Journal of Energy Storage 55 (2022) 105663

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Review Article

Superconducting magnetic energy storage systems: Prospects and challenges for renewable energy applications

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ARTICLE INFO

Keywords:
Superconducting magnetic energy storage
Renewable energy
Energy storage system
Power systems
Superconductivity

ABSTRACT

This paper provides a clear and concise review on the use of superconducting magnetic energy storage (SMES) systems for renewable energy applications with the attendant challenges and future research direction. A brief history of SMES and the operating principle has been presented. Also, the main components of SMES are discussed. A bibliographical software was used to analyse important keywords relating to SMES obtained from top 1240 most relevant research on superconducting magnetic energy storage system that have been published in reputable journals in recent times. Comparison of SMES with other competitive energy storage technologies is presented in order to reveal the present status of SMES in relation to other viable energy storage systems. In addition, various research on the application of SMES for renewable energy applications are reviewed including control strategies and power electronic interfaces for SMES. Important technology road map and set targets for SMES development from year 2020 to 2050 are summarized. This paper also discusses important challenges facing the development and application of SMES and points out vital future research direction on the development and improvement of SMES systems for renewable energy applications. This work will be of significant interest and will provide important insights for researchers in the field of renewable energy and energy storage, utilities and government agencies.

1. Introduction

Renewable energy utilization for electric power generation has attracted global interest in recent times [1–3]. However, due to the intermittent nature of most mature renewable energy sources such as wind and solar, energy storage has become an important component of any sustainable and reliable renewable energy deployment. Several cutting edge research has been carried out on viable energy storage systems for renewable energy applications. Some of the most widely investigated renewable energy storage system include battery energy storage systems (BESS), pumped hydro energy storage (PHES), compressed air energy storage (CAES), flywheel, supercapacitors and superconducting magnetic energy storage (SMES) system. These energy storage technologies are at varying degrees of development, maturity and commercial deployment.

One of the emerging energy storage technologies is the SMES. SMES operation is based on the concept of superconductivity of certain materials. Superconductivity is a phenomenon in which some materials when cooled below a specific critical temperature exhibit precisely zero electrical resistance and magnetic field dissipation [4]. This phenomenon was discovered by a Dutch scientist named Heike Kamerlingh in 1911. Fig. 1 depicts a graph of electrical resistivity against temperature for superconductors. The graph shows how the resistivity rapidly approaches zero at critical temperatures (Tc) as opposed to normal metals.

The first concept on SMES was proposed by Ferrier in 1969 [5]. In 1971, research carried out at the University of Wisconsin in the United States resulted in the creation of the first superconducting magnetic energy system device. High temperature superconductors (HTS) first appeared on the market in the late 1990s [5]. American Superconductors produced the first substantial size HTS-SMES in 1997. Afterwards, it was connected to a larger grid in Germany. In SMES systems, energy is stored in dc form by flowing current along the superconductors and conserved as a dc magnetic field [6]. The current-carrying conductor functions at cryogenic (extremely low) temperatures, thus becoming a superconductor with negligible resistive losses while it generates magnetic field. In this condition, a coil's current can flow indefinitely [7]. This is further demonstrated by the time constant of a coil, $t = L/R$, where L is the inductance and R is the resistance. When R tends to zero, t

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https://doi.org/10.1016/j.est.2022.105663
Received 16 June 2022; Received in revised form 7 September 2022; Accepted 9 September 2022
Available online 15 September 2022

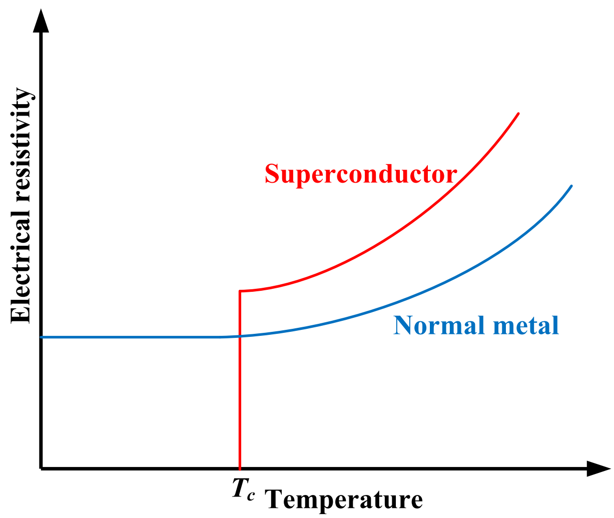

Fig. 1. Graph of electrical resistivity against temperature.

approaches infinity.

The operation of SMES is based on the notion that a current will continue to flow in a superconductor even after the voltage across it is eliminated [8]. A superconducting coil with minimal (zero) resistance is one that has been cooled beneath its critical superconducting temperature. Consequently, the current keeps flowing through it. The coil conducts electricity in any state of charge. In the charging phase, the current flows in only one direction and the power conditioning system must generate a positive voltage across the coil in order to store energy. In the discharging phase, the power conditioning system is modified to mimic the system as a load across the coil by generating a reverse voltage that causes the coil to discharge. SMES systems are capable of quick response. They can change from charge to discharge mode and vice versa in a matter of seconds. Some additional benefits are the absence of moving components and high cycling efficiency. SMES systems can also be used in locations where other energy storage technologies such as pumped hydro storage and compressed air energy storage are impracticable.

The application of SMES for renewable energy integration has gained prominence in recent times. SMES has been demonstrated has a viable and competitive option for applications such as mitigation of output power fluctuation, frequency control, transient stability enhancement and power quality improvements of grid-connected renewable energy systems such as wind energy conversion systems (WECS) and solar photovoltaic systems. Several reviews on energy storage technologies have been carried out in general. However, relatively few researchers have conducted detailed reviews on SMES development and applications. Brief review of SMES for various power system applications has been provided in [9,10]. In addition, the review in [11] discusses applications of SMES in microgrids, electric vehicles and renewable energy systems. The authors in [12] also carried out an economic analysis of utilizing SMES and HTS transformers based on reports from utilities. In [13], the authors discussed the developments of SMES coil, design of the associated power electronic converters and sizing requirements for power system applications.

In view of the paucity of review works on SMES applications, this present review is therefore necessary to provide further details on the state-of-the-art and future research direction on the applications of SMES for renewable energy applications. Relevant studies on SMES development and applications are categorized into six based on recent published research in the last ten years (from 2013 to 2022). In addition, this review paper presents a VOSviewer-based bibliographic analysis of important keywords related to SMES using bibliographical data obtained from 1240 publications in reputable journals. This provides insights on the most commonly studied subjects in relation to SMES. To the best of the author's knowledge, this is the first time such analysis is carried out for SMES. This work also presents a comparison of SMES with other energy storage technologies in order to depict the present status of SMES in relation to other competitive energy storage systems. A summary of the technology roadmap and set targets for SMES development and applications from 2020 to 2050 is also provided in this work. Furthermore, important aspects of SMES development that requires further investigations and improvement are highlighted and discussed. Ultimately, this work will provide significant insights for researchers, utilities and government agencies on SMES for renewable energy applications.

The rest of this paper is structured as follows: Section 2 gives an overview of components of the SMES. Detailed comparison of SMES with other viable energy storage technologies is provided in Section 3 and Section 4 presents a review of various research on SMES for renewable energy applications with VOS-viewer-based bibliographic analysis of important keywords associated with SMES and a summary of control techniques and power electronic interfaces of SMES with renewable energy systems. Section 5 presents the roadmap and set targets for SMES development and applications. Finally, Section 6 details important future research direction and the study is concluded in Section 7.

2. SMES system components

2.1. Magnetized superconducting coil

The magnetized superconducting coil is the most essential component of the Superconductive Magnetic Energy Storage (SMES) System. Conductors made up of several tiny strands of niobium titanium(NbTi) alloy inserted in a copper substrate are used in winding majority of superconducting coils [14]. The size of the coil is determined by the amount of energy to be stored and the coil geometry.

2.2. The power conditioning system (PCS)

The PCS serves as an interface between the superconductor magnet and the alternating current power system. There are three commonly used configurations available, which are thyristor-based PCS, voltage source converter (VSC)-based PCS and current source converter (CSC)-based PCS.

PCS based on thyristors: The basic structure of a thyristor-based SMES system is shown in Fig. 2, which includes a Wye-Delta transformer, a superconducting coil and an ac/dc thyristor-driven bridge converter [14]. The converter applies either positive or negative voltage to the superconducting coil. Charge and discharge are easily regulated by adjusting the delay angle that governs the firing of the thyristors [14]. If it is less than 90°, the converter will function in charging mode (rectification). If it is larger than 90°, the converter will function in discharging mode (inversion). Consequently, power may be absorbed or released from the power system as required.

PCS with voltage source converters: The basic structure of the VSC-based SMES system is shown in Fig. 3, consisting of a Wye-Delta transformer, insulated-gate bipolar transistor (IGBT)-based pulse width modulation (PWM) converter, dc-dc chopper, and a superconducting coil [8]. A dc link capacitor connects the pulse width modulator inverter and the dc to dc chopper.

PCS based on current source converters: The fundamental setup of the current source converter based SMES system is depicted in Fig. 4. The dc side counterpart of the current source converter is linked straight to the superconducting coil, while the ac counterpart is linked to the power supply [8]. Capacitor banks are attached to the CSC input port to buffer the stored energy in line inductances during the commutation of the alternating line current trajectory [8]. Additionally, the capacitors can filter the alternating line current's elevated harmonics. In CSC, the

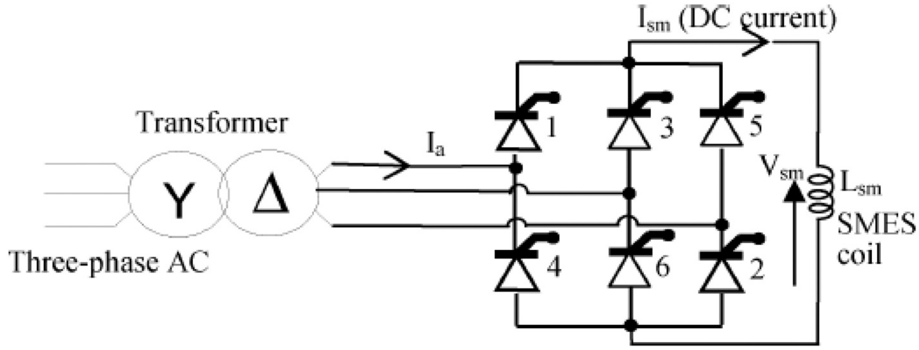

Fig. 2. SMES unit with six-pulse bridge ac/dc thyristor-controlled converter.

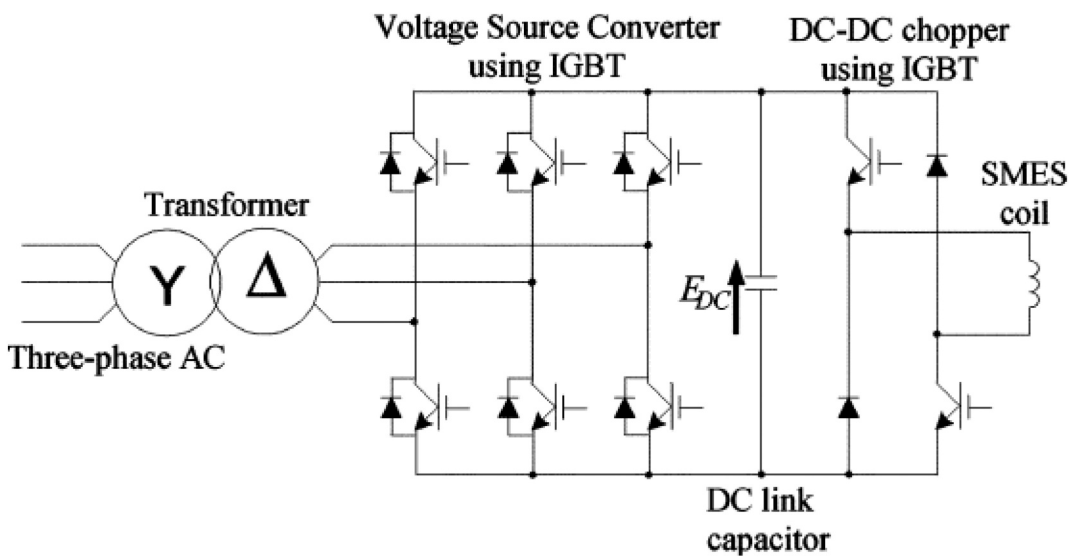

Fig. 3. Basic configuration of VSC-based SMES system.

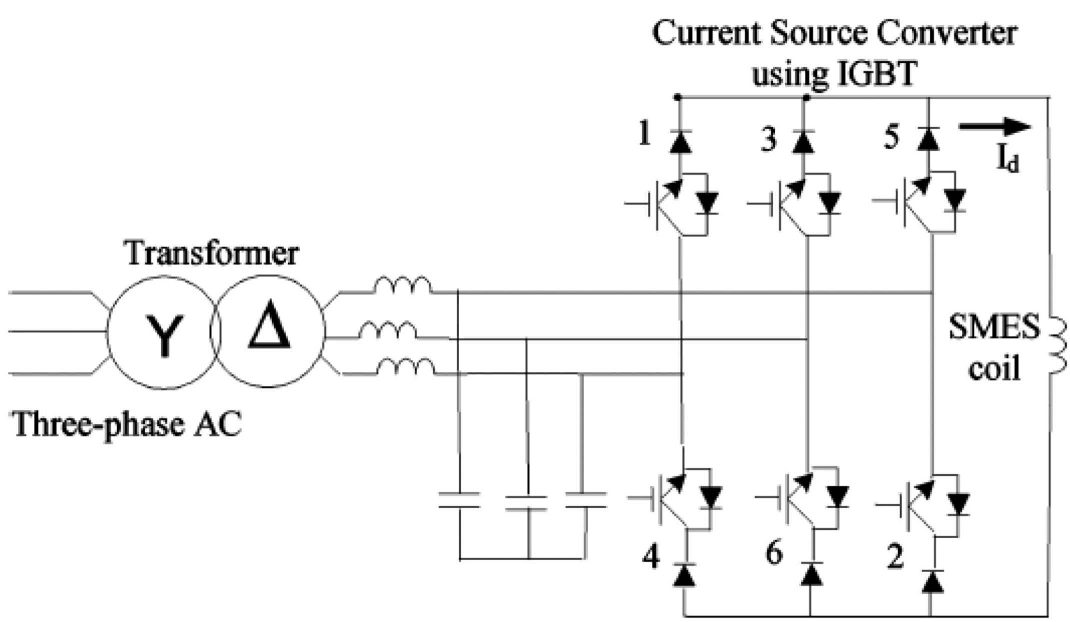

Fig. 4. SMES system with a CSC.

current in the superconducting coil may be modified to create programmable 3-phase pulse width modulated current on the alternating current counterpart by adjusting the switch devices' triggering signal.

2.3. The cryogenic system

The SMES system coil must always be maintained at sufficiently low temperatures to retain the wires in a superconducting state. For recent commercial Low Temperature Superconductors (LTS) SMES this temperature is in the neighborhood of 4.5 K (−452 °F or − 269 °C) [15]. To attain and sustain this temperature, a dedicated cryogenic refrigerator that utilizes helium as the coolant or liquid nitrogen in the case of HTS is used [15]. The structure of SMES cryogenic system is depicted in Fig. 5. The refrigerator is made up of one or more pneumatic helium compressors and a vacuum containment known as a chilled chamber, that collects pressurized, room temperature helium gas and generates liquid helium/nitrogen to cool the coil [16]. Because of impacts on the overall cost and efficiency of the SMES system, loss features such as cold to hot current lead, radiation, conduction, alternating current, and so on should be minimized in order to produce a more productive and less expensive SMES system.

2.4. Control system

The control system initiates a connection between the power grid demands and the power flow to and from the SMES coils. It gets dispatch signals from the grid as well as the coil status. It also monitors the system's safety and conveys system's state to the operator [17]. This usually comprises discrete signal processing based interface circuits or microcontrollers. Modern systems are linked to the internet to allow for remote monitoring and control.

3. Comparison of SMES with other energy storage technologies

There are several energy storage technologies presently in use for renewable energy applications. In general, energy storage systems can be categorized into five. These are electrochemical, chemical, electrical, mechanical and thermal systems as shown in Fig. 6.

The chart in Fig. 7 depicts the application-technology matrix for different energy storage technologies. The left vertical axis shows the discharge time for each technology represented and the horizontal axis indicates the range of power ratings for each technology.

Table 1 details the comparison of specific performance characteristics of different energy storage systems and Table 2 provides comparisons based on stages of development, advantages and disadvantages of.

4. Review of research into renewable energy applications of SMES

This section provides review of various works that have been carried out on SMES.

4.1. Bibliographic analysis

Several investigations have been carried out on the development and applications of SMES for renewable energy applications. The top 1240 most relevant research publications on superconducting magnetic energy storage system have been searched on ScienceDirect and IEEE Xplore and their bibliographical details downloaded. The selected articles were analysed using a bibliographic analysis software called VOSviewer. The occurrence of keywords relating to SMES has been carried out using full counting method. There were 3833 keywords in total. However, only 149 of these meet the threshold when the minimum number of occurrences of a keyword was set to 10. For each of the 149 keywords, the total strength of the co-occurrence links with other keywords was calculated. The keywords with the highest total link strength include superconducting magnetic energy storage and its variants such as SMES (Occurrence = 721; Total link strength = 3327), superconducting magnets (Occurrence = 177; Total link strength = 868), high-temperature superconductors (Occurrence = 161; Total link strength = 858), and power system stability (Occurrence = 115 Total link strength = 628). Others include coils, energy storage, voltage control etc.

Fig. 8 depicts the network visualization diagram for the selected keywords. The network comprises of five clusters indicated by different colours. The proximity of items in each cluster is a measure of how closely related they are and the thickness of the links show the extent of co-occurrence of the connected terms in literature. The sizes of the circle and the labels for each keyword is an indication of how pronounced such keyword has been researched in relation to superconducting magnetic energy storage. The red and blue clusters represent keywords that align with SMES research on fundamental designs, development and fabrications of SMES components and systems. The green and yellow clusters indicates aspects of research that touches on SMES application in power system stability enhancements, voltage and frequency control, renewable energy systems and hybrid energy storage systems. The purple cluster shows some keywords that are found in studies on optimization and control of SMES systems. It should be noted that not all the keyword labels are visibly displayed in the network diagram in order to avoid overlapping of terms, which could make the figure unreadable.

Furthermore, Table 3 shows some of the most relevant research carried out in the last ten years (2013 to 2022) on important aspects of superconducting magnetic energy storage systems.

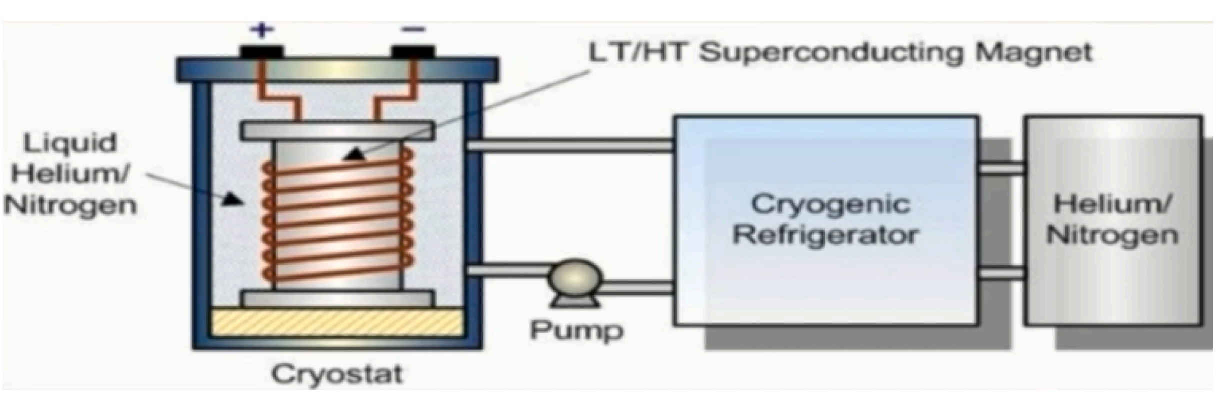

Fig. 5. Structure of SMES cryogenic system [11].

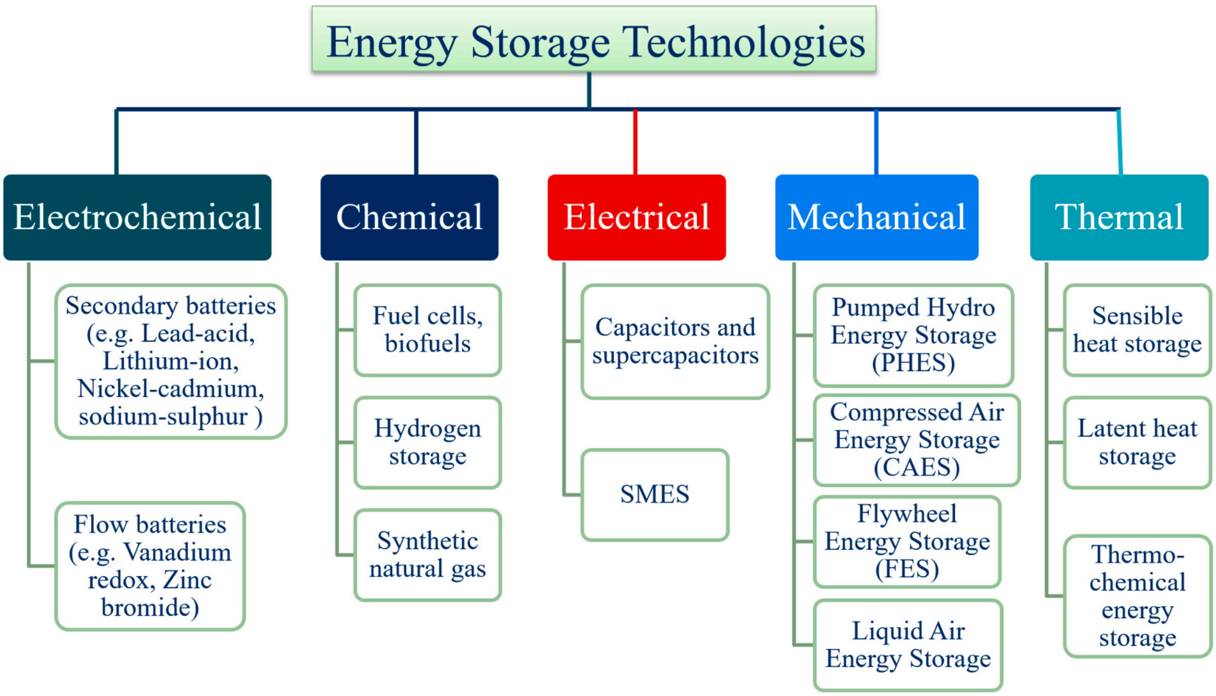

Fig. 6. Classification of energy storage systems.

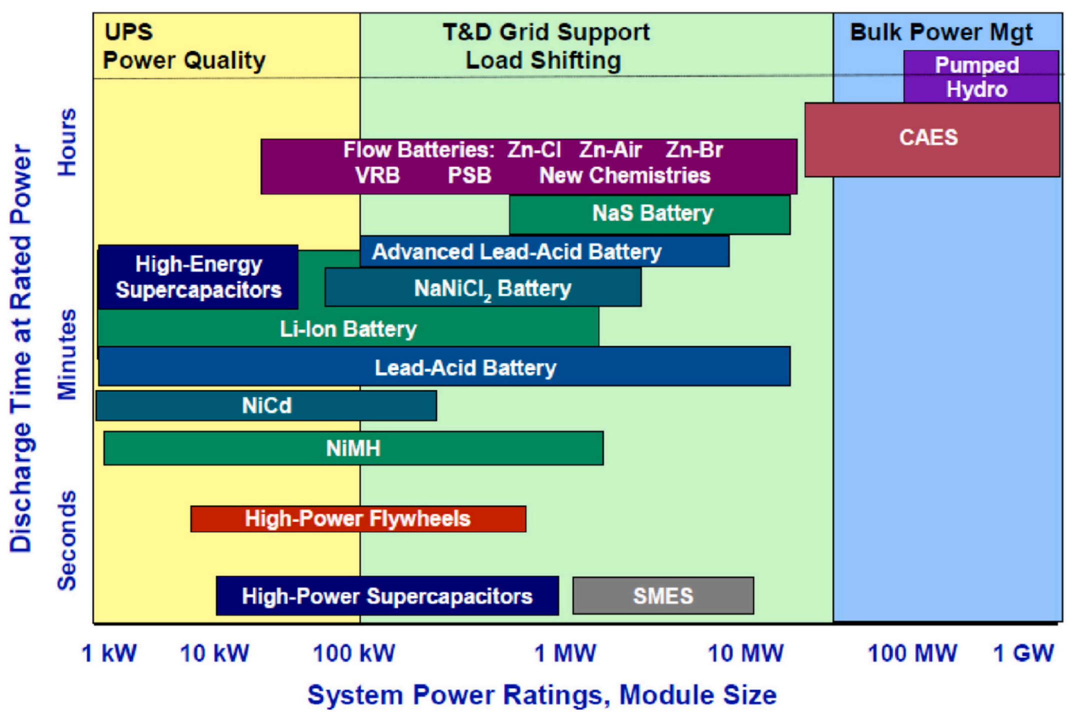

Fig. 7. Discharge time, power ratings and application areas of energy storage technologies (Source: [18]).

4.2. Review of relevant works on renewable energy applications of SMES

A typical layout of SMES usage with grid-connected renewable energy systems is illustrated in Fig. 9. Review of various works on SMES applications with renewable energy systems are discussed in the rest of this section.

In [63], the authors investigated the integration of Static Synchronous Compensator (STATCOM) coupled with SMES controller to alleviate transient stability concerns in the presence of a DFIG connected system. The study offers a new control strategy for the DC link chopper circuit of SMES and STATCOM. MATLAB/Simulink environment was used to conduct a comparative evaluation of several system parameters with and without SMES controller. The results showed that the suggested control strategy can dampen the system's oscillations fast and establish its equilibrium state as soon as possible, thereby enhancing the system's stability.

The authors in [64] proposed a superconducting magnetic energy storage system that can minimize both high frequency wind power

Table 1
Comparison of energy storage technologies: Key features ([19–25]).

Category	Type	Rated power (MW)	Energy density (Wh/kg)	Power density (W/kg)	Discharge Time	Life (years)	Efficiency
Electrochemical	Lead-acid	≤100	30–50 Wh/kg	75–300	≤8 h	5–20	70–90 %
	Li-ion	≤100	75–200 Wh/kg	150–315	≤2 h	5–15	85–98 %
	NaS	≤50	150–240 Wh/kg	90–230	≤8 h	10–15	75–90 %
	NiCd	≤40	50–75 Wh/kg	150–300	≤10 h	10–20	60–90 %
	Vanadium RFB	≤50	10–25 Wh/kg (16–33 Wh/L)	Up to 2.78 W/cm2	≤12 h	5–10	80–90 %
	ZnBr FB	≤10	75–85 Wh/kg	Up to 150 W/kg	≤10 h	5–10	70–80 %
Chemical	Fuel cells	≤50	8000–10,000 Wh/kg	500–3000	≤24 h	5–15	20–66 %
Mechanical	PHES	≤5000	0.2–2 Wh/L	–	≤24+ hrs	40–70	70–87 %
	CAES	≤3000	3–12 Wh/L	0.5–2 W/L	≤24+ hrs	20–40	60–89 %
	FES	≤10	10–30 Wh/kg	400–1500	≤1 h	15–20	80–95 %
Thermal	Thermo-chemical ES	≤50	70 Wh/kg (280 Wh/L)	–	hours	10–30	60–90 %
Electrical	Supercapacitors	≤10	2.5–15 Wh/kg	500–2000	≤1 min	20–40	60–95 %
	SMES	≤100	0.5–5 Wh/kg	500–5000	≤1 min	20–40	95–98 %

Table 2
Comparison of energy storage technologies: maturity, advantages and disadvantages ([19–25]).

Category	Type	Stage of development	Advantages	Disadvantages
Electrochemical	Lead-acid	Mature	High cycle efficiency, high reliability and low capital cost	Low energy density and produces toxic remains with negative impact on the environment
	Li-ion	Mature	Higher power energy densities, highly efficient and high reliability	High cost; requires complex circuitry for safety and protection.
	NaS	Commercial	Higher power and energy densities, low self-discharge rate, and non-toxic	High capital cost, requires high temperature (290–390°C) to operate when the constituent elements are in the liquid state.
	NiCd	Commercial	High energy density, long cycle life and high reliability	Negative environmental impact and affected the by memory effect
	Vanadium RFB	Demonstration	High efficiency and cycle life.	Very low energy density
	ZnBr FB	Developed	Fast response time and flexible for wide range of applications	Prone to corrosion.
Chemical	Fuel cells	Developing	Does not require recharging, very low self-discharge	High capital cost
Mechanical	PHES	Mature	Longest lifetime and low maintenance costs	Subject to environmental constraints, high capital cost.
	CAES	Commercial	Very small self-discharge, long lifetime, fast response time.	Location is subject to geographical constraints.
	FES	Commercial	Fast charging speed, and high cycle efficiency	Noisy operation and high self-discharge
Thermal	Thermo-chemical ES	Developed	High energy density, relatively low cost, long-term stable storage period and low energy loss	Poor heat transfer performance
Electrical	Supercapacitors	Developed	Very high power density and fast response time.	Low energy density, high self-discharge rate.
	SMES	Demonstration	High power density, fast response, exceptionally very high efficiency and long lifetime	Very low energy density, high self-discharge rate, generates very strong magnetic field

fluctuation and HVAC cable system's transient overvoltage. A 60 km submarine cable was modelled using ATP-EMTP in order to explore the transient issues caused by cable operation. They observed that HVAC submarine cables have a higher capacitance impact, resulting in more significant transient issues. Furthermore, the unpredictable wind power provided by offshore wind farms have an unfavorable influence on the onshore electricity grid. The technical viability and economic analysis of a 5 MJ SMES in a practical renewable power system in China was carried out in [65] using PSCAD/EMTDC simulation environment. By utilizing real power transmission characteristics, an ideal placement of SMES in Zhangbei wind farm was presented. Cost comparison of wind power generation system incorporating SMES and battery was performed as well. The analysis provided an indication of SMES's practical application capability in addressing the cost-benefit balance.

Morever, the study in [140] incorporated a fuzzy logic-based integral controller and a superconducting magnetic energy storage in an independent micro-grid to address load frequency control (LFC) problems. Simulations were carried out in MATLAB/Simulink environment. The findings showed that the load frequency control system utilizing fuzzy logic-based integral regulator and SMES device provides a better dynamic performance than previous LFC systems. Also, in [175], the influence of SMES on a two-agent restructured power system operating in an open market has been investigated. The proposed deregulated electricity system was researched with various contract scenarios. The suggested system was chosen as a two-agent, hydro-thermal restructured system to enhance the assessment of load frequency control issues within the deregulated power system. To mitigate several LFC issues, a UPFC unit in conjunction with the SMES unit was recommended.

Furthermore, the study in [66] presented an improved block-sparse adaptive Bayesian algorithm for completely controlling proportional-integral (PI) regulators in superconducting magnetic energy storage (SMES) devices. The results indicate that regulated SMES units can increase the power quality of wind farms. The authors in [67] proposed a SMES device based on a shunt active power filter (SAPF) for restricting harmonic and unbalanced currents along with minimizing power alterations in a photovoltaic (PV) microgrid. Fuzzy logic controller was utilized to stabilize the DC-link voltage and decrease the SMES's depth of discharge. The effectiveness of the proposed method was demonstrated through modeling correlations with a conventional PI controller and a sliding-mode controller under different scenarios.

An adaptive power oscillation damping (APOD) technique for a superconducting magnetic energy storage unit to control inter-area oscillations in a power system has been presented in [123]. The APOD technique was based on the approaches of generalized predictive control and model identification. The results indicate that the proposed APOD consistently outperforms the conventional lead–lag POD in terms of damping performance over a wide range of operating circumstances and disturbances. In [68], transient stability of a multi-machine power

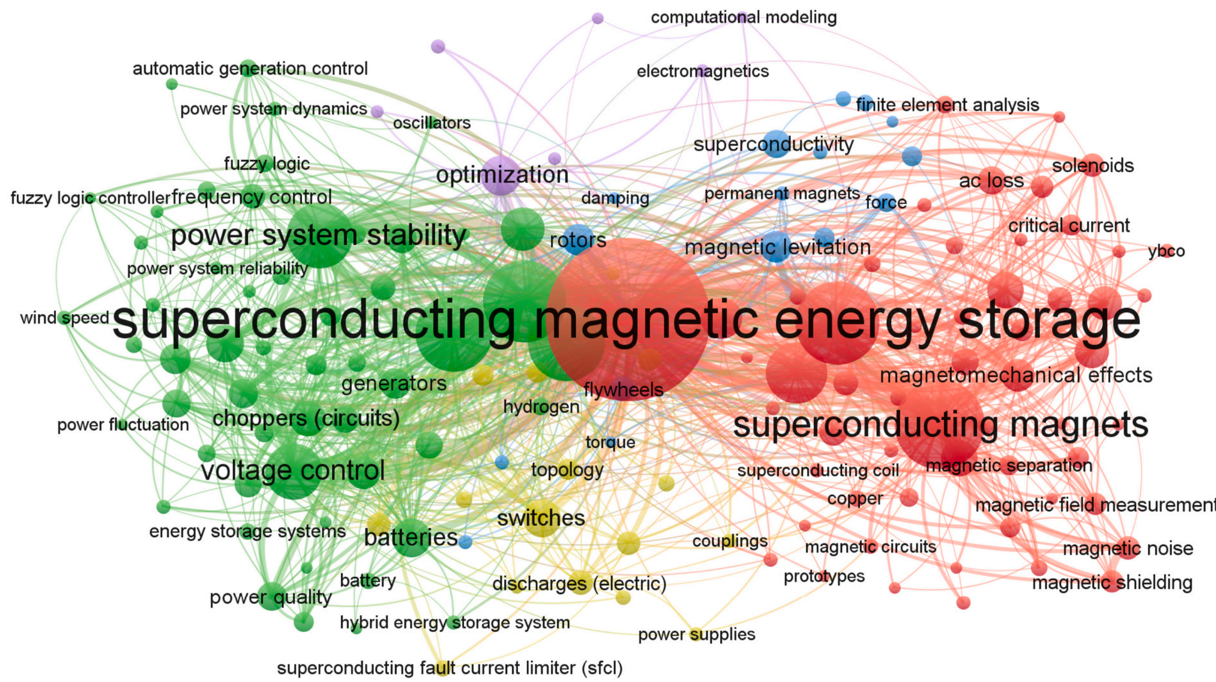

Fig. 8. Network visualization of keywords.

Table 3
Relevant published research from 2013 to 2022 on important aspects of SMES.

S/N	Subject of studies	Publications
1.	Fundamental designs, development and fabrications of SMES components and systems	[13,26–62]
2.	Application of SMES in power systems integrated with renewable energy (wind energy conversion systems and/or photovoltaic systems)	[63–122]
3.	Power system stability enhancements and oscillation damping using SMES with conventional and/or advanced controllers	[21,32,63,84,112,117–119,123–139]
4.	Frequency control of power systems using power converter-based SMES	[78,125,140–144]
5.	SMES with other energy storage systems in hybrid utilization	[81,83,138,145–165]
6	Application of SMES in electric vehicles and other electric propulsion systems	[82,149,154,158,161,166–173]

system coupled with wind farm and an SMES unit was carried out using a sensitivity-based index. The index was obtained via the DFIG-based wind farm's terminal voltage. The analysis was performed using variable speed wind profiles at different penetration levels.

The study in [176] investigated the influence of SMES on unit commitment scheduling. The findings show that incorporating highly efficient SMES has significant effect on daily load scheduling of thermal units and can pave way for optimal unit commitment with reduced load shedding, while meeting the load demands. The findings in [11] shows that SMES can minimize low frequency fluctuations thereby increasing transmission capacity and boosting voltage stability. Also, SMES systems can provide energy for Flexible Alternating current Transmission System (FACTS).

In the grid integration of wind energy conversion systems (WECS), four different SMES locations have been suggested in literature [94]. These include connections at WECS terminal [177], the power converter system [178], the point of common coupling (PCC) [71,98], and the tie line of a multi-bus power system to which the WECS is connected [179]. The pros and cons of these SMES placements are detailed in [94].

In [79], two of the commonly suggested SMES locations are investigated for the grid integration of a DFIG-based WECS. The first scenario considers SMES connection through a Type-D chopper with the dc side of DFIG-based WECS while SMES connection is made at the point of common coupling in the second case. The results of the study indicates that SMES supports the grid stability and reliability in both cases but the second case achieves more effective smoothening of DFIG power fluctuations. In addition, the work in [73] shows that the optimal location of SMES in the case study distribution system depends on the load characteristics and hourly load demand variation in the system. Relatively few works have been done on optimal location of SMES with renewable energy conversion systems. Therefore, more research need to be conducted to determine the optimal locations of SMES with renewable energy systems.

4.3. *Control techniques and power electronic interfaces of SMES with renewable energy sources*

This section highlights various control techniques and power electronic converter interfaces of SMES when utilized for renewable energy applications. The summary of these techniques are provided in Table 4 together with the specific renewable application areas.

5. Roadmap for SMES technology

LTS-SMES systems have already been deployed up to a scale of 10 MW and 5.556 kWh (20 MW). For instance, Japan already has more than three LTS-SMES systems since 2011 for providing instantaneous voltage sag compensation of critical industrial loads [186]. However, the considerably high cost of SMES system has slowed down market penetration of LTS-SMES even though the technology has been successfully tested and demonstrated.

The cost of cryogenic system for SMES operation is a major limitation for its widespread usage. However, the growth in the development of

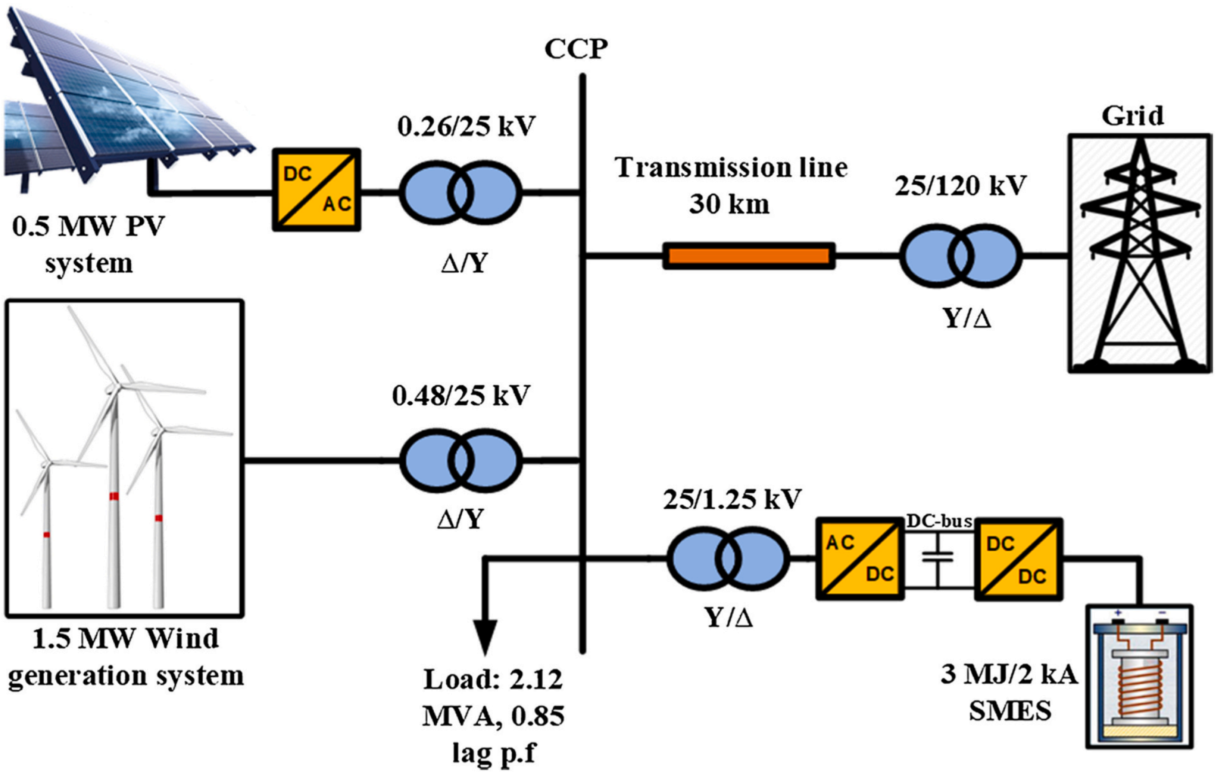

Fig. 9. SMES and renewable energy systems integrated to the grid [174].

HTS and second-generation superconducting wires brings new opportunities for cost reduction and further research and development of HTS-SMES, which can operate at higher temperatures of up to −223.15, greater magnetic flux densities of up to 20 Teslas and consequently, higher efficiencies. There are also ongoing efforts to realize systems with higher magnetic flux density, improved HTS coil manufacturing, and simplified, cost-effective cooling system.

In general, the total cost of energy storage systems is dependent on the amount of energy supplied or power produced, therefore, cost is usually measured in \$/kWh or \$/kW. In recent years, the cost of producing SMES coil with the associated auxiliary components is reducing due to improved manufacturing processes and the use of more readily accessible materials with similar superconducting properties. This has paved way for a wide range of cost depending on the element used. The cost of energy ranges from 700 to 10,000 \$/kWh and the power cost from 130 to 515 \$/kW [187].

Furthermore, the potential use of SMES together with other large-scale, energy application storage systems is paving way for broader SMES applications. Studies on hybrid storage systems comprising of SMES with other storage technologies are gaining prominence. Such hybrid systems are expected to be of great benefits in power and energy applications.

In order to foster the rapid development and deployment of SMES to maturity stage, various international agencies and government bodies have presented considerable roadmap for SMES technology [188–192]. From the information gathered from the existing roadmap documents, Fig. 10 summarises the set targets for SMES technology development.

6. Challenges and future research direction on the development and improvement of SMES for renewable energy applications

The main drawback of SMES technique is the requirement for a significant amount of power to maintain the coil at a low temperature combined with the hefty total cost of using such unit [7]. To obtain commercially relevant levels of storage, about 1 GWh (3.6 TJ) of SMES installation would require a 100-mile loop (160 km) [193]. Another issue is the required infrastructure for system implementation. The wire loop must also be confined within a vacuum of helium or liquid nitrogen [14]. This also requires stable support, which typically results to underground installation. Furthermore, SMES is characterized with high power density and low energy density. Therefore, its application is largely limited to high power, low energy applications due to short discharge time. The rest of this section therefore highlights important aspects of research that needs to be intensified for SMES to become more economically viable for renewable energy applications.

6.1. *Additional protection*

Research in the area of additional protection is ongoing as the power per unit mass can be massively high. Thus, the system is contained in an excellent electric isolation [194]. In situation of coil failure, energy is either released or the coil gets damaged. Upon the application of SMES, protecting a sensitive electrical load from voltage sags requires the design of the system to have a discharge time in milliseconds or seconds while for load levelling the discharge time is required in hours or weeks. Therefore, appropriate protection design is required for diverse power system applications.

6.2. *SMES structure*

During charging and discharging of a HTS tape, the Lorentz force imposes immense strain and stress on the HTS tape. Lorentz force creates excessive vibrations in the system, which is undesirable [195]. Therefore, special care is required for designing the supporting structure and more work needs to be done in improving the structure of the superconducting magnetic energy storage system to handle the Lorentz force.

6.3. *Optimal controllers*

The use of advanced intelligent controllers such as artificial neural

Table 4
Control techniques and power electronic interface.

Control techniques	Specific examples	Renewable energy application
Proportional Integral (PI) controllers	Self-tuned proportional integral control of SMES systems using continuous mixed p-norm algorithm. Control strategy was based on VSC and DC chopper to control the exchange of active and reactive power with the grid respectively [180].	Mitigation of output power fluctuations of two grid-connected fixed speed wind farms using 10MVA, 21.1H SMES unit each. Each wind farm comprises five 2MVA induction generators.
	Hybrid Big Bang Big Crunch meta-heuristic optimization algorithm was used to optimize the PI gains of DFIG, SMES and superconducting fault current limiter parameters [83].	Enhancement of fault-ride-through capability of DFIG and mitigation of output power fluctuations.
	SMES control strategy was based on a 12-pulse thyristor-controlled bridge converter. Particle Swarm Optimization algorithm was utilized to optimize the PI controller gains in order to minimize frequency deviations of the study system [181].	Frequency stability improvement of power grid with high renewable energy (wind and solar) penetration.
Fuzzy logic controllers (FLC)	Fuzzy logic controllers with control strategy of SMES based on an IGBT-based sinusoidal PWM VSC and a two-quadrant dc-dc chopper [182].	Stabilization of grid connected WECS.
	SMES control strategy based on ac/dc thyristor-controlled bridge converter. FLC was used to control the firing angle of the thyristor [183].	Transient stability improvement of power systems.
	Fuzzy logic control (FLC) was used to control the dc-dc chopper circuit of SMES for active power flow control [174].	Mitigation of active and reactive power fluctuations and voltage regulation at point of common coupling for a grid-integrated hybrid renewable energy system consisting of solar PV and WECS.
Combined proportional integral and fuzzy logic controllers	PI an FLC controllers was employed for the VSC and chopper circuits respectively to control the reactive and active power between SMES unit and the grid [69].	Voltage, active and reactive power control during normal and abnormal wind speeds.
Artificial neural network (ANN) controllers	The control strategy was based on a sinusoidal PWM VSC and an adaptive ANN-controlled dc–dc IGBT-based converters [80].	Transient stability improvement of grid-connected WECS.
	SMES control strategy was based on combined control scheme of a VSC and a two-quadrant dc-dc chopper using IGBTs. The ANN controller was employed to control the duty cycle of the dc-dc chopper [184].	Transient stability improvement of a grid-connected WECS.
Model predictive control (MPC)	The SMES is interfaced into the power system through a dc-dc chopper and a three-phase inverter [185].	Voltage stability enhancement, reliability improvement and power levelling of power grid with solar photovoltaic integration.
	Modelled as controlled current sources, SMES and static var. compensator were used to control the active and reactive power respectively using an adaptive MPC technique [137].	Voltage and frequency control of an isolated hybrid wind-diesel power system.

network, fuzzy logic and neuro-fuzzy interfaced to SMES system are found to better than the conventional controllers [13]. These controllers are needed for transient, small signal and dynamic voltage stability. However, more research is needed in the area of optimal and robust controllers to be used depending on the area of SMES applications.

6.4. Cooling structure design

The cooling structure design of a superconducting magnetic energy storage is a compromise between dynamic losses and the superconducting coil protection [196]. It takes about a 4-month period to cool a superconducting coil from ambient temperature to cryogenic operating temperature. In cases of coil failure, it takes the about the same amount of time to recover from the operating temperature to room temperature [197]. In view of this, more significant level of research is required to address this challenge.

6.5. Cooling medium

The use of liquid helium rather than liquid nitrogen in the cryonic unit rapidly results to faster cooling of the superconducting coil below the critical temperature. Liquid helium has a critical temperature of 5.5 K to 3.3 K while liquid nitrogen has 44.4 K critical temperature. Helium is preferred because it is the only viable material that can get to the temperature of 4.4 K without changing to its solid state [194]. Therefore, the application of helium medium as coolant needs further investigation in order to improve the performance of the SMES system.

6.6. SMES length reduction

Operating the superconducting coil at higher currents could be employed to reduce the total length of the superconductor as it can reduce the overall cost of the system [6]. This brings about increased cost effectiveness and hence commercialization usage as the structure of the system is made relative to the length of the coil. However, the downside of employing higher currents need to be carefully investigated as there would be new system requirements such as the increased sizing of protective devices to handle higher currents.

6.7. Hybrid energy storage incorporating SMES

Opportunities for broader SMES applications are gaining traction particularly in the area of hybrid energy storage technologies incorporating SMES and other storage technologies. Some of the proposed hybrid configuration in literature includes hybrid SMES-BESS [156,158,198], Liquid hydrogen with SMES (LIQHYSMES) [150,199,200]. While SMES-BESS hybrid storage has been widely studied, emerging hybrid storage systems such as LIQHYSMES still require further investigations.

7. Conclusion

The review of superconducting magnetic energy storage system for renewable energy applications has been carried out in this work. SMES system components are identified and discussed together with control

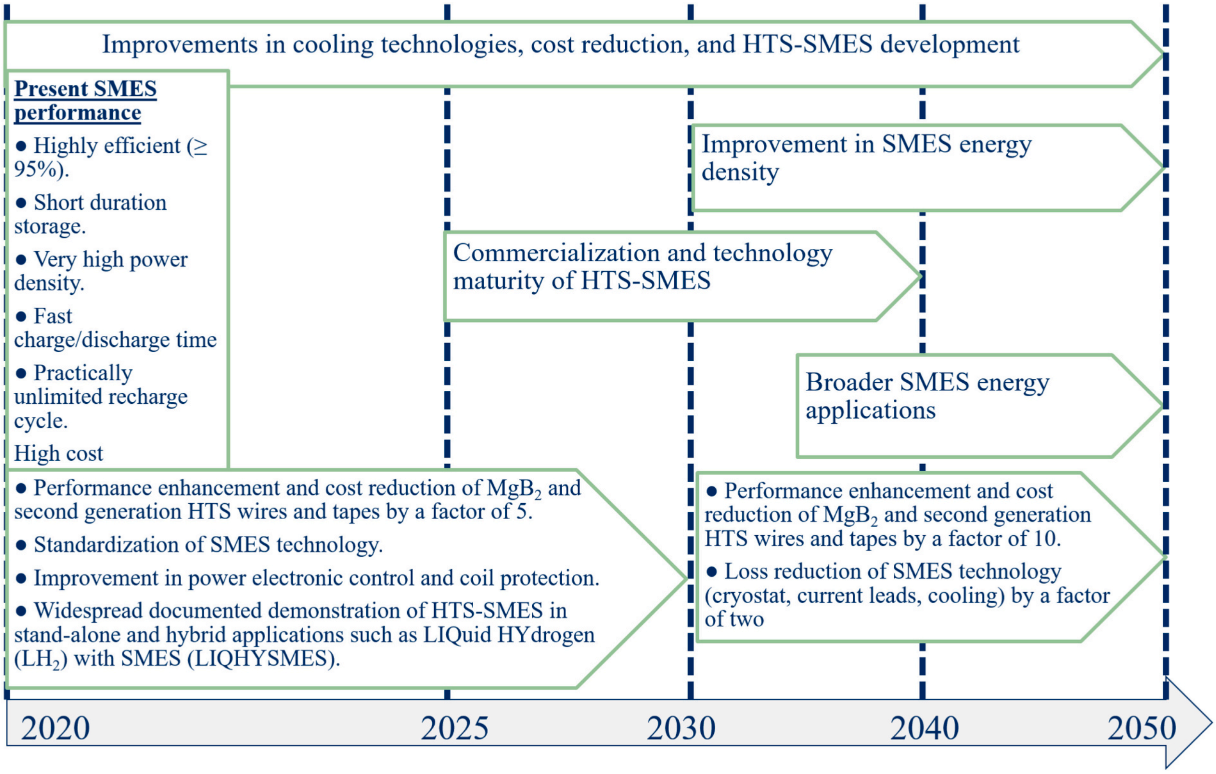

Fig. 10. Target roadmap for SMES technology.

strategies and power electronic interfaces for SMES systems for renewable energy system applications. In addition, this paper has presented a bibliographic analysis of important keywords relating to SMES using data obtained from top 1240 relevant research publications on SMES. Comparison of SMES with other storage technologies has also been provided in order to reveal the present status of SMES in relation to other competitive energy storage technologies. Roadmap for SMES technology and set targets from 2020 to 2050 has also been summarized. Important challenges of SMES and future research direction on the development and application of SMES are also discussed. The review shows that additional protection, improvement in SMES component designs and development of hybrid energy storage incorporating SMES are important future studies to enhance the competitiveness and maturity of SMES system on a global scale.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] B.B. Adetokun, C.M. Muriithi, J.O. Ojo, Voltage stability analysis and improvement of power system with increased SCIG-based wind system integration, in: 2020 IEEE PES/IAS PowerAfrica, 2020, pp. 1–5.

[2] B.B. Adetokun, J.O. Ojo, C.M. Muriithi, Reactive power-voltage-based voltage instability sensitivity indices for power grid with increasing renewable energy penetration, IEEE Access 8 (2020) 85401–85410.

[3] B.B. Adetokun, J.O. Ojo, C.M. Muriithi, Application of large-scale grid-connected solar photovoltaic system for voltage stability improvement of weak national grids, Sci. Rep. 11 (1) (2021) 24526.

[4] S. Nishijima, S. Eckroad, A. Marian, K. Choi, W.S. Kim, M. Terai, et al., Superconductivity and the environment: a roadmap, Supercond. Sci. Technol. 26 (11) (2013) 113001.

[5] V.A. Boicea, Energy storage technologies: the past and the present, Proc. IEEE 102 (11) (2014) 1777–1794.

[6] R. Boom, H. Peterson, Superconductive energy storage for power systems, IEEE Trans. Magn. 8 (3) (1972) 701–703.

[7] W. Yuan, W. Xian, M. Ainslie, Z. Hong, Y. Yan, R. Pei, et al., Design and test of a superconducting magnetic energy storage (SMES) coil, IEEE Trans. Appl. Supercond. 20 (3) (2010) 1379–1382.

[8] M.H. Ali, B. Wu, R.A. Dougal, An overview of SMES applications in power and energy systems, IEEE Trans. Sustain. Energy 1 (1) (2010) 38–47.

[9] D. Sutanto, K.W.E. Cheng, Superconducting magnetic energy storage systems for power system applications, in: 2009 International Conference on Applied Superconductivity and Electromagnetic Devices, 2009, pp. 377–380.

[10] X.D. Xue, K.W.E. Cheng, D. Sutanto, A study of the status and future of superconducting magnetic energy storage in power systems, Supercond. Sci. Technol. 19 (6) (2006) R31–R39.

[11] V.S.G. Vulusala, S. Madichetty, in: Application of Superconducting Magnetic Energy Storage in Electrical Power and Energy Systems: A Review 42, 2018, pp. 358–368, no. 2.

[12] R. Soman, H. Ravindra, X. Huang, K. Schoder, M. Steurer, W. Yuan, et al., Preliminary investigation on economic aspects of superconducting magnetic energy storage (SMES) systems and high-temperature superconducting (HTS) transformers, IEEE Trans. Appl. Supercond. 28 (4) (2018) 1–5.

[13] P. Mukherjee, V.V. Rao, Design and development of high temperature superconducting magnetic energy storage for power applications - a review, Phys. C 563 (2019) 67–73.

[14] L. Chen, Y. Liu, A.B. Arsoy, P.F. Ribeiro, M. Steurer, M.R. Iravani, Detailed modeling of superconducting magnetic energy storage (SMES) system, IEEE Trans. Power Deliv. 21 (2) (2006) 699–710.

[15] H.K. Yeom, Y.J. Hong, S.J. Park, T.B. Seo, K.C. Seong, H.J. Kim, Study of cryogenic conduction cooling systems for an HTS SMES, IEEE Trans. Appl. Supercond. 17 (2) (2007) 1955–1958.

[16] P. Han, Y. Wu, H. Liu, L. Li, H. Yang, Structural design and analysis of a 150 kJ HTS SMES cryogenic system, Phys. Procedia 67 (2015) 360–366.

[17] M.G. Molina, P.E. Mercado, E.H. Watanabe, Improved superconducting magnetic energy storage (SMES) controller for high-power utility applications, IEEE Trans. Energy Convers. 26 (2) (2011) 444–456.

[18] A.Z. Al Shaqsi, K. Sopian, A. Al-Hinai, Review of energy storage services, applications, limitations, and benefits, Energy Rep. 6 (2020) 288–306.

[19] M. Beaudin, H. Zareipour, A. Schellenberg, W. Rosehart, Chapter 1 - Energy storage for mitigating the variability of renewable electricity sources, in: P. Du, N. Lu (Eds.), Energy Storage for Smart Grids, Academic Press, Boston, 2015, pp. 1–33.

[20] M.S. Guney, Y. Tepe, Classification and assessment of energy storage systems, Renew. Sust. Energ. Rev. 75 (2017) 1187–1197.
[21] A. Boudia, S. Messalti, A. Harrag, M. Boukhnifer, New hybrid photovoltaic system connected to superconducting magnetic energy storage controlled by PID-fuzzy controller, Energy Convers. Manag. 244 (2021), 114435.
[22] M.M. Rana, M. Uddin, M.R. Sarkar, G.M. Shafiullah, H. Mo, M. Atef, A review on hybrid photovoltaic – battery energy storage system: current status, challenges, and future directions, J. Energy Storage 51 (2022), 104597.
[23] A.K. Rohit, K.P. Devi, S. Rangnekar, An overview of energy storage and its importance in indian renewable energy sector: part I - technologies and comparison, J. Energy Storage 13 (2017) 10–23.
[24] O. Palizban, K. Kauhaniemi, Energy storage systems in modern grids—Matrix of technologies and applications, J. Energy Storage 6 (2016) 248–259.
[25] H.R. Jiang, J. Sun, L. Wei, M.C. Wu, W. Shyy, T.S. Zhao, A high power density and long cycle life vanadium redox flow battery, Energy Storage Mater. 24 (2020) 529–540.
[26] M. Abdel-Salam, A. Elnozahy, M. Elgamal, Minimum power loss based design of SMES as influenced by coil material, J. Energy Storage 30 (2020), 101461.
[27] U. Bhunia, S. Saha, A. Chakrabarti, Design optimization of superconducting magnetic energy storage coil, Phys. C 500 (2014) 25–32.
[28] U. Bhunia, S. Saha, A. Chakrabarti, Pareto optimal design of sectored toroidal superconducting magnet for SMES, Phys. C 505 (2014) 6–13.
[29] A. Hekmati, R. Hekmati, Double pancake superconducting coil design for maximum magnetic energy storage in small scale SMES systems, Cryogenics 80 (2016) 74–81.
[30] X. Lin, Y. Lei, Y. Zhu, A novel superconducting magnetic energy storage system design based on a three-level T-type converter and its energy-shaping control strategy, Electr. Power Syst. Res. 162 (2018) 64–73.
[31] Y. Makida, T. Shintomi, T. Asami, G. Suzuki, T. Takao, T. Hamajima, et al., Design study of the cooling scheme for SMES system in ASPCS by using liquid hydrogen, Physica C 494 (2013) 208–212.
[32] G.Sathish Kumar, V.Agnes Idhaya Selvi, K. Pandiyan, Design and analysis of ML-VSC based SMES with improved power quality features, Materials Today: Proceedings (2021). Article in press.
[33] J. Shi, Y. Xu, M. Liao, S. Guo, Y. Li, L. Ren, et al., Integrated design method for superconducting magnetic energy storage considering the high frequency pulse width modulation pulse voltage on magnet, Appl. Energy 248 (2019) 1–17.
[34] T. Yagai, S. Mizuno, T. Okubo, S. Mizuochi, M. Kamibayashi, M. Jimbo, et al., Development of design for large scale conductors and coils using MgB2 for superconducting magnetic energy storage device, Cryogenics 96 (2018) 75–82.
[35] H. Zhang, D. Lin, D. Wang, J. Shi, B. Zhu, S. Ma, et al., Design and control of a new power conditioning system based on superconducting magnetic energy storage, J. Energy Storage 51 (2022), 104359.
[36] S. Sparacio, A. Napolitano, L. Savoldi, S. Viarengo, F. Laviano, Design of a Module for a 10 MJ toroidal YBCO superconducting magnetic energy storage, IEEE Trans. Appl. Supercond. 32 (4) (2022) 1–5.
[37] J. Shi, W. Yang, Z. Song, X. Zhou, M. Liao, Z. Chen, et al., Influence analysis of SMES magnet design scheme on its voltage distribution characteristic, IEEE Trans. Appl. Supercond. 32 (1) (2022) 1–11.
[38] J. Gómez, B. Pérez, P. Suárez, A. Álvarez, B. Rivera, Theoretical and experimental studies of SMES configurations for design optimization, IEEE Trans. Appl. Supercond. 31 (5) (2021) 1–5.
[39] P. Song, J. Zhu, T. Qu, P. Chen, F. Feng, M. Qiu, Design and test of a double pancake coil for SMES application wound by HTS roebel cable, IEEE Trans. Appl. Supercond. 28 (4) (2018) 1–5.
[40] L. Chen, H. Chen, J. Yang, H. He, Y. Yu, G. Li, et al., Conceptual design and evaluation of an HTS magnet for an SMES used in improving transient performance of a grid-connected PV system, IEEE Trans. Appl. Supercond. 28 (3) (2018) 1–8.
[41] A. Zhou, J. Shi, Q. Dai, Z. Zhang, Z. Xia, X. Zhou, et al., The supplementary design method of HTS SMES system considering voltage distribution characteristic, IEEE Trans. Appl. Supercond. 27 (4) (2017) 1–5.
[42] Y. Xu, L. Ren, Y. Tang, C. Xu, Z. Zhang, W. Chen, et al., A study on the design and comparison of 1–100-MJ-class SMES magnet with different coil configurations, IEEE Trans. Appl. Supercond. 27 (5) (2017) 1–9.
[43] J. Ciceron, A. Badel, P. Tixador, F. Forest, Design considerations for high-energy density SMES, IEEE Trans. Appl. Supercond. 27 (4) (2017) 1–5.
[44] A. Morandi, M. Fabbri, B. Gholizad, F. Grilli, F. Sirois, V.M.R. Zermeño, Design and comparison of a 1-MW/5-s HTS SMES with toroidal and solenoidal geometry, IEEE Trans. Appl. Supercond. 26 (4) (2016) 1–6.
[45] G. Lei, C. Liu, M. Jafari, J. Zhu, Y. Guo, Multilevel robust design optimization of a superconducting magnetic energy storage based on a benchmark study, IEEE Trans. Appl. Supercond. 26 (7) (2016) 1–5.
[46] R. Gupta, M. Anerella, P. Joshi, J. Higgins, S. Lalitha, W. Sampson, et al., Design, construction, and testing of a large-aperture high-field HTS SMES coil, IEEE Trans. Appl. Supercond. 26 (4) (2016) 1–8.
[47] S. Nomura, R. Shimada, H. Sato, T. Shintomi, Design study on pulsed power supplies for the J-PARC Main ring magnets using SMES, IEEE Trans. Appl. Supercond. 25 (3) (2015) 1–5.
[48] S. Nie, J. Shi, J. Deng, Y. Xu, L. Su, Y. Liu, et al., Quench detection design for HTS SMES, IEEE Trans. Appl. Supercond. 25 (3) (2015) 1–5.
[49] F. Trillaud, L.S. Cruz, Conceptual design of a 200-kJ 2G-HTS solenoidal μ-SMES, IEEE Trans. Appl. Supercond. 24 (3) (2014) 1–5.
[50] Q. Sun, Z. Zhang, L. Lin, Q. Qiu, D. Liu, G. Zhang, et al., Design method of SMES magnet considering inhomogeneous superconducting properties of YBCO tapes, IEEE Trans. Appl. Supercond. 24 (3) (2014) 1–5.
[51] Y. Saichi, D. Miyagi, M. Tsuda, A suitable design method of SMES coil for reducing superconducting wire usage considering maximum magnetic flux density, IEEE Trans. Appl. Supercond. 24 (3) (2014) 1–5.
[52] H. Zhang, Z. Nie, X. Xiao, R. Aggarwal, Q. Kang, M. Ainslie, et al., Design and simulation of SMES system using YBCO tapes for direct drive wave energy converters, IEEE Trans. Appl. Supercond. 23 (3) (2013) 5700704.
[53] K.P. Yi, J.S. Ro, S. Lee, J.K. Lee, K.C. Seong, K. Choi, et al., A design methodology for toroid-type SMES using analytical and finite-element method, IEEE Trans. Appl. Supercond. 23 (3) (2013) 4900404.
[54] T. Shintomi, T. Asami, G. Suzuki, N. Ota, T. Takao, Y. Makida, et al., Design study of MgB2 SMES coil for effective use of renewable energy, IEEE Trans. Appl. Supercond. 23 (3) (2013) 5700304.
[55] F. Jiao, Y. Tang, T. Jin, S. Zhou, T. Ge, Q. He, et al., Electromagnetic and thermal design of a conduction-cooling 150 kJ/100 kW hybrid SMES system, IEEE Trans. Appl. Supercond. 23 (3) (2013) 5701404.
[56] N. Amaro, J.M. Pina, J. Martins, J.M. Ceballos, A. Álvarez, A fast algorithm for initial design of HTS coils for SMES applications, IEEE Trans. Appl. Supercond. 23 (3) (2013) 4900104.
[57] A.H.K. Asadi, A. Jahangiri, M. Zand, M. Eskandari, M.A. Nasab, H. Meyar-Naimi, Optimal Design of High Density HTS-SMES Step-Shaped Cross- Sectional Solenoid to mechanical stress reduction, in: 2022 International Conference on Protection and Automation of Power Systems (IPAPS) 16, 2022, pp. 1–6.
[58] X.Y. Chen, J.X. Jin, X. Zhou, Y.G. Guo, J.G. Zhu, Y. Xin, et al., Design and experiment of a bridge-type chopper for low-voltage SMES application, in: 2013 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, 2013, pp. 1–2.
[59] A. Dolan, F. Stefanescu, Optimization of modular toroid coil geometry of a superconducting magnetic energy storage device using design of experiments and FEM, in: 2014 International Conference on Applied and Theoretical Electricity (ICATE), 2014, pp. 1–7.
[60] Y.J. Feng, L. Zeng, Y. Chen, X.D. Liu, Y. Liu, Q. Xie, et al., Structural design and test of a solenoidal SMES magnet, in: 2018 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), 2018, pp. 1–2.
[61] F. Jiakun, Z. Chen, S. Chi, Y. Wei, J. Wen, Design of anti-windup compensator for superconducting magnetic energy storage, in: 2013 IEEE Power & Energy Society General Meeting, 2013, pp. 1–5.
[62] M. Xue, T. Wang, Y. Hou, H. Wang, Y. Du, J. Chen, Monitoring and protection system design for high temperature SMES, in: 2019 22nd International Conference on Electrical Machines and Systems (ICEMS), 2019, pp. 1–4.
[63] Sonia, A.K. Dahiya, Superconducting magnetic energy storage coupled static compensator for stability enhancement of the doubly fed induction generator integrated system, J. Energy Storage 44 (2021) 103232.
[64] J. Li, M. Zhang, J. Zhu, Q. Yang, Z. Zhang, W. Yuan, Analysis of superconducting magnetic energy storage used in a submarine HVAC cable based offshore wind system, Energy Procedia 75 (2015) 691–696.
[65] J. Zhu, P. Chen, C. Gu, H. Zhang, J. Li, H. Zhang, et al., Techno-economic analysis of MJ class high temperature superconducting magnetic energy storage (SMES) systems applied to renewable power grids, Glob. Energy Interconnect. 1 (2) (2018) 172–178.
[66] H.M. Hasanien, R.A. Turky, M. Tostado-Véliz, S.M. Muyeen, F. Jurado, Enhanced block-sparse adaptive bayesian algorithm based control strategy of superconducting magnetic energy storage units for wind farms power ripple minimization, J. Energy Storage 50 (2022), 104208.
[67] J.X. Jin, J. Wang, R.H. Yang, T.L. Zhang, S. Mu, Y.J. Fan, et al., A superconducting magnetic energy storage with dual functions of active filtering and power fluctuation suppression for photovoltaic microgrid, J. Energy Storage 38 (2021), 102508.
[68] A. Mitra, D. Chatterjee, A sensitivity based approach to study the stability of the power systems integrated with wind farm and superconducting magnetic energy storage, IFAC-PapersOnLine 48 (30) (2015) 560–565.
[69] M.M. Aly, M. Abdel-Akher, S.M. Said, T. Senjyu, A developed control strategy for mitigating wind power generation transients using superconducting magnetic energy storage with reactive power support, Int. J. Electr. Power Energy Syst. 83 (2016) 485–494.
[70] M.M. Aly, E.A. Mohamed, H.S. Salama, S.M. Said, M. Abdel-Akher, Y. Qudaih, A developed voltage control strategy for unbalanced distribution system during wind speed gusts using SMES, Energy Procedia 100 (2016) 271–279.
[71] A.P. Antony, D.T. Shaw, Empowering the electric grid: can SMES coupled to wind turbines improve grid stability? Renew. Energy 89 (2016) 224–230.
[72] M. Elshiekh, A. Elwakeel, S. Venuturumilli, H. Alafnan, X. Pei, M. Zhang, et al., Utilising SMES-FCL to improve the transient behaviour of a doubly fed induction generator DC wind system, Int. J. Electr. Power Energy Syst. 131 (2021), 107099.
[73] M. Hashem, M. Abdel-Salam, M.T. El-Mohandes, M. Nayel, M. Ebeed, Optimal placement and sizing of wind turbine generators and superconducting magnetic energy storages in a distribution system, J. Energy Storage 38 (2021), 102497.
[74] M. Hashem, M. Abdel-Salam, M. Nayel, M.T. El-Mohandes, A bi-level optimizer for reliability and security assessment of a radial distribution system supported by wind turbine generators and superconducting magnetic energy storages, J. Energy Storage 51 (2022), 104356.
[75] J.X. Jin, R.H. Yang, R.T. Zhang, Y.J. Fan, Q. Xie, X.Y. Chen, Combined low voltage ride through and power smoothing control for DFIG/PMSG hybrid wind energy conversion system employing a SMES-based AC-DC unified power quality conditioner, Int. J. Electr. Power Energy Syst. 128 (2021), 106733.
[76] A. Komijani, M. Sedighizadeh, M. Kheradmandi, Improving fault ride-through in meshed microgrids with wind and PV by virtual synchronous generator with SFCL and SMES, J. Energy Storage 50 (2022), 103952.

[77] K.M. Kotb, M.F. Elmorshedy, H.S. Salama, A. Dán, Enriching the stability of solar/wind DC microgrids using battery and superconducting magnetic energy storage based fuzzy logic control, J. Energy Storage 45 (2022), 103751.
[78] E.A. Mohamed, E. Gouda, Y. Mitani, Impact of SMES integration on the digital frequency relay operation considering high PV/wind penetration in micro-grid, Energy Procedia 157 (2019) 1292–1304.
[79] P. Mukherjee, V.V. Rao, Effective location of SMES for power fluctuation mitigation of grid connected doubly fed induction generator, J. Energy Storage 29 (2020), 101369.
[80] S.M. Muyeen, H.M. Hasanien, A. Al-Durra, Transient stability enhancement of wind farms connected to a multi-machine power system by using an adaptive ANN-controlled SMES, Energy Convers. Manag. 78 (2014) 412–420.
[81] Z. Rafiee, S.S. Najafi, M. Rafiee, M.R. Aghamohammadi, M. Pourgholi, Optimized control of coordinated series resistive limiter and SMES for improving LVRT using TVC in DFIG-base wind farm, Phys. C 570 (2020) 1353607.
[82] H.S. Salama, I. Vokony, Comparison of different electric vehicle integration approaches in presence of photovoltaic and superconducting magnetic energy storage systems, J. Clean. Prod. 260 (2020), 121099.
[83] M. Sedighizadeh, H. Yarmohammadi, M. Esmaili, Enhancing FRT performance and smoothing output power of DFIG wind farm equipped by SFCL and SMES in a fuzzy framework, Eng. Sci. Technology 22 (3) (2019) 801–810.
[84] X. Wang, J. Yang, X. Zhang, X. Yu, An action dependent heuristic dynamic programming-controlled superconducting magnetic energy storage for transient stability augmentation, Phys. Procedia 65 (2015) 286–290.
[85] Y. Zhai, J. Zhang, Z. Tan, X. Liu, B. Shen, T. Coombs, et al., Research on the application of superconducting magnetic energy storage in the wind power generation system for smoothing wind power fluctuations, IEEE Trans. Appl. Supercond. 31 (5) (2021) 1–5.
[86] A.M.S. Yunus, A. Abu-Siada, M.I. Mosaad, H. Albalawi, M. Aljohani, J.X. Jin, Application of SMES Technology in Improving the performance of a DFIG-WECS connected to a weak grid, IEEE Access 9 (2021) 124541–124548.
[87] Q. Xie, Z. Zheng, X. Xiao, C. Huang, J. Zheng, J. Ren, Enhancing HVRT capability of DFIG-based wind farms using cooperative rotor-side SMES considering the blocking fault of LCC-HVDC system, CSEE J. Power Energy Syst. 7 (4) (2021) 698–707.
[88] J. Ren, X. Xiao, Z. Zheng, Z. Ma, A SMES-based dynamic current limiter to improve the LVRT capability of DFIG-based WECS, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–5.
[89] H. Peng, L. Luan, Z. Xu, W. Mo, Y. Wang, Event-triggered mechanism based control method of SMES to improve microgrids stability under extreme conditions, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–4.
[90] J. Pahasa, I. Ngamroo, Two-stage optimization based on SOC control of SMES installed in hybrid wind/PV system for stabilizing voltage and power fluctuations, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–5.
[91] A.M.S. Yunus, A. Abu-Siada, M.A.S. Masoum, M.F. El-Naggar, J.X. Jin, Enhancement of DFIG LVRT capability during extreme short-wind gust events using SMES technology, IEEE Access 8 (2020) 47264–47271.
[92] X. Xiao, R. Yang, Z. Zheng, Y. Wang, Cooperative rotor-side SMES and transient control for improving the LVRT capability of grid-connected DFIG-based wind farm, IEEE Trans. Appl. Supercond. 29 (2) (2019) 1–5.
[93] M.N. Musarrat, M.R. Islam, K.M. Muttaqi, 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 Trans. Appl. Supercond. 29 (2) (2019) 1–6.
[94] P. Mukherjee, V.V. Rao, Superconducting magnetic energy storage for stabilizing grid integrated with wind power generation systems, J. Modern Power Syst. Clean Energy 7 (2) (2019) 400–411.
[95] C. Huang, X.Y. Xiao, Z. Zheng, Y. Wang, Cooperative control of SFCL and SMES for protecting PMSG-based WTGs under grid faults, IEEE Trans. Appl. Supercond. 29 (2) (2019) 1–6.
[96] L. Chen, G. Li, H. Chen, Y. Tao, X. Tian, X. Liu, et al., Combined use of a resistive SFCL and DC-link regulation of a SMES for FRT enhancement of a DFIG wind turbine under different faults, IEEE Trans. Appl. Supercond. 29 (2) (2019) 1–8.
[97] M.E. Elshiekh, D.A. Mansour, M. Zhang, W. Yuan, H. Wang, M. Xie, New technique for using SMES to limit fault currents in wind farm power systems, IEEE Trans. Appl. Supercond. 28 (4) (2018) 1–5.
[98] I. Ngamroo, Optimization of SMES-FCL for augmenting FRT performance and smoothing output power of grid-connected DFIG wind turbine, IEEE Trans. Appl. Supercond. 26 (7) (2016) 1–5.
[99] I. Ngamroo, T. Karaipoom, Improving low-voltage ride-through performance and alleviating power fluctuation of DFIG wind turbine in DC microgrid by optimal SMES with fault current limiting function, IEEE Trans. Appl. Supercond. 24 (5) (2014) 1–5.
[100] I. Ngamroo, T. Karaipoom, Cooperative control of SFCL and SMES for enhancing fault ride through capability and smoothing power fluctuation of DFIG wind farm, IEEE Trans. Appl. Supercond. 24 (5) (2014) 1–4.
[101] H.M. Hasanien, A set-membership affine projection algorithm-based adaptive-controlled SMES units for wind farms output power smoothing, IEEE Trans. Sustain. Energy 5 (4) (2014) 1226–1233.
[102] A.M.S. Yunus, A. Abu-Siada, M.A.S. Masoum, Application of SMES unit to improve DFIG power dispatch and dynamic performance during intermittent misfire and fire-through faults, IEEE Trans. Appl. Supercond. 23 (4) (2013) 5701712.
[103] Z. Wang, B. Yuwen, Y. Lang, M. Cheng, Improvement of operating performance for the wind farm with a novel CSC-type wind turbine-SMES hybrid system, IEEE Trans. Power Delivery 28 (2) (2013) 693–703.
[104] S. Kim, B. Kang, S. Bae, J. Park, Application of SMES and grid code compliance to wind/photovoltaic generation system, IEEE Trans. Appl. Supercond. 23 (3) (2013) 5000804.
[105] S.M. Said, M.M. Aly, M. Abdel-Akher, B. Hartmann, Voltage control of large-scale distribution systems during wind speed transients using SMES, in: 2020 International Conference on Innovative Trends in Communication and Computer Engineering (ITCE), 2020, pp. 391–396.
[106] J. Ren, W. Hu, C. Li, An interline SMES to improve power quality of the distributed wind generation system, in: 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), 2020, pp. 1–2.
[107] J. Pahasa, I. Ngamroo, Adaptive Output Power Smoothing of Grid-Connected Hybrid Wind-Photovoltaic by SMES, in: 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), 2020, pp. 1–2.
[108] L. Chen, X. Zhang, P. Han, H. Chen, Y. Xu, L. Ren, et al., Optimization of SMES-battery hybrid energy storage system for wind power smoothing, in: 2020 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), 2020, pp. 1–2.
[109] Z. Tan, Y. Zhai, F. Wang, Research on improving the operation stability of wind farms connected to power grid by using VSC-HVDC containing SMES, in: 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), 2019, pp. 1873–1877.
[110] E.F. Shaaban, A.E.W. Hassan, D.E.A. Mansour, Using SMES for voltage stabilization of PMSG based wind energy system, in: 2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE), 2019, pp. 181–185.
[111] H.S. Salama, M.M. Aly, I. Vokony, Voltage/frequency control of isolated unbalanced radial distribution system fed from intermittent wind/PV power using fuzzy logic controlled-SMES, in: International Conference on Innovative Trends in Computer Engineering (ITCE) 2019, 2019, pp. 414–419.
[112] M.H. Qais, H.M. Hasanien, S. Alghuwainem, M.A. Elgendy, Output power smoothing of grid-tied PMSG-based variable speed wind turbine using optimal controlled SMES, in: 2019 54th International Universities Power Engineering Conference (UPEC), 2019, pp. 1–6.
[113] W. Gil-González, A. Garcés, O.D. Montoya, Mitigating fluctuations of wind power generation using superconducting magnetic energy storage: a passivity-based approach, in: 2019 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC), 2019, pp. 1–6.
[114] R. Yang, X. Xiao, Z. Zheng, C. Li, Integrated DFIG-based wind farm protection with rotor-side SMES and advanced control under grid faults, in: IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD) 2018, 2018, pp. 1–2.
[115] S.M. Said, A. Selim, B. Hartmann, Enhancement of voltage profile for unbalanced distribution system with wind energy and superconducting magnetic energy storage, in: 2018 International Conference on Innovative Trends in Computer Engineering (ITCE), 2018, pp. 289–295.
[116] S.M. Said, M.M. Aly, B. Hartmann, Application of SMES for voltage control of power systems with high wind power penetration, in: 2018 International Conference on Innovative Trends in Computer Engineering (ITCE), 2018, pp. 461–466.
[117] P. Mukherjee, V.V. Rao, Fuzzy logic controlled superconducting magnetic energy storage for leveling power fluctuation of grid connected wind generator, in: 2018 International Conference on Power Energy, Environment and Intelligent Control (PEEIC), 2018, pp. 665–669.
[118] E.A. Mohamed, S.M. Said, B. Hartmann, Y. Mitani, An efficient fuzzy logic controlled-SMES for isolated-microgrid system considering high wind power penetration, in: 2018 5th International Conference on Electric Power and Energy Conversion Systems (EPECS), 2018, pp. 1–6.
[119] G. Magdy, E.A. Mohamed, G. Shabib, A.A. Elbaset, Y. Mitani, Enhancement LFC of a realistic multi-source power system concerning wind farms using SMES and new optimized PID controller, in: 2018 5th International Conference on Electric Power and Energy Conversion Systems (EPECS), 2018, pp. 1–7.
[120] H. Jiang, C. Zhang, Coordinated control scheme for superconducting magnetic energy storage unit to boost transient stability of wind farm connected power system, in: IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD) 2018, 2018, pp. 1–2.
[121] S.M. Said, M.M. Aly, M. Abdel-Akher, Application of superconducting magnetic energy storage (SMES) for voltage sag/swell supression in distribution system with wind power penetration, in: 2014 16th International Conference on Harmonics and Quality of Power (ICHQP), 2014, pp. 92–96.
[122] A. Mitra, D. Chatterjee, Stability enhancement of wind farm connected power system using superconducting magnetic energy storage unit, in: Eighteenth National Power Systems Conference (NPSC) 2014, 2014, pp. 1–6.
[123] W. Yao, L. Jiang, J. Fang, J. Wen, S. Cheng, Q.H. Wu, Adaptive power oscillation damping controller of superconducting magnetic energy storage device for interarea oscillations in power system, Int. J. Electr. Power Energy Syst. 78 (2016) 555–562.
[124] S. Chaine, M. Tripathy, Design of an optimal SMES for automatic generation control of two-area thermal power system using cuckoo search algorithm, J. Electr. Syst. Information Technol. 2 (1) (2015) 1–13.
[125] M. Farahani, S. Ganjefar, Solving LFC problem in an interconnected power system using superconducting magnetic energy storage, Phys. C 487 (2013) 60–66.
[126] W. Gil-González, O.D. Montoya, Active and reactive power conditioning using SMES devices with PMW-CSC: a feedback nonlinear control approach, Ain Shams Eng. J. 10 (2) (2019) 369–378.
[127] W. Gil-González, O.D. Montoya, A. Garces, Control of a SMES for mitigating subsynchronous oscillations in power systems: a PBC-PI approach, J. Energy Storage 20 (2018/12/01/ 2018.) 163–172.

[128] J. Zhu, M. Qiu, B. Wei, H. Zhang, X. Lai, W. Yuan, Design, dynamic simulation and construction of a hybrid HTS SMES (high-temperature superconducting magnetic energy storage systems) for Chinese power grid, Energy 51 (2013) 184–192.
[129] J. Wang, S. Mu, Q. Zhou, Y.J. Li, T.L. Zhang, Design and performance analysis of PV-SMES-based microgrid integrated with power fluctuation suppression and active filtering control, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–5.
[130] S.M. Said, A. Ali, B. Hartmann, Tie-line power flow control method for grid-connected microgrids with SMES based on optimization and fuzzy logic, J. Modern Power Syst. Clean Energy 8 (5) (2020) 941–950.
[131] A.M.S. Yunus, I. Habriansyah, A. Abu-Siada, M.A.S. Masoum, Sag and flicker reduction using hysteresis-fuzzy control-based SMES unit, Can. J. Electr. Comput. Eng. 42 (1) (2019) 52–57.
[132] S.M. Said, M. Aly, B. Hartmann, A.G. Alharbi, E.M. Ahmed, SMES-based fuzzy logic approach for enhancing the reliability of microgrids equipped with PV generators, IEEE Access 7 (2019) 92059–92069.
[133] J. Liu, H. Zhang, Y. Zhang, Coordinated control strategy of scalable superconducting magnetic energy storage, IEEE Trans. Smart Grid 9 (3) (2018) 1778–1786.
[134] Y. Tang, C. Mu, H. He, SMES-based damping controller design using fuzzy-GrHDP considering transmission delay, IEEE Trans. Appl. Supercond. 26 (7) (2016) 1–6.
[135] I. Ngamroo, S. Vachirasricirikul, Design of Optimal SMES controller considering SOC and robustness for microgrid stabilization, IEEE Trans. Appl. Supercond. 26 (7) (2016) 1–5.
[136] I. Ngamroo, S. Vachirasricirikul, Optimized SFCL and SMES units for multimachine transient stabilization based on kinetic energy control, IEEE Trans. Appl. Supercond. 23 (3) (2013) 5000309.
[137] M.Y. Zargar, M. Mufti, S.A. Lone, Voltage and frequency control of a hybrid wind-diesel system using SVC and predictively controlled SMES, in: 2017 6th International Conference on Computer Applications In Electrical Engineering-Recent Advances (CERA), 2017, pp. 25–30.
[138] A.H.M.A. Rahim, M.H. Khan, An adaptive optimum SMES controller for a PMSG wind generation system, in: 2013 IEEE Power & Energy Society General Meeting, 2013, pp. 1–5.
[139] M. Anju, R. Rajasekaran, Co-ordination of SMES with STATCOM for mitigating SSR and damping power system oscillations in a series compensated wind power system, in: 2013 International Conference on Computer Communication and Informatics, 2013, pp. 1–6.
[140] K. Iyswarya Annapoorani, V. Rajaguru, S. Anantha Padmanabhan, K. Manoj Kumar, S. Venkatachalam, Fuzzy logic-based integral controller for load frequency control in an isolated micro-grid with superconducting magnetic energy storage unit, Mater. Today: Proc. 58 (2022) 244–250.
[141] M. Elsisi, M. Soliman, M.A.S. Aboelela, 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, J. Energy Storage 12 (2017) 311–318.
[142] M. Farhadi Kangarlu, M.R. Alizadeh Pahlavani, Cascaded multilevel converter based superconducting magnetic energy storage system for frequency control, Energy 70 (2014) 504–513.
[143] N.J.V. Kumar, M.M. Thameem Ansari, A new design of dual-mode type-II fuzzy logic load frequency controller for interconnected power systems with parallel AC–DC tie-lines and superconducting magnetic energy storage unit, Energy 89 (2015) 118–137.
[144] M. Nandi, C.K. Shiva, V. Mukherjee, Frequency stabilization of multi-area multi-source interconnected power system using TCSC and SMES mechanism, J. Energy Storage 14 (2017/12/01/ 2017.) 348–362.
[145] S. Bae, S.U. Jeon, J.-W. Park, A study on optimal sizing and control for hybrid energy storage system with SMES and battery, IFAC-PapersOnLine 48 (30) (2015) 507–511.
[146] N. Bizon, Effective mitigation of the load pulses by controlling the battery/SMES hybrid energy storage system, Appl. Energy 229 (2018) 459–473.
[147] J. Li, A.M. Gee, M. Zhang, W. Yuan, Analysis of battery lifetime extension in a SMES-battery hybrid energy storage system using a novel battery lifetime model, Energy 86 (2015) 175–185.
[148] J. Li, Q. Yang, F. Robinson, F. Liang, M. Zhang, W. Yuan, Design and test of a new droop control algorithm for a SMES/battery hybrid energy storage system, Energy 118 (2017) 1110–1122.
[149] E.-L. Molina-Ibáñez, E. Rosales-Asensio, C. Pérez-Molina, F.M. Pérez, A. Colmenar-Santos, Analysis on the electric vehicle with a hybrid storage system and the use of superconducting magnetic energy storage (SMES), Energy Rep. 7 (2021) 854–873.
[150] M. Sander, F. Brighenti, R. Gehring, T. Jordan, M. Klaeser, D. Kraft, et al., LIQHYSMES – Liquid H2 and SMES for renewable energy applications, International Journal of Hydrogen Energy 39 (23) (2014) 12007–12017.
[151] M. Sedighizadeh, M. Esmaili, H. Parvaneh, Coordinated optimization and control of SFCL and SMES for mitigation of SSR using HBB-BC algorithm in a fuzzy framework, J. Energy Storage 18 (2018) 498–508.
[152] Q. Sun, D. Xing, H. Alafnan, X. Pei, M. Zhang, W. Yuan, Design and test of a new two-stage control scheme for SMES-battery hybrid energy storage systems for microgrid applications, Appl. Energy 253 (2019/11/01/ 2019.), 113529.
[153] Q. Sun, D. Xing, Q. Yang, H. Zhang, J. Patel, A new Design of Fuzzy Logic Control for SMES and battery hybrid storage system, Energy Procedia 105 (2017) 4575–4580.
[154] B. Yang, T. Zhu, X. Zhang, J. Wang, H. Shu, S. Li, et al., Design and implementation of Battery/SMES hybrid energy storage systems used in electric vehicles: a nonlinear robust fractional-order control approach, Energy 191 (2020), 116510.
[155] Y. Zhou, C. Ji, Z. Dong, S. Zhang, Cooperative control of SFCL and SMES-battery HESS for mitigating effect of ground faults in DC microgrids, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–5.
[156] Q. Xie, R.B. Zhao, M.G. Tang, S.Y. Hu, H.Y. Xu, X.S. Tan, et al., A DC voltage sag compensator based on SMES-battery hybrid energy storage, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–5.
[157] Y.H. Wang, S.J. Hu, Y.Y. Song, Q. Zeng, Z.S. Zheng, Robust co-planning of transmission network and B-SMES, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–4.
[158] Q. Sun, H. Lv, S. Wang, S. Gao, K. Wei, Optimized state of charge estimation of lithium-ion battery in SMES/Battery hybrid energy storage system for electric vehicles, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–6.
[159] T. Li, Y. Chen, H.Y. Gou, X.Y. Chen, M.G. Tang, Y. Lei, A DC voltage swell compensator based on SMES emulator and Lead-acid battery, IEEE Trans. Appl. Supercond. 29 (2) (2019) 1–4.
[160] Z. Zheng, X. Xiao, X. Chen, C. Huang, L. Zhao, C. Li, Performance evaluation of a MW-class SMES-BES DVR system for mitigation of voltage quality disturbances, IEEE Trans. Ind. Appl. 54 (4) (2018) 3090–3099.
[161] H. Alafnan, M. Zhang, W. Yuan, J. Zhu, J. Li, M. Elshiekh, et al., Stability improvement of DC power systems in an all-electric ship using hybrid SMES/battery, IEEE Trans. Appl. Supercond. 28 (3) (2018) 1–6.
[162] Z. Zheng, X. Chen, X. Xiao, C. Huang, Design and evaluation of a mini-size SMES magnet for hybrid energy storage application in a kW-class dynamic voltage restorer, IEEE Trans. Appl. Supercond. 27 (7) (2017) 1–11.
[163] X. Lin, Y. Lei, Coordinated control strategies for SMES-battery hybrid energy storage systems, IEEE Access 5 (2017) 23452–23465.
[164] A.M. Gee, F. Robinson, W. Yuan, A superconducting magnetic energy storage-emulator/battery supported dynamic voltage restorer, IEEE Trans. Energy Convers. 32 (1) (2017) 55–64.
[165] J. Li, M. Zhang, Q. Yang, Z. Zhang, W. Yuan, SMES/Battery hybrid energy storage system for electric buses, IEEE Trans. Appl. Supercond. 26 (4) (2016) 1–5.
[166] H.S. Salama, S.M. Said, I. Vokony, B. Hartmann, Adaptive coordination strategy based on fuzzy control for electric vehicles and superconducting magnetic energy storage—towards reliably operating utility grids, IEEE Access 9 (2021) 61662–61670.
[167] Z. Li, S. Chen, B. Zhou, Electric vehicle peer-to-peer energy trading model based on SMES and blockchain, IEEE Trans. Appl. Supercond. 31 (8) (2021) 1–4.
[168] M.A. Sheba, D.A. Mansour, A.M. Azmy, Mitigating the Impact of Electric Vehicles Integration to DC Microgrids through Using SMES, in: 2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE), 2019, pp. 238–243.
[169] H.S. Salama, I. Vokony, Application of controlled SMES with integrating PV system and electric vehicles into power system, in: 2019 7th International Youth Conference on Energy (IYCE), 2019, pp. 1–6.
[170] Y.Q. Xing, J.X. Jin, Y.L. Wang, B.X. Du, S.C. Wang, An electric vehicle charging system using an SMES implanted smart grid, IEEE Trans. Appl. Supercond. 26 (7) (2016) 1–4.
[171] S.C. Wang, J.X. Jin, Y.L. Wang, SMES effect in a smart grid with electric vehicles, in: 2015 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices (ASEMD), 2015, pp. 530–531.
[172] J.X. Jin, X.Y. Chen, L. Wen, S.C. Wang, Y. Xin, Cryogenic power conversion for SMES application in a liquid hydrogen powered fuel cell electric vehicle, IEEE Trans. Appl. Supercond. 25 (1) (2015) 1–11.
[173] H. Alafnan, M. Elshiekh, X. Pei, S. Altouq, S.M. Fazeli, Q. Sun, et al., Application of SMES-FCL in electric aircraft for stability improvement, IEEE Trans. Appl. Supercond. 29 (5) (2019) 1–6.
[174] S.M. Said, H.S. Salama, B. Hartmann, I. Vokony, A robust SMES controller strategy for mitigating power and voltage fluctuations of grid-connected hybrid PV–wind generation systems, Electr. Eng. 101 (3) (2019/09/01 2019.) 1019–1032.
[175] D.K. Mishra, T.K. Panigrahi, A. Mohanty, P.K. Ray, Effect of superconducting magnetic energy storage on two agent deregulated power system under open market, Mater. Today: Proc. 21 (2020) 1919–1929.
[176] SS, SB, Optimal size allocation of superconducting magnetic energy storage system based unit commitment, J. Energy Storage 20 (2018) 173–189.
[177] T. Kinjo, T. Senjyu, N. Urasaki, H. Fujita, Terminal-voltage and output-power regulation of wind-turbine generator by series and parallel compensation using SMES, IET Gener. Transm. Distrib. 153 (3) (2006) 276–282.
[178] K. Zhang, C. Mao, J. Lu, D. Wang, X. Chen, J. Zhang, Optimal control of state-of-charge of superconducting magnetic energy storage for wind power system, IET Renew. Power Generation 8 (1) (2014) 58–66.
[179] S. Dechanupaprittha, K. Hongesombut, M. Watanabe, Y. Mitani, I. Ngamroo, Stabilization of tie-line power flow by robust SMES controller for interconnected power system with wind farms, IEEE Trans. Appl. Supercond. 17 (2) (2007) 2365–2368.
[180] M.H. Qais, H.M. Hasanien, S. Alghuwainem, Output power smoothing of wind power plants using self-tuned controlled SMES units, Electr. Power Syst. Res. 178 (2020/01/01/ 2020.), 106056.
[181] G. Magdy, G. Shabib, A.A. Elbaset, Y. Mitani, Optimized coordinated control of LFC and SMES to enhance frequency stability of a real multi-source power system considering high renewable energy penetration, Protection and Control of Modern Power Systems 3 (1) (2018) 39.
[182] M.H. Ali, M. Park, I.K. Yu, T. Murata, J. Tamura, Improvement of wind-generator stability by fuzzy-logic-controlled SMES, IEEE Trans. Ind. Appl. 45 (3) (2009) 1045–1051.

[183] M.H. Ali, T. Murata, J. Tamura, A fuzzy logic-controlled superconducting magnetic energy storage for transient stability augmentation, IEEE Trans. Control Syst. Technol. 15 (1) (2007) 144–150.
[184] H.M. Hasanien, S.Q. Ali, S.M. Muyeen, Wind generator stability enhancement by using an adaptive artificial neural network-controlled superconducting magnetic energy storage, in: 2012 15th International Conference on Electrical Machines and Systems (ICEMS), 2012, pp. 1–6.
[185] A. Bakeer, H.S. Salama, I. Vokony, Integration of PV system with SMES based on model predictive control for utility grid reliability improvement, Protection and Control of Modern Power Systems 6 (1) (2021) 14.
[186] S. Nagaya, N. Hirano, T. Katagiri, T. Tamada, K. Shikimachi, Y. Iwatani, et al., The state of the art of the development of SMES for bridging instantaneous voltage dips in Japan, Cryogenics 52 (12) (2012) 708–712.
[187] A. Colmenar-Santos, E.-L. Molina-Ibáñez, E. Rosales-Asensio, J.-J. Blanes-Peiró, Legislative and economic aspects for the inclusion of energy reserve by a superconducting magnetic energy storage: application to the case of the spanish electrical system, Renew. Sust. Energ. Rev. 82 (2018/02/01/ 2018.) 2455–2470.
[188] EASE-EERA, European Energy Storage Technology Development Roadmap 2017 Update. https://ease-storage.eu/publication/ease-eera-energy-storage-technology-development-roadmap-2017/, 2017.
[189] M. Lott, S.-I. Kim, C. Tam, D. Elzinga, S. Heinen, L. Munuera, et al., Technology Roadmap: Energy Storage, International Energy Agency, 2014.
[190] B.G. Marchionini, Y. Yamada, L. Martini, H. Ohsaki, High-temperature superconductivity: a roadmap for electric power sector applications, 2015–2030, IEEE Trans. Appl. Supercond. 27 (4) (2017) 1–7.
[191] S. Nomura, T. Shintomi, S. Akita, T. Nitta, R. Shimada, S. Meguro, Technical and cost evaluation on SMES for electric power compensation, IEEE Trans. Appl. Supercond. 20 (3) (2010) 1373–1378.
[192] ICEF, Energy Storage Roadmap. https://www.icef.go.jp/pdf/summary/roadmap/icef2017_roadmap2.pdf, 2017.
[193] T. Saravanan, M. Sundar Raj, K. Gopalakrishnan, SMES technology, SMES and FACTS system, applications, advantages and technical limitations, Middle-East J. Sci. Res. 20 (11) (2014) 1353–1358.
[194] M.A. Zaman, S. Ahmed, N. Monira, An Overview of Superconducting Magnetic Energy Storage (SMES) and Its Applications, 2018.
[195] A. Kumar, J.V.M.L. Jeyan, A. Agarwal, Electromagnetic analysis on 2.5MJ high temperature superconducting magnetic energy storage (SMES) coil to be used in uninterruptible power applications, Mater. Today Proc. 21 (2020) 1755–1762.
[196] Y. Xu, L. Ren, Z. Zhang, Y. Tang, J. Shi, C. Xu, et al., Analysis of the loss and thermal characteristics of a SMES (Superconducting Magnetic Energy Storage) magnet with three practical operating conditions, Energy 143 (2018) 372–384.
[197] C. Hsu, W. Lee, Superconducting magnetic energy storage for power system applications, IEEE Trans. Ind. Appl. 29 (5) (1993) 990–996.
[198] M. Elmorshedy, M.M. Amin, F.F.M. El-Sousy, O.A. Mohammed, DC-bus voltage control of MPPT-based wind generation system using hybrid BESS-SMES system for pulse loads in ship power applications, in: 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 76–82.
[199] F. Hornung, M. Klaeser, P. Leys, T. Schneider, Construction and test of MgB2 mock-up coils for LIQHYSMES, IEEE Trans. Appl. Supercond. 26 (4) (2016) 1–5.
[200] M. Sander, R. Gehring, H. Neumann, LIQHYSMES—a 48 GJ toroidal MgB2-SMES for buffering minute and second fluctuations, IEEE Trans. Appl. Supercond. 23 (3) (2013) 5700505.