivert, "H infinity controller design for primary frequency control of energy storage in islanding microgrid," in *European Conference on Power Electronics and Applications*. IEEE, 2013, pp. 1–11.

[160] X. Pan, H. Xu, J. Song, and C. Lu, "Capacity optimization of battery energy storage systems for frequency regulation," in *International Conference on Automation Science and Engineering*. IEEE, 2015, pp. 1139–1144.

[161] Y. Liu, W. Du, L. Xiao, H. Wang, and J. Cao, "A method for sizing energy storage system to increase wind penetration as limited by grid frequency deviations," *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 729–737, 2016.

[162] L. Sigrist, I. Egido, E. L. Miguélez, and L. Rouco, "Sizing and controller setting of ultracapacitors for frequency stability enhancement of small isolated power systems," *IEEE Transactions on Power Systems*, vol. 30, no. 4, pp. 2130–2138, 2015.

[163] D. Mejía-Giraldo, G. Velásquez-Gomez, N. Muñoz-Galeano, J. B. Cano-Quintero, and S. Lemos-Cano, "A BESS sizing strategy for primary frequency regulation support of solar photovoltaic plants," *Energies*, vol. 12, no. 2, p. 317, 2019.

[164] S. M. Lukic, S. G. Wirasingha, F. Rodriguez, J. Cao, and A. Emadi, "Power management of an ultracapacitor/battery hybrid energy storage system in an HEV," in *IEEE Vehicle Power and Propulsion Conference*. IEEE, 2006, pp. 1–6.

[165] Y. Kim, V. Raghunathan, and A. Raghunathan, "Design and management of battery–supercapacitor hybrid electrical energy storage systems for regulation services," *IEEE Transactions on Multi-Scale Computing Systems*, vol. 3, no. 1, pp. 12–24, 2016.

[166] S. B. Peterson, J. Apt, and J. Whitacre, "Lithium–ion battery cell degradation resulting from realistic vehicle and vehicle–to–grid utilization," *Journal of Power Sources*, vol. 195, no. 8, pp. 2385–2392, 2010.

[167] J. Cao and A. Emadi, "A new battery/ultracapacitor hybrid energy storage system for electric, hybrid, and plug-in hybrid electric vehicles," *IEEE Transactions on power electronics*, vol. 27, no. 1, pp. 122–132, 2012.

[168] U. Akram, M. Khalid, and S. Shafiq, "An innovative hybrid wind–solar and battery–supercapacitor microgrid system—-development and optimization," *IEEE Access*, vol. 5, pp. 25 897–25 912, 2017.

[169] U. Akram and M. Khalid, "A coordinated frequency regulation framework based on hybrid battery-ultracapacitor energy storage technologies," *IEEE Access*, vol. 6, pp. 7310–7320, 2018.

[170] J. Li, M. Zhang, Q. Yang, Z. Zhang, and W. Yuan, "SMES/battery hybrid energy storage system for electric buses," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 4, pp. 1–5, 2016.

[171] J. Hou, J. Sun, and H. Hofmann, "Control development and performance evaluation for battery/flywheel hybrid energy storage solutions to mitigate load fluctuations in all–electric ship propulsion systems," *Applied Energy*, vol. 212, pp. 919–930, 2018.

[172] H. Bevarani, R. F. Mohammad, and A. Sirwan, "Robust frequency control in an islanded microgrid: H_∞ and μ– synthesis approaches," *IEEE Transactions on Smart Grid*, vol. 7, pp. 706–716, 2016.

[173] N. Gyawali and Y. Ohsawa, "Effective voltage and frequency control strategy for a stand-alone system with induction generator/fuel cell/ultracapacitor," in *Joint Symposium Integration of Wide-Scale Renewable Resources into the Power Delivery System*. IEEE, 2009, pp. 1–11.

[174] A. Fathi, Q. Shafiee, and H. Bevrani, "Robust frequency control of microgrids using an extended virtual synchronous generator," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6289–6297, 2018.

[175] D.-J. Lee and L. Wang, "Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system part I: Time-domain simulations," *IEEE Transactions on Energy Conversion*, vol. 23, no. 1, pp. 311–320, 2008.

[176] S. Hajiaghasi, A. Salemnia, and M. Hamzeh, "Hybrid energy storage system for microgrids applications: a review," *Journal of Energy Storage*, vol. 21, pp. 543–570, 2019.

[177] L. W. Chong, Y. W. Wong, R. K. Rajkumar, and D. Isa, "An optimal control strategy for standalone PV system with battery-supercapacitor hybrid energy storage system," *Journal of Power Sources*, vol. 331, pp. 553–565, 2016.

[178] A. A. Khan, M. Q. Khan, S. G. Satti, and M. Adil, "Robust control of hybrid distributed generation for frequency regulation," in *International Bhurban Conference on Applied Sciences and Technology*. IEEE, 2017, pp. 285–290.

[179] D. Xu, J. Liu, X.-G. Yan, and W. Yan, "A novel adaptive neural network constrained control for a multi-area interconnected power system with hybrid energy storage," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 8, pp. 6625–6634, 2018.

[180] J. Fang, Y. Tang, H. Li, and X. Li, "A battery/ultracapacitor hybrid energy storage system for implementing the power management of virtual synchronous generators," *IEEE Transactions on Power Electronics*, vol. 33, no. 4, pp. 2820–2824, 2018.

[181] X. Zhou, C. Dong, J. Fang, and Y. Tang, "Enhancement of load frequency control by using a hybrid energy storage system," in *Conference on Energy, Power and Transportation Electrification*. IEEE, 2017, pp. 1–6.

[182] H. Bevrani, F. Habibi, P. Babahajyani, M. Watanabe, and Y. Mitani, "Intelligent frequency control in an AC microgrid: online PSO-based fuzzy tuning approach," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1935–1944, 2012.

[183] Y. Liu, W. Du, L. Xiao, H. Wang, S. Bu, and J. Cao, "Sizing a hybrid energy storage system for maintaining power balance of an isolated system with high penetration of wind generation," *IEEE Transactions on Power Systems*, vol. 31, no. 4, pp. 3267–3275, 2016.

[184] U. Akram and M. Khalid, "A coordinated frequency regulation framework based on hybrid battery–ultracapacitor energy storage technologies," *IEEE Access*, vol. 6, pp. 7310–7320, 2018.

[185] J. Cao, W. Du, H. Wang, and M. McCulloch, "Optimal sizing and control strategies for hybrid storage system as limited by grid frequency deviations," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5486–5495, 2018.

[186] G. Magdy, E. A. Mohamed, G. Shabib, A. A. Elbaset, and Y. Mitani, "SMES based a new PID controller for frequency stability of a real hybrid power system considering high wind power penetration," *IET Renewable Power Generation*, vol. 12, no. 11, pp. 1304–1313, 2018.

[187] A. V. Savkin, M. Khalid, and V. G. Agelidis, "A constrained monotonic charging/discharging strategy for optimal capacity of battery energy storage supporting wind farms," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 3, pp. 1224–1231, 2016.

[188] ——, "Optimal size of battery energy storage and monotonic charging/discharging strategies for wind farms," in *IEEE Conference on Control Applications*. IEEE, 2014, pp. 1372–1376.

[189] A. Oudalov, D. Chartouni, and C. Ohler, "Optimizing a battery energy storage system for primary frequency control," *IEEE Transactions on Power Systems*, vol. 22, no. 3, pp. 1259–1266, 2007.

[190] P. Mercier, R. Cherkaoui, and A. Oudalov, "Optimizing a battery energy storage system for frequency control application in an isolated power system," *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1469–1477, 2009.

[191] M. Khalid and A. V. Savkin, "Model predictive control based efficient operation of battery energy storage system for primary frequency control," in *International Conference on Control Automation Robotics & Vision*. IEEE, 2010, pp. 2248–2252.

[192] M. R. Aghamohammadi and H. Abdolahinia, “A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded microgrid,” *International Journal of Electrical Power & Energy Systems*, vol. 54, pp. 325–333, 2014.

[193] J. Yu, J. Fang, and Y. Tang, “Inertia emulation by flywheel energy storage system for improved frequency regulation,” in *Southern Power Electronics Conference*. IEEE, 2018, pp. 1–8.

[194] Y. J. A. Zhang, C. Zhao, W. Tang, and S. H. Low, “Profit–maximizing planning and control of battery energy storage systems for primary frequency control,” *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 712–723, 2018.

[195] G. Delille, B. Francois, and G. Malarange, “Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system’s inertia,” *IEEE Transactions on Sustainable Energy*, vol. 3, no. 4, pp. 931–939, 2012.

[196] L. Xiong, Y. Li, Y. Zhu, P. Yang, and Z. Xu, “Coordinated control schemes of super-capacitor and kinetic energy of DFIG for system frequency support,” *Energies*, vol. 11, no. 1, p. 103, 2018.

[197] M. Yue and X. Wang, “Grid inertial response–based probabilistic determination of energy storage system capacity under high solar penetration,” *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 1039–1049, 2015.

[198] J. P. Lee and H. G. Kim, “Design of load frequency controller for flywheel energy storage system,” in *International Conference on Electrical Machines and Systems*. IEEE, 2013, pp. 381–384.

[199] H. Jia, Y. Mu, and Y. Qi, “A statistical model to determine the capacity of battery–supercapacitor hybrid energy storage system in autonomous microgrid,” *International Journal of Electrical Power & Energy Systems*, vol. 54, pp. 516–524, 2014.

[200] M. Mahdavi, G. Gharehpetian, P. Ranjbaran, and H. Azizi, “Frequency regulation of AUT microgrid using modified fuzzy PI controller for flywheel energy storage system,” in *Annual Power Electronics, Drives Systems and Technologies Conference*. IEEE, 2018, pp. 426–431.

[201] Q. Yan, Q. Bo, Y. Jingjie, M. Yunfei, and G. Bingqing, “Frequency control strategy of hybrid energy storage system for microgrid based on frequency hysteretic loop,” *Energy Procedia*, vol. 103, pp. 328–332, 2016.

[202] S. Prakash and S. Sinha, “ALFC of hybrid multi-generation power system using UC and TCPS by ANFIS control technique,” *International Journal of Electronics*, vol. 106, no. 2, pp. 174–211, 2019.

[203] I. Ngamroo, “Robust frequency control of wind-diesel hybrid power system using superconducting magnetic energy storage,” *International Journal of Emerging Electric Power Systems*, vol. 10, no. 2, 2009.

[204] M. Nayeripour, M. Hoseintabar, and T. Niknam, “Frequency deviation control by coordination control of FC and double-layer capacitor in an autonomous hybrid renewable energy power generation system,” *Renewable Energy*, vol. 36, no. 6, pp. 1741–1746, 2011.

[205] Y. Han, P. M. Young, A. Jain, and D. Zimmerle, “Robust control for microgrid frequency deviation reduction with attached storage system,” *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 557–565, 2015.

[206] N. Jayalakshmi and D. Gaonkar, “Performance study of isolated hybrid power system with multiple generation and energy storage units,” in *International Conference on Power and Energy Systems*. IEEE, 2011, pp. 1–5.

[207] M. ud din Mufti, S. A. Lone, S. J. Iqbal, M. Ahmad, and M. Ismail, “Super-capacitor based energy storage system for improved load frequency control,” *Electric Power Systems Research*, vol. 79, no. 1, pp. 226–233, 2009.

[208] S. Iqbal, M. Mufti, S. Lone, and I. Mushtaq, “Intelligently controlled superconducting magnetic energy storage for improved load frequency control,” *International Journal of Power & Energy Systems*, vol. 29, no. 4, p. 241, 2009.

[209] K. Vidyanandan and N. Senroy, “Frequency regulation in a wind–diesel powered microgrid using flywheels and fuel cells,” *IET Generation, Transmission & Distribution*, vol. 10, no. 3, pp. 780–788, 2016.

[210] A. Lucas and S. Chondrogiannis, "Smart grid energy storage controller for frequency regulation and peak shaving, using a vanadium redox flow battery," *International Journal of Electrical Power & Energy Systems*, vol. 80, pp. 26–36, 2016.

[211] J. Li, R. Xiong, Q. Yang, F. Liang, M. Zhang, and W. Yuan, "Design/test of a hybrid energy storage system for primary frequency control using a dynamic droop method in an isolated microgrid power system," *Applied Energy*, vol. 201, pp. 257–269, 2017.

[212] V. Knap, R. Sinha, M. Swierczynski, D.-I. Stroe, and S. Chaudhary, "Grid inertial response with lithium-ion battery energy storage systems," in *International Symposium on Industrial Electronics*. IEEE, 2014, pp. 1817–1822.

[213] J. Li, Q. Yang, P. Yao, Q. Sun, Z. Zhang, M. Zhang, and W. Yuan, "A novel use of the hybrid energy storage system for primary frequency control in a microgrid," *Energy Procedia*, vol. 103, pp. 82–87, 2016.

[214] E. Thorbergsson, V. Knap, M. Swierczynski, D. Stroe, and R. Teodorescu, "Primary frequency regulation with Li-ion battery based energy storage system-evaluation and comparison of different control strategies," in *International Telecommunications Energy Conference, Smart Power and Effeciency*. VDE, 2013, pp. 1–6.

[215] U. Akram, M. Khalid, and S. Shafiq, "A novel operation strategy of battery-supercapacitor hybrid energy storage system providing frequency regulation service," in *International Symposium on Industrial Electronics*. IEEE, 2018, pp. 31–36.

[216] P. Indu and M. Jayan, "Frequency regulation of an isolated hybrid power system with superconducting magnetic energy storage," in *2015 International conference on power, instrumentation, control and computing*. IEEE, 2015, pp. 1–6.

[217] S. R. Mohanty, N. Kishor, and P. K. Ray, "Robust H-infinite loop shaping controller based on hybrid PSO and harmonic search for frequency regulation in hybrid distributed generation system," *International Journal of Electrical Power & Energy Systems*, vol. 60, pp. 302–316, 2014.

[218] C. Brivio, S. Mandelli, and M. Merlo, "Battery energy storage system for primary control reserve and energy arbitrage," *Sustainable Energy, Grids and Networks*, vol. 6, pp. 152–165, 2016.

[219] A. Saha and L. C. Saikia, "Utilisation of ultra–capacitor in load frequency control under restructured STPP-thermal power systems using WOA optimised PIDN-FOPD controller," *IET Generation, Transmission & Distribution*, vol. 11, no. 13, pp. 3318–3331, 2017.

[220] M. Datta and T. Senjyu, "Fuzzy control of distributed PV inverters/energy storage systems/electric vehicles for frequency regulation in a large power system," *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 479–488, 2013.

[221] F. M. Gonzalez-Longatt and S. M. Alhejaj, "Enabling inertial response in utility–scale battery energy storage system," in *Innovative Smart Grid Technologies-Asia*. IEEE, 2016, pp. 605–610.

[222] L. Toma, M. Sanduleac, S. A. Baltac, F. Arrigo, A. Mazza, E. Bompard, A. Musa, and A. Monti, "On the virtual inertia provision by BESS in low inertia power systems," in *International Energy Conference*. IEEE, 2018, pp. 1–6.

[223] S. Chen, T. Zhang, H. B. Gooi, R. D. Masiello, and W. Katzenstein, "Penetration rate and effectiveness studies of aggregated BESS for frequency regulation," *IEEE Transactions on Smart Grid*, vol. 7, no. 1, pp. 167–177, 2016.

[224] F. Gonzalez-Longatt, S. Alhejaj, A. Bonfiglio, R. Procopio, and J. L. Rueda, "Inertial frequency response provided by battery energy storage systems: probabilistic assessment," in *International Conference on Clean Electrical Power*. IEEE, 2017, pp. 403–409.

[225] D. Zhu and Y.-J. A. Zhang, "Optimal coordinated control of multiple battery energy storage systems for primary frequency regulation," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 555–565, 2019.

[226] V. P. Singh, S. R. Mohanty, N. Kishor, and P. K. Ray, "Robust H-infinity load frequency control in hybrid distributed generation system," *International journal of electrical power & energy systems*, vol. 46, pp. 294–305, 2013.

[227] I. Egido, L. Sigrist, E. Lobato, L. Rouco, and A. Barrado, “An ultra-capacitor for frequency stability enhancement in small-isolated power systems: models, simulation and field tests,” *Applied Energy*, vol. 137, pp. 670–676, 2015.

[228] N. Miller, D. Lew, and R. Piwko, *Technology capabilities for fast frequency response*, 2017.

[229] D. Wilson, S. Clark, S. Norris, and J. Yu, “Advances in wide area monitoring and control to address emerging requirements related to inertia, stability and power transfer in the GB power system,” *CIGRE Paris Session*, pp. C2–208, 2016.