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Invited Review

Energy storage for black start services: A review

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Abstract: With the increasing deployment of renewable energy-based power generation plants, the power system is becoming increasingly vulnerable due to the intermittent nature of renewable energy, and a blackout can be the worst scenario. The current auxiliary generators must be upgraded to energy sources with substantially high power and storage capacity, a short response time, good profitability, and minimal environmental concern. Difficulties in the power restoration of renewable energy generators should also be addressed. The different energy storage methods can store and release electrical/thermal/mechanical energy and provide flexibility and stability to the power system. Herein, a review of the use of energy storage methods for black start services is provided, for which little has been discussed in the literature. First, the challenges that impede a stable, environmentally friendly, and cost-effective energy storage-based black start are identified. The energy storage-based black start service may lack supply resilience. Second, the typical energy storage-based black start service, including explanations on its steps and configurations, is introduced. Black start services with different energy storage technologies, including electrochemical, thermal, and electromechanical resources, are compared. Results suggest that hybridization of energy storage technologies should be developed, which mitigates the disadvantages of individual energy storage methods, considering the deployment of energy storage-based black start services.

Keywords: black start; renewable energy; electrochemical energy storage; thermal energy storage; electromechanical energy storage; hybrid energy storage

1. Introduction

With more than twelve decades of development, modern power systems are highly reliable, and numerous methods have been developed to maintain these systems within a safe operation margin [1–2]. Power systems have been undergoing a paradigm shift in configuration, from large conventional synchronous generation units to small distributed generation (DG) units [3]. Many DG units are powered by intermittent renewable resources, which pose a significant effect on various aspects of system operations, particularly dispatch and commitment processes. In addition, the risk of blackouts increases due to a high amount of renewable energy in the power system as well as unpredicted extreme weather conditions and human errors. These conditions can lead to a series of cascading failures, eventually causing major blackouts. The northeast blackout of 1965 in the United States and Canada was initially caused by the incorrect set of a protective relay, which eventually led to a significant disruption of the electricity supply. More than 30 million people in 8 provinces/states were left without electricity for 13 h [4]. Recent examples include the power outage on 9 August, 2019 in the UK [5] and the deadly power outage in Texas in February, 2021 [6].

A black start procedure must be implemented after the tripping to restore power. This procedure, as shown in Fig. 1, comprises the following three steps: (1) the black start provider starts its auxiliary generator to energize the main generator and establish a power island using local demand; (2) the black start provider energizes the transmission network to restore electricity supply to another nonblack start provider; (3) the black start and nonblack start providers progressively restore the demand across the system until full restoration is achieved.

Reliability councils and electricity system operators worldwide have all enacted regulations and standards to provide a guideline on the black start of power grids. The national grid electricity system operators (ESO) impose technical requirements for a qualified black start service. For example, the requirements from the national grid ESO in the

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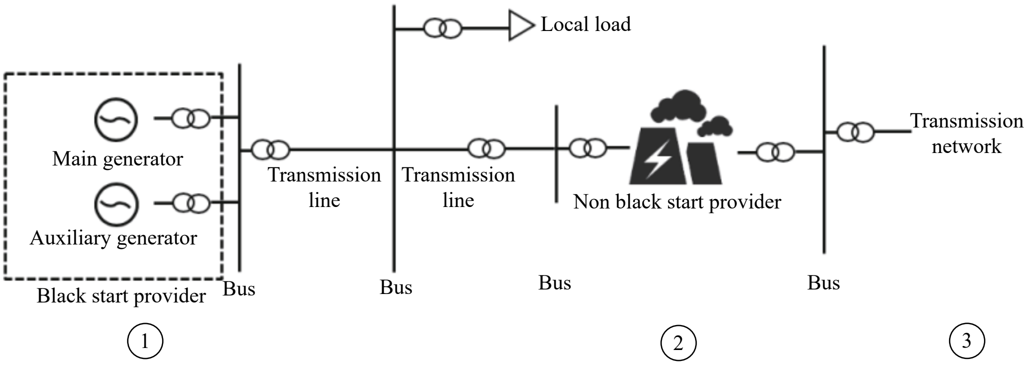

Fig. 1. Typical black start procedure.

UK are as follows: 2 h of connection time after receiving instruction, 20 MW of instantaneous loading, frequency range within 47.5 to 52 Hz, three sequential black starts in case of tripping, 10 h of resilience in supply, and 100 MV·A of reactive capacity [7].

Many countries have commonly chosen auxiliary gas turbines or auxiliary diesel engines as auxiliary black start generators. The Great Britain grid code [8] specifies that the initial power source in case of a blackout is from an auxiliary gas turbine or an auxiliary diesel engine. Limited work has been conducted on the upgrade of auxiliary generators, and the major current auxiliary generators have remained largely unchanged for many years mainly because these generators have a high technical maturity (gas turbines and diesel generators); hence, the drive for further research is lacking. However, these generators have a long response time, which may cause large spikes when started, leading to uncertainties to load recovery. The generators may not also provide sufficient power to the main load units, causing voltage and frequency fluctuations and hence failure of the black start. From an economic viewpoint, diesel engines and gas turbines are not cost-effective because their sole role is for black start and could not provide other grid services, such as frequency regulation and load shifting. In addition, despite their irregular use, these existing auxiliary generators utilize fossil fuels, which are not sustainable and incompatible with the net-zero energy future. Therefore, replacing the existing auxiliary generators with clean energy generators, such as electricity storage sources, is urgently needed.

Recent research interest in black start has been focused on the use of a high voltage direct current (HVDC) system or a microgrid to reduce restoration time and provide load pickup capability. For the studies on the HVDC, Li *et al.* [9] proposed a line-commutated converter HVDC system and showed a significant reduction in the recovery time compared with the conventional black start strategy of the Guangzhou power system. Xia *et al.* [10] investigated a frequency regulation strategy for an alternating current (AC)–direct current (DC) system and developed a validated model for the optimization of the HVDC transmission power with a minimized frequency deviation. In addition to the HVDC, the black start using microgrid has also been studied in recent years. The microgrid allows the integration of additional DG units into the power system through converter interfaces. Such a microgrid is enabled to operate in connection to the utility or islanded grid by implementing grid-following or grid-forming converter control [11]. In islanded applications, energy storage devices are usually expected to cover the power fluctuations from DG units [12]. These devices also offer the possibility to use microgrids for the black start and restoration of power systems [12–14]. That is, the reliability of the power supply can be increased by building local microgrids and performing an island operation during power system blackouts, and a bottom-up system restoration process can be performed. Che *et al.* [15] proposed the use of a microgrid to accelerate black start. Such a microgrid can be within the restoration path, which can be started in island mode to provide load. The microgrid can also help restore the low voltage distribution along with the conventional black start provider, energizing the high-voltage network using a hierarchical approach.

This paper focuses on the use of energy storage for the black start service, for which remarkably few studies have been found in the literature. Some literature review articles and research papers studying novel black start services are available. However, these studies are substantially related to integrations with renewable energy sources [16], HVDC systems [9], or microgrids [15]. Current challenges in the black start will be examined, and barriers to the upgrade of the black start provision will be identified. Perspectives in the use of electrochemical, electromechanical, and thermal energy storages for the provision of a black start service are then discussed to achieve a fast, reliable, efficient, and environmentally friendly black start.

2. Challenges in black starts for net-zero future

The energy landscape has dramatically changed globally over the last decade. In 2019, renewables supplied 38.4% of electricity in China, 37.4% of electricity in the UK, and 18.49% in the USA [17–19]. An increase in drastic changes will be observed while the world continues to move toward a net-zero energy future. All these changes will introduce additional challenges to the black start for the power grid.

First, with the high penetration of renewables (mainly from wind and solar), the intermittent fluctuation of renewable energy may induce considerable instability and uncertainty to the power grid, thus increasing the risk of blackouts. Therefore, various services of the power system must be upgraded to enhance the stability and security of the grid, including the black start service.

Second, the current black start strategy has been mainly dependent on conventional power generation methods. With the replacement of traditional power plants by renewable and nontraditional power plants, additional renewable energy-based black start power plants are also needed to replace the fossil fuel-based black start power plants. Compared with other traditional power generation methods, such as hydropower, renewable energy sources have substantially quick restoration time and can accelerate the load pickup when acting as the main generator during blackouts [20]. These characteristics can further help restore the transmission system, frequency control, and load pickup, eventually reestablishing the entire power system. Pagnani *et al.* [16] investigated the possibility of integrating offshore wind farms with black start service. A self-starter is essential for the system, which can be a synchronous generator or a power electronic unit. However, several barriers may slow down and even interrupt the black start procedure of renewable energy plants as main generators.

(1) The wind turbine will require auxiliary power with 5%–10% of its capacity for self-starting at the initial stage of the restoration. Meanwhile, the existing and planned wind farms normally do not have sufficient auxiliary power supply.

(2) Solar photovoltaic (PV) can only start during the daytime.

(3) Renewable energy may encounter resource uncertainty during restoration, which will reduce the capacity during the stage of powering nonblack start providers.

(4) The renewable energy suppliers, especially wind turbines, may not be able to cope with the frequency and voltage fluctuations of the connected island.

Energy storage can provide a solution to overcome these barriers and challenges. High power and energy capacity can be used as the auxiliary generator for renewable energy-based black start power plants. Moreover, this generator can potentially operate as a standalone black start power plant to deal with the grid blackout and improve the stability and reliability of the grid. However, the application of energy storage for black start shows considerable advantages and disadvantages compared with traditional black start methods. Battery energy storage technology is taken as an example herein for comparison.

Currently, the most promising battery storage technology has considerable advantages of operational cost reduction and immediate response. The Hornsdale Power Reserve of Tesla with 100 MW power and 129 MWh capacity was built in Australia for frequency control and ancillary services. The cost of frequency ancillary services was reportedly reduced by 90% compared with conventional energy sources [21]. The eight battery energy storage facilities for enhanced frequency response in the UK are expected to result in costs savings of approximately USD 262 million within four years [22]. Battery energy storage technology has remarkable potential for black start applications due to its excellent characteristics; however, this technology also has some shortcomings compared with conventional methods. The difference between the traditional black start based on diesel engine and the innovative black start based on battery storage has been detailed in Table 1. Comparison results indicate that the battery energy storage-based black start service has relatively low capacity in supply resilience (e.g., short restoration period) but shows advantages in grid formation, reactive power support, and frequency and voltage control.

Table 1. Comparison between the traditional black start (diesel and gas based) and innovative black start (based on battery energy storage) [7,23]

Type of black start service	Technical capability								
	Availability of black start service / %	Timescale to start up	Reactive capability to energize the network / Mvar	Capability for instantaneous loading / MW	Number of sequential black starts / times	Supply resilience of black start service / h	Supply resilience of black start auxiliary units / h	Voltage control / %	Frequency control / Hz
Traditional	≥90	≤2 h	≥100	≥35	≥3	≥10	≥72	±10	47.5–52
Battery energy storage based	≤80	Sub seconds	≥100	≥100	≥3	≤10	≤10	±10	47.5–52

3. Energy storage-based black start

3.1. Brief introduction to energy storage-based black start

The establishment of a reliable black start strategy is essential to the power grid. A typical power system restoration plan comprises three stages: preparation, system restoration, and load restoration (Fig. 2) [24]. In the first stage, the system status is analyzed, and a strategy is developed to black start the system. In the second stage, generators with black-start capability are started and then used to energize transmission lines and start other nonblack start generators. In the final stage, the system load is rapidly restored [25].

Energy storage systems usually have different operating objectives in the three black-start stages. These objectives usually focus on their static characteristics (rated capacity,

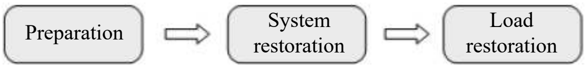

Fig. 2. Power system restoration plan.

stage of charge limits, and location) in the first stage. Energy storage systems are required to operate isochronously in the second stage. In addition to the specific black-starting control, a grid-forming control is also expected to establish a constant frequency and magnitude voltage source. Therefore, the frequency and voltage at the outlet bus of energy storage systems could be retained at the nominated values. The load pickup is programmed in the final load restoration stage, while any change in generation and load is impactful on a small system. Autonomous frequency and voltage controls are respectively required to ensure that frequencies and voltages are within acceptable operating limits, as shown in Fig. 3. In addition, sufficient operating reserves must be held to provide a buffer against load and generation changes and avoid a potential system collapse. While a parallel restoration approach is being designed after a global blackout, multiple black start capable units would be powered up simultaneously. These units help create several electrically isolated islands. Once these islands are stable and sufficiently large, their synchronization and interconnection are expected to be programmed to establish a complete and recovered grid. A synchronization control is needed in this course. The pairing of energy storage systems with DGs would be considerably appealing and promising to continue powering a microgrid even under a black main grid.

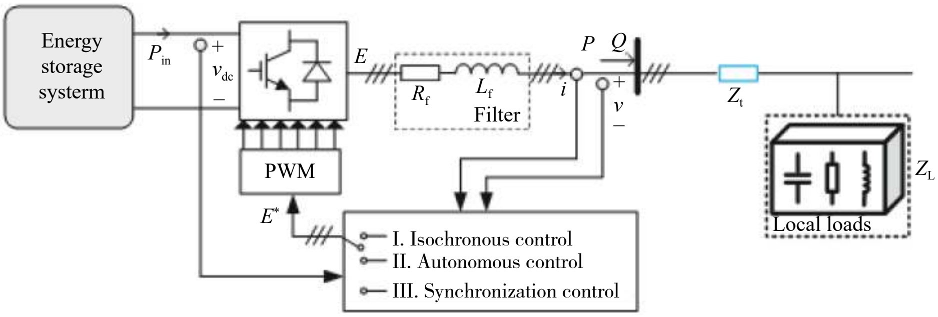

Fig. 3. Using a black-start capable energy storage system to power a local load. P_{in} represents the power fed from the energy storage system; v_{dc} denotes the DC-side voltage; E^* and E represent the reference and real value of the field voltage vector, respectively; v and i represent the terminal voltage and the current; P and Q are the active and reactive power delivery to the grid, respectively; R_f and L_f are the resistance and inductance of the filter, respectively; Z_t and Z_L represent the line and the load reactance, respectively; PWM is the shorthand of pulse width modulation.

The energy storage system can be located on either the generator or the grid side. Fig. 4 shows the two possible configurations of a black start system, in which the batteries and wind power are respectively used as examples of energy storage systems and renewable energy sources in the grid [26]. In mode 1, the energy storage systems are equipped close to renewable energy sources. Therefore, energy storage systems can stabilize the total output power and voltage fluctuation of renewable energy. In mode 2, the energy storage systems are established in the position of the grid-connected renewable energy sources. The energy storage systems in mode 2 can provide many functions, such as smooth output, plan tracking, automatic generation control, frequency modulation, peak load shifting, and black start.

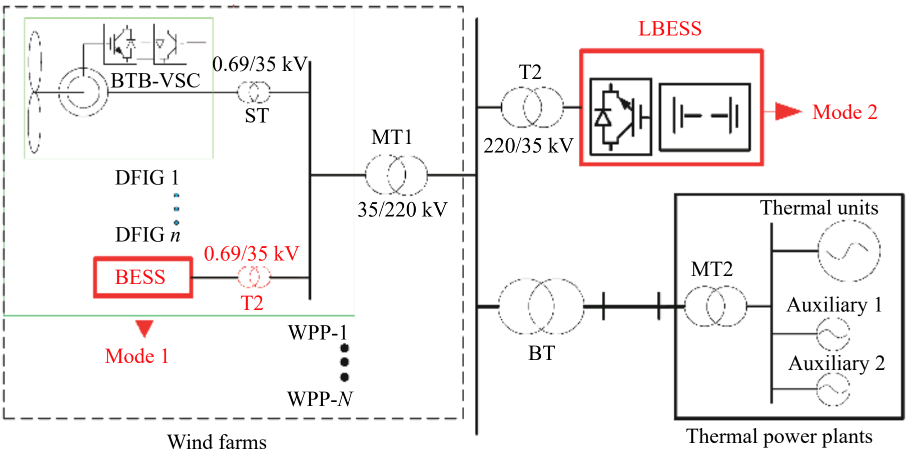

Fig. 4. Two configuration modes of energy storage participating in black start with wind power [26]. DFIG represents doubly fed induction generator, WPP represents wind power plant, BESS represents battery energy storage system, BTB-VSC represents back-to-back voltage-sourced converter, PCS represents power conditioning system, BS represents battery storage, LBESS represents lithium-based energy storage system, ST represents substation transformer, BT represents booster transformer, and MT represents medium voltage transformer.

3.2. Pumped hydro energy storage

Among several energy storage technologies, pumped hydro storage (PHS), which is a mature technology used for black start, currently accounts for over 90% of the global energy storage capacity [27]. A schematic of a typical PHS plant is shown in Fig. 5, which mainly comprises an upper reservoir, a lower reservoir for water, and a power generation unit with hydro turbines/pumps. Water is pumped into the upper reservoir when electricity demand is low. The accumulated water in the upper reservoir will be released to the lower reservoir when a black start is required, passing through the power station where the hydro turbine is turned on to provide power. A field test was conducted to check the performances of the governor and voltage regulator of the Taishan pumped storage plant (China), ensure the feasibility of the control strategy, and investigate the capability of providing black-start services without disturbing customers [28]. The test results showed that the generation efficiency of the pumped storage unit could only reach 16% during the black start process due to the very small load of 5% and the abnormal working condition of the unit.

Table 2 summarizes the major advantages and disadvantages of the PHS technology. The PHS can meet all technical requirements as a black start generator, providing fast responses, long periods, and reliable black starts. However, geographic restrictions limit the further deployment of the PHS. Many countries have already exhausted PHS sites due to the continuous construction of PHS plants over the past 100 years. The remaining sites for PHS encounter unprofitability problems and environmental concerns. Therefore, developing and deploying alternative energy storage technologies to provide black starts and other grid-related services is crucial. Other energy storage technologies include electrochemical (e.g., lithium-ion batteries (LIBs) and supercapacitors), mechanical (e.g., flywheel and weight lift), chemical (e.g., hydrogen, ammonia, and methanol), thermomechanical (e.g., compressed air and pumped thermal electrical), and thermal (e.g., sensible, latent, and thermochemical and liquid air energy storage) energy storages. These energy storage technologies are useful choices for meeting the black start requirements. Some of these technologies will be discussed in the following section.

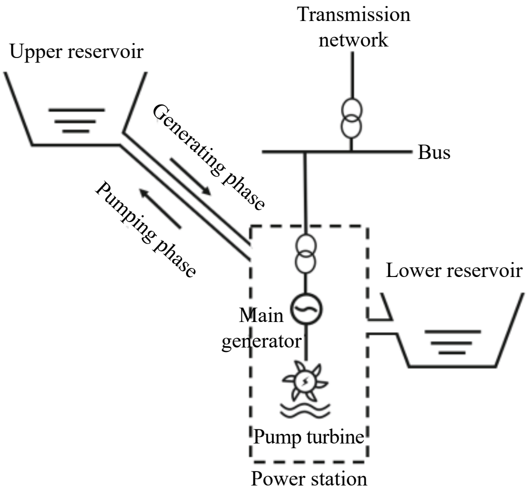

Fig. 5. Schematic of a conventional pumped hydro storage system with black start service.

Table 2. Advantages and disadvantages of pumped hydro energy storage for black start (data based on the Global Energy Storage Database [29])

Advantages	(1) High storage capacity (10 GWh level) and power capacity (GW level); (2) minute level response time; (3) long discharge time at rated power (days); (4) good round trip efficiency (70%–84%); (5) low self-discharge (cross season storage); (6) high depth of discharge (80%–100%); (7) long cycle life (~20000 cycles) [30]; (8) low capital cost (10 – 100 $/kWh); (9) high technical maturity.
Disadvantages	(1) Low energy density (0.1–2 Wh/L); (2) geographic restrictions.

3.3. Electrochemical energy storage

As one of the electrochemical energy storage methods, LIB has been popular due to their potential large-scale deployment in electric vehicles. In addition to the black start function, LIB can offer a wide range of applications, including active power services (frequency regulation, frequency response, and peak shaving) and reactive power services (voltage control, voltage droop, and power factor control). Around 600 MW battery energy storage utilities have been built in the UK and over 1 GW in the pipeline planning. LIB energy storage can efficiently operate as a power load to energize a transmission line at the initial stage of the black start. LIB can also optimize the power flow distribution and ancillary services, such as speed governors and excitation regulators of the generator [31]. Flow batteries, another electrochemical storage method, can also act as the "auxiliary generator" to initialize the black start process. The advantages and disadvantages of lithium-ion and flow batteries are respectively compared in Tables 3 and 4. LIB has a high energy density but a low storage capacity and some safety concerns. By contrast, flow batteries show a low energy density but have a large storage capacity, long asset life, and safe operation. Thus, LIB can deliver considerable amounts of energy in a short period, while flow batteries are effective in delivering a consistent amount of minimal energy over a long period (up to 10 h). The current market indicates the superiority of LIB because most of the recently deployed grid-scale electrochemical storage systems comprise LIB. Another electrochemical energy storage is the supercapacitor, which has the highest power density of 100 kW/L, approximately ten times that of LIB. The supercapacitor can only last a few seconds of discharge; thus, it is not ideal for the black start services (though it can be part of the solution) because the entire process normally takes hours.

Table 5 shows some examples of battery installations with several megawatt scales, which are claimed to have the capability for the black start. Two examples are located in America and are reported to have performed successful trials as the black start unit for a gas turbine. Fig. 6 schematically illustrates a battery energy storage system connected with a wind farm that can provide black start services. The battery system stores excess energy when available. The LIB starts to discharge once the black start is required to energize the transmission line and provide energy to start up the main generator.

Table 3. Advantages and disadvantages of the LIB energy storage system for black start (data based on the Global Energy Storage Database [29])

Advantages	(1) Good power capacity (500 MW level); (2) high energy density (200–600 Wh/L); (3) second level response time; (4) high round trip efficiency (>90%); (5) low self-discharge (cross season storage); (6) 80% depth of discharge; (7) acceptable capital cost (200–800 $/kWh for large scale); (8) good technical maturity.
Disadvantages	(1) Relatively low storage capacity (100 MWh level); (2) relatively short discharge time at rated power (minutes–hours); (3) relatively short cycle life (~4000 cycles) [32].

Table 4. Advantages and disadvantages of flow battery energy storage system for black start (data based on the Global Energy Storage Database [29])

Advantages	(1) Good energy density (20–70 Wh/L); (2) second level response time; (3) good discharge time at rated power (10 h); (4) good round trip efficiency (70%); (5) low self-discharge (cross season storage); (6) >90% depth of discharge; (7) good technical maturity; (8) good cycle life (~15000 cycles); (9) acceptable capital cost (300–1500 $/kWh).
Disadvantages	(1) Relatively low power capacity (100 MW level).

Table 5. Megawatt scale battery storage systems with black start capability

Country	Utility company/ state agency	Battery technology and provider	Power output / MW	Storage capacity / MWh	Successful demonstration of black start	Black start object	Ref.
America	Imperial Irrigation District	LIB-Samsung SDI	33	20	Yes	44 MW combined-cycle natural gas turbine	[33]
America	General Electric	LIB -Samsung SDI/LG	7.4	7.4	Yes	150 MW heavy-duty gas turbine gas turbine	[34]
America	IPL Advancion Energy Storage Array	LIB -Samsung SDI	20	20	—	—	[35]
America	IPL Advancion Energy Storage Array	LIB -Samsung SDI	20	20	—	—	[35]
Germany	RedoxWind	Vanadium Flow Batteries-Fraunhofer ICT	2	8	—	—	[36]
Germany	WEMAG	LIB -Samsung SDI	5	5	—	—	[37]
China	Rongke Power	Vanadium Flow Batteries-UniEnergy Technologies	200	800	—	—	[38]

Reports on commercial applications of electrochemical battery storage systems to provide the black start of renewable energy systems are limited; thus, these applications have attracted considerable research interest. Ghoddami *et al.* [39] described the black start process of a 3 MW integrated wind–photovoltaic-battery system. The system was disconnected from the grid at the initial stage of the black start. The PV subsystem immediately provided power, while the wind subsystem took 0.88 s to reach the rotor speed threshold to generate power. The battery system discharged with the variation of the wind power, and the total power output successfully addressed the demand. Liu *et al.* [40] conducted a feasibility study on the black start capability of a 1.55 MW wind farm with a battery storage system. The wind farm was used to black start a local 150 MW thermal power plant. The battery energy store provides power to the pitch and yaw systems of the induction generators and starts the wind turbines when a black start is required. The wind farm can be further used to energize the transmission line, power the auxiliary motors, and eventually start up the thermal power plant. The wind farm and the thermal power plant can work as independent systems that can power the grid load and start up the power plants in the nearby area. Li *et al.* [41] proposed to use a photovoltaic (40 MW)-battery energy storage system (15 MW/5.5 MWh) (denoted as PV-BESS) as a black start resource for restoration, with the black start process as shown in Fig. 7. The PV-BESS can successfully complete the black start process on sunny and cloudy days (Fig. 8) but not on rainy days through the optimization of the control strategy. In addition to lithium-ion battery energy storage, Dong *et al.* [42] studied the performance of a microgrid containing vanadium redox flow battery (VRB, 13.5 MW) as a black start source to restore the main grid during blackouts (Fig. 9). The VRB storage system can inject or absorb extra power during the black start process to minimize power imbalance, and their results showed that microgrids with VRBs can reduce the total restoration time of a network.

3.4. Thermal energy storage

Thermal energy storage (TES) stores hot or cold thermal

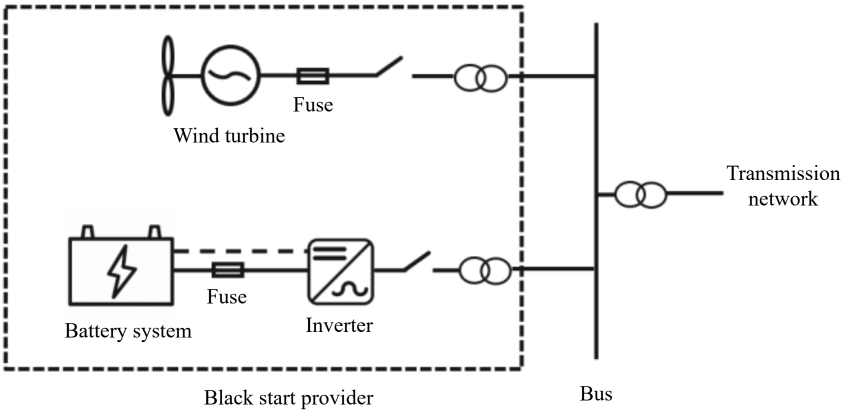

Fig. 6. Schematic of a LIB energy storage system integrated with a wind farm for black start services.

energy in different types of storage media, such as sensible heat storage materials (e.g., thermal oil and molten salts without phase change occurrences in the charge/discharge processes), phase change materials (e.g., salts, paraffin wax, and metals with phase transition during the charge/discharge processes), and thermochemical materials (e.g., water–zeolite and CaO–$CaCO_3$ with either sorption and/or reversible chemical reactions occurring in the charge/discharge processes) [43]. Stored thermal energy can be later used for heating, cooling, and/or power generation. Low-temperature TES (LT-TES) and high-temperature TES (HT-TES) are the two types of TES that can potentially be used for black start processes.

3.4.1. High-temperature thermal energy storage

HT-TES has been widely applied in concentrating solar thermal power (CSP) plants with molten salt as heat transfer fluid and storage media. The HT-TES system stores the excess solar heat during sunny daytime, serving a valley-filling role in the power system. Meanwhile, this system releases the stored heat for heating/hot water supply or electricity genera-

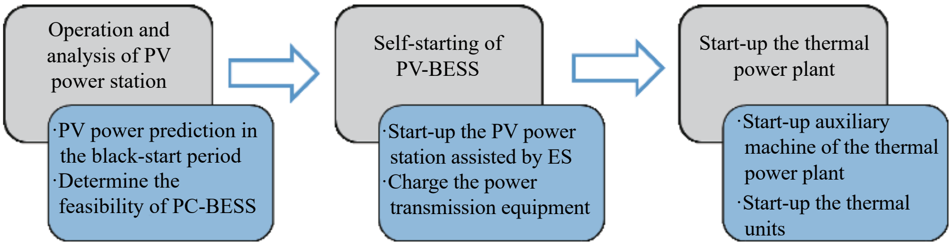

Fig. 7. Black-start process of power grid based on PV-BESS [41]. ES represents energy storage.

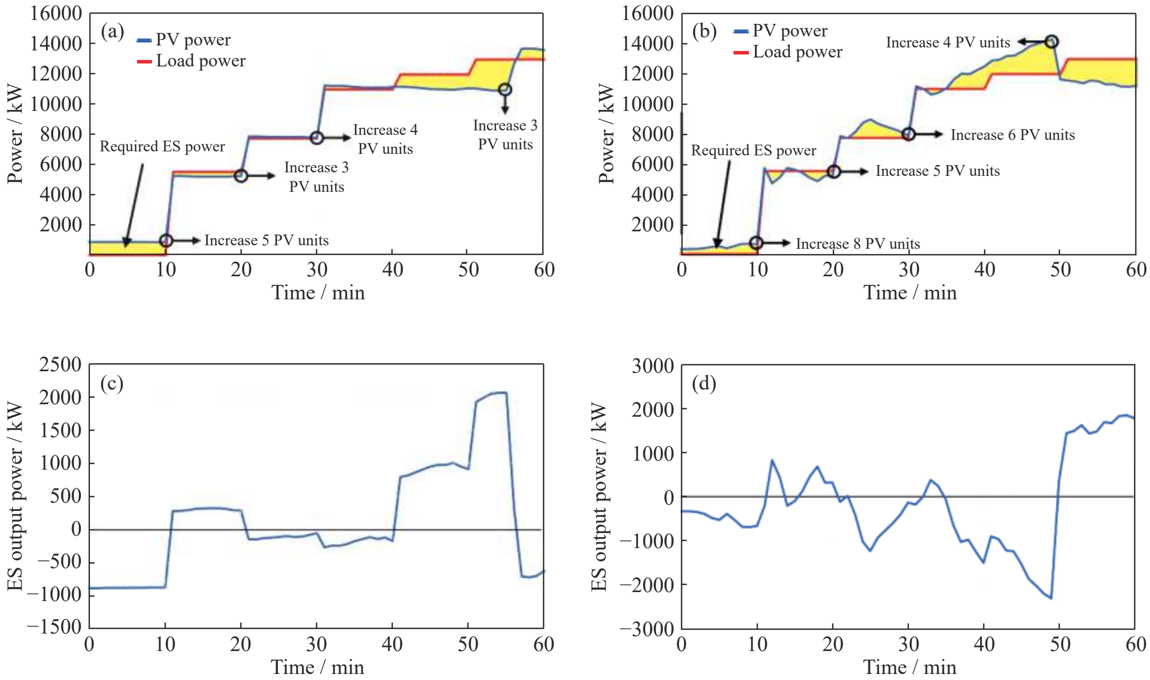

Fig. 8. Load power and PV output power on (a) typical sunny day and (b) typical cloudy day; ES output power on (c) typical sunny day and (d) typical cloudy day in the black-start [41].

Fig. 9. Test system using microgrid-VRB for black start.

tion through a steam turbine during nighttime or in the absence of sunshine, serving a peak-shaving role in the power system. Thus, the HT-TES system in such a configuration cannot be used directly for fast-response applications in the power system due to its long start-up time (tens of minutes to hours) [44]. However, if equipped with a steam accumulator and/or integrated with other fast-response technologies, this system can be used as a part of the solution to the black start. The HT-TES system has remarkably low daily self-discharging, and the thermal energy can even be stored for months if thermochemical storage materials are used. These conditions contribute to the possibility of seasonal load shifting services for the power system [45]. The storage capacity of the HT-TES can reach a ten gigawatt-hour scale with an efficiency depending on the type of storage medium, storage process, system design, size, and application scenario [46]. A large storage capacity provides a stable output at rated power for days. Furthermore, the HT-TES is economically feasible with a substantially low capital cost of 3–60 $/kWh [47–48]. In addition to the CSP plant, wind turbines can also be integrated with the TES technology [49], wherein wind turbines directly convert wind energy into thermal energy.

Fig. 10 shows the proposed design for black start providers with HT-TES as the auxiliary generator. Table 6 presents the features of the HT-TES black start system. The most significant advantage lies in the provision of a remarkably large power and storage capacity to address the large power requirement for the self-starting of renewable energy power plants. Meanwhile, the proposed design could provide a stable power output for hours as the main generator to handle the intermittent problem of renewable energy sources.

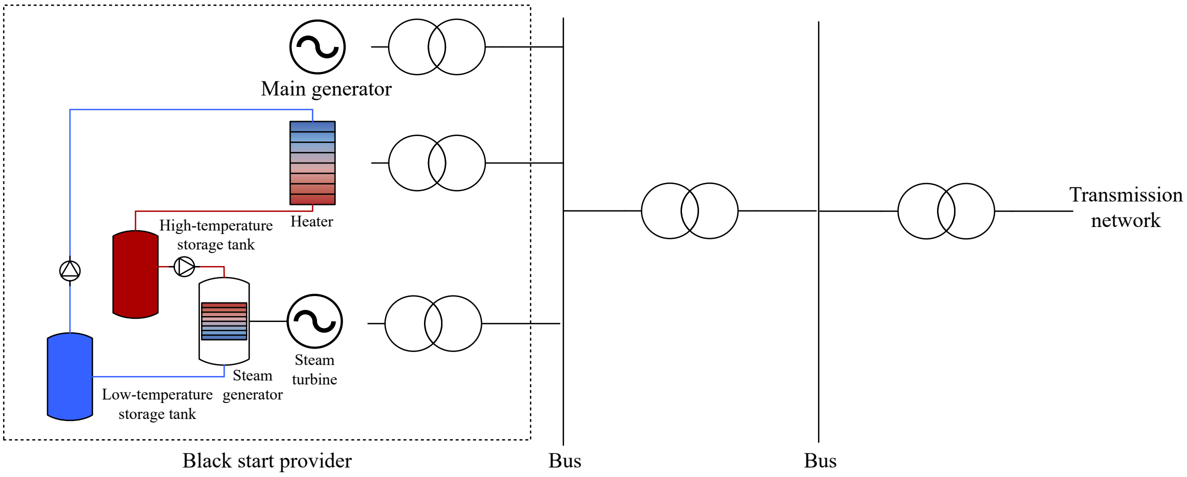

Fig. 10. Schematic of a high-temperature thermal energy storage system for black start services.

Table 6. Advantages and disadvantages of the high-temperature thermal energy storage system for black start (data based on the Global Energy Storage Database [29])

Advantages	(1) Good storage capacity (GWh level); (2) high energy density (270–340 Wh/L); (3) good discharge time (hours); (4) acceptable self-discharge (months of storage duration); (5) long cycle life (~10000 cycles) [50]; (6) low capital cost (3–60 $/kWh); (6) good technical maturity.
Disadvantages	(1) Relatively low power capacity (100 MW level); (2) long response time (hours); (3) relatively low efficiency (60%–70%).

3.4.2. Cryogenic energy storage

Cryogenic energy storage (CES) is a large-scale energy storage technology (at gigawatt-hour level), which uses liquid air or liquid nitrogen as an energy carrier/storage medium [51]. Thus, CES is also called liquid air energy storage (LAES). The LAES stores electricity during off-peak hours by driving an air liquefaction unit for liquid air production (energy is stored mainly in liquid air). The stored liquid air is highly pressurized when electricity is needed, evaporated by the environment heat and/or other heat sources in a cascading manner. The high-pressure air then drives an air turbine to generate electricity. Highview power built and tested the first grid-scale LAES plant (5 MW/15 MWh) in the world and is currently building a 50 MW/250 MWh plant in the north of England [52–53]. The LAES technology has the advantages of high energy density (120–230 Wh/L), which is a hundred times that of the PHS (0.2–2 Wh/L) and 20–70 times that of the compressed air energy storage (2–6 Wh/L) [54]. The storage medium of the LAES is the abundant ambient air. LAES plants can be built in cities or university campuses with few environmental and geographical restrictions. A standalone LAES system has a system-level efficiency of approximately 50%–60%.

The power recovery unit of the LAES system can deliver power outputs within 5 min from instruction. Thus, the LAES plants can provide several balancing services to a power grid, such as Short-Term Operating Reserve and Fast Reserve, as well as to black start. Fig. 11 shows a proposed configuration for the black start provision with the LAES as the auxiliary generator.

Table 7 shows the results of the performance analyses on the LAES system. LAES has almost all the advantages over the HT-TES and can perform effectively in some respects. Moreover, the LAES can overcome some shortcomings of the HT-TES (e.g., long response time). These findings indicate that LAES has a better potential for undertaking black start services than the HT-TES.

3.5. Mechanical and thermomechanical energy storage

Mechanical energy storage stores energy in the form of kinetic or potential energy. One typical example is flywheel energy storage. By contrast, thermomechanical energy storage involves the storage of mechanical and thermal energy, with the representative being compressed air energy storage (CAES).

3.5.1. Flywheel energy storage

Flywheel energy storage (FES) stores electricity in the form of motion energy through a rotor. A motor drives a rotor spinning during charging. Meanwhile, the motor acts as a generator driven by the spinning rotor for power generation during discharging (Fig. 12 shows the principle). The energy storage amount of a FES depends on the rotating speed and size of the rotor.

The advantages and disadvantages of FES technology are listed in Table 8. FES is a short-term energy storage method because its discharging time only lasts up to several minutes [56]. The self-discharging of FES is remarkably serious, which is almost 20% of energy loss per hour. Hence, the suitable storage duration of FES ranges from seconds to minutes [57]; beyond this range, a significant portion of the stored energy is dissipated. FES is normally applied to fast responses (primary and secondary responses), spinning reserves, and other short-term power quality services despite its remarkably short response time in the second level. The efficiency of FES can reach 85%, and the power capacity of the FES can be around 500 MW. The so-called JET flywheel generator used to supply power to the European tokamak reactor has successfully operated for more than 30 years with 85000 cycles [58].

The FES can be used as the auxiliary generator in the black start unit to help with the self-starting and frequency/voltage regulation of renewable energy power plants with the minute-level self-starting capability due to its fast response. However, the FES can only deliver the full power within a few minutes, implying that it could not handle the intermittent problem of renewable energy sources alone. The FES cannot be used as the main generator for the black start in the absence of power output of renewable energy or under seriously inadequate renewable energy.

3.5.2. Compressed air energy storage

CAES is a large-scale energy storage method based on traditional gas turbine technology. The principle of the conventional CAES is described as follows. The ambient air is compressed to high pressure and stored in an underground cavity or an overground container (charging process). The compressed air is released during discharging, heated by heat sources if available through a recuperator, mixed with natural gas, and burned in a conventional combustion turbine for power generation. In addition to the previously mentioned pumped hydro energy storage, the conventional CAES is the only successfully commercialized energy storage technology on a ten gigawatt-hour scale. Thus far, only two commercial CAES power plants are in operation: Huntorf, Germany in 1978 (approximately 300 MW) and McIntosh, Alabama,

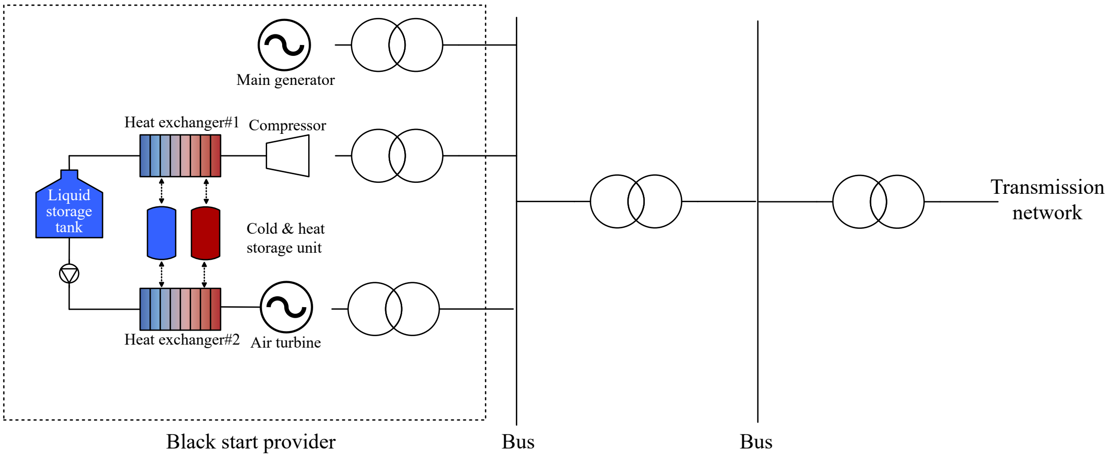

Fig. 11. Schematic of a liquid air energy storage system with black start services.

Table 7. Advantages and disadvantages of liquid air energy storage system for black start (data based on the Global Energy Storage Database [29])

Advantages	(1) Good storage capacity (GWh level); (2) high energy density (up to 230 Wh/L); (3) minute-level response time; (4) good discharging time at rated power (hours); (5) acceptable self-discharge (weeks of storage duration); (6) long cycle life (~20000 cycles) [30]; (7) acceptable capital cost (100–200 $/kWh for large scale).
Disadvantages	(1) Relatively low power capacity (100 MW level for the existing demonstration plants, potential to be 300 MW– 1 GW [55]); (2) relatively low efficiency (<60%); (3) only a few demonstrations.

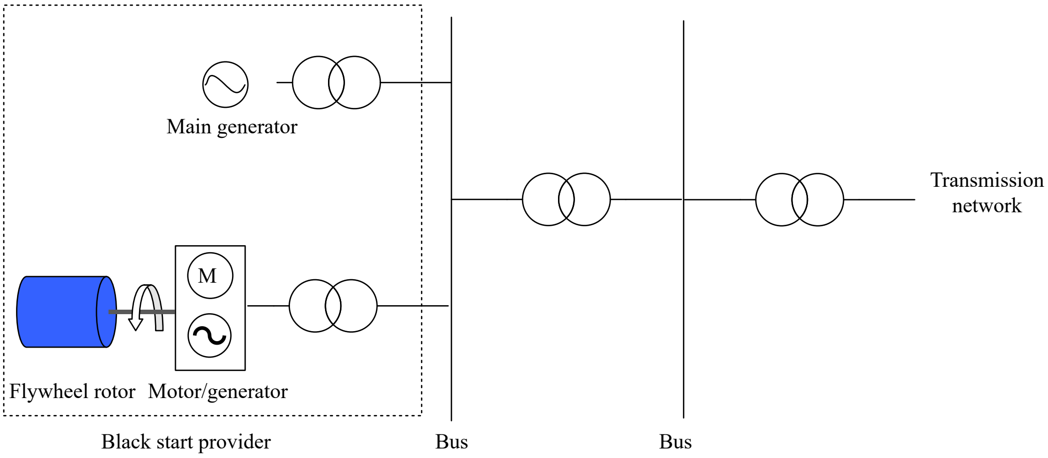

Fig. 12. Schematic of a flywheel energy storage system with black start service.

Table 8. Advantages and disadvantages of flywheel energy storage system for black start (data based on the Global Energy Storage Database [29])

Advantages	(1) Good power capacity (500 MW level); (2) second scale response time; (3) high round trip efficiency (85%); (4) high depth of discharge (90%); (5) long cycle life (~100000 cycles) [30]; (6) high energy density (25–200 Wh/L).
Disadvantages	(1) Relatively low storage capacity (100 MWh level); (2) very short discharging time (up to minutes); (3) very quick self-discharge (minutes of storage); (4) high capital cost (1000–6000 $/kWh); (5) only a few demonstrations.

USA in 1991 (110 MW). Off-peak electricity is used in both cases to produce compressed air, and natural gas is used to burn the compressed air for power generation.

The advantages and disadvantages of the CAES are listed in Table 9. The storage duration of the CAES can be seasonal [27]. The discharge duration of a CAES system at the rated power varies from hours to days depending on storage capacity [44]. The CAES can also provide a fast response at a minute level (similar to LAES discussed above). Other advantages of the CAES include relatively good efficiency [59], long lifespan (20–40 years), and low capital cost (50–80 $/kWh) [60]. These advantages contribute to the possible application of CAES in renewable energy power plants for the black start (Fig. 13). However, the main drawbacks that limit the development of CAES include the low energy density (2–6 Wh/L), the dependence on geological locations (nearby rock mines and salt caverns), and environmental pollution caused by fuel combustion (conventional CAES).

Table 9. Advantages and disadvantages of traditional compressed air energy storage system for black start

Advantages	(1) Large storage capacity (10 GWh level) and good power capacity (500 MW level); (2) second-minute level response time; (3) long discharging time (up to days); (4) good efficiency (70%–80%); (5) low self-discharge (cross season storage); (6) long cycle life (~20000 cycles) [30]; (7) low capital cost (50–80 $/kWh); (8) good technical maturity.
Disadvantages	(1) Low energy density (2–6 Wh/L); (2) low depth of discharge (35%–50%); (3) geographic restrictions; (4) environment pollution.

Therefore, recent studies of the CAES are focused on removing the combustion part, leading to the development of advanced CAES, which are still under the demonstration stage. One of these advancements is the so-called advanced adiabatic CAES (AA-CAES). The AA-CAES is a combination of CAES with TES, in which the compression heat of the charging process is recovered, stored, and reused in the discharging process to reheat the compressed air before expansion. The combustion process of the fuel gas is eliminated from AA-CAES, and an efficiency of 63%–74% could be achieved in accordance with the data from the first underground AA-CAES pilot plant [61].

3.6. Hybrid energy storage

As reviewed above, realizing a fast, stable, and long-lasting method for black start services with a single energy storage technology is difficult, and hybridization of technologies provides a potential route. A hybrid energy storage system integrates at least two energy storage technologies, exploiting the advantages of the respective technologies to overcome their disadvantages. Table 10 compares the features of different energy storage technologies. These energy storage technologies with large-scale storage and power capacities (HT-TES, LAES, and CAES) can be coupled with those fast-responses but small-scale storage systems (LIB and flywheel). Therefore, the hybrid energy storage system can meet the high self-starting power requirements of the main generators and provide fast response services to maintain the stability of the frequency and voltage. Furthermore, the power output reliability of the renewable power plants is substantially lower than the traditional power station, given the inherent instability and intermittence of renewables. As the main black start generator, renewable energy power plants cannot ensure sufficient power delivery to restore downstream nonblack start power plants during large-scale blackouts. Thus, the integrated hybrid energy storage system can

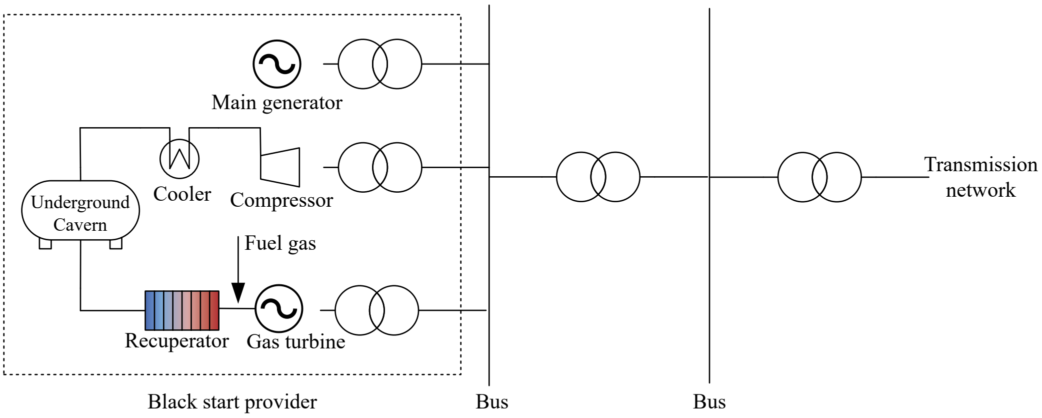

Fig. 13. Schematic of a compressed air energy storage system for black start services.

Table 10. Comparison of different energy storage technologies (data based on the Global Energy Storage Database [29])

Energy storage technology	Storage capacity / MWh	Power capacity / MW	Energy density / (Wh·L^{-1})	Response time	Discharge time	Round trip efficiency / %	Self-discharge	Depth of discharge / %	Cycle life / cycles	Capital cost / (\$·kW^{-1}·h^{-1})	Technology maturities
Lithium-ion battery	100	500	200–600	Seconds	Minutes–hours	90	Season	80–100	4000	200–800	Deployed
Flow battery	100	100	20–70	Seconds	Hours	70	Season	90–100	15000	300–1500	Deployed
High-temperature thermal energy storage	1000	100	270–340	Hours	Hours	60–70	Months	Medium	10000	3–60	Deployed
Liquid air energy storage	1000	100	120–230	Minutes	Hours	60	Weeks	100	20000	100–200	Demo
Flywheel energy storage	100	500	25–200	Seconds	Minutes	85	Minutes	90	100000	1000–6000	Demo
Compressed air energy storage	10000	500	2–6	Seconds–minutes	Hours–days	70–80	Season	35–50	20000	50–80	Deployed
Pumped hydro	10000	1000	0.1–2	Minutes	Days	70–84	Season	80–100	20000	10–100	Deployed

temporarily substitute the main generator, providing stable power output for hours. In addition, the capital cost of a fast-response energy storage system is usually substantially higher than that of a slow-response energy storage system for a given set of requirements. Thus, an effective and optimal combination of a small-scale fast-response energy storage system with a large-scale slow-response energy storage system would reduce the total investment cost for the entire black start process. Economically, the hybrid energy storage system can also provide other grid-scale services, including frequency regulation, peak shaving, voltage control, and voltage droop. Traditional PHS systems often store dumped electricity from renewable energy sources when the grid could not take the electricity. The hybrid energy storage system can take the same role in locations where PHS is not feasible, leading to economically viable cases.

A limited number of studies on hybrid energy storage systems are currently available, mostly focusing on the combination of batteries and supercapacitors [62–63] and only a few for the black start services. The study in Refs. [64–65] investigated the performance of hybrid energy storage systems containing battery systems and supercapacitors in black start conditions, as shown in Fig. 14. The results show that this hybrid energy storage system can effectively inhibit the inrush current (mainly completed by supercapacitor), support the power quality requirements, and maintain a continuous power supply during black starts. Ding *et al.* [66] proposed to use a combination of the LAES and Li-ion battery pack to provide the black start and the frequency regulation services to the power grid, and its working principle is shown in Fig. 15. They found that the battery pack is first used to power the discharging process of the LAES system (cryopumps and valves) rapidly (within seconds) during blackouts. Then, the LAES system can start (2–5 min) to supply power to other power plants and the entire grid to restore power within a short period.

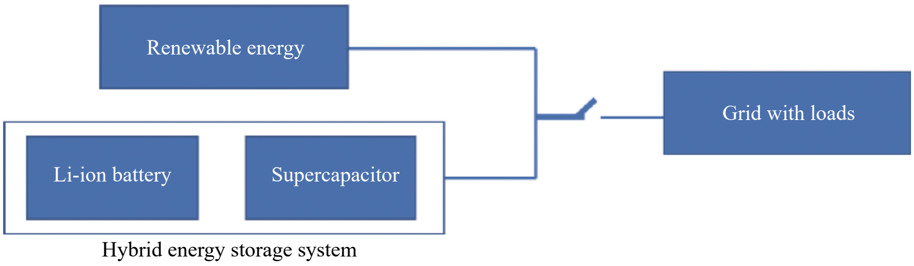

Fig. 14. Configuration of the combination of battery and supercapacitor for black start.

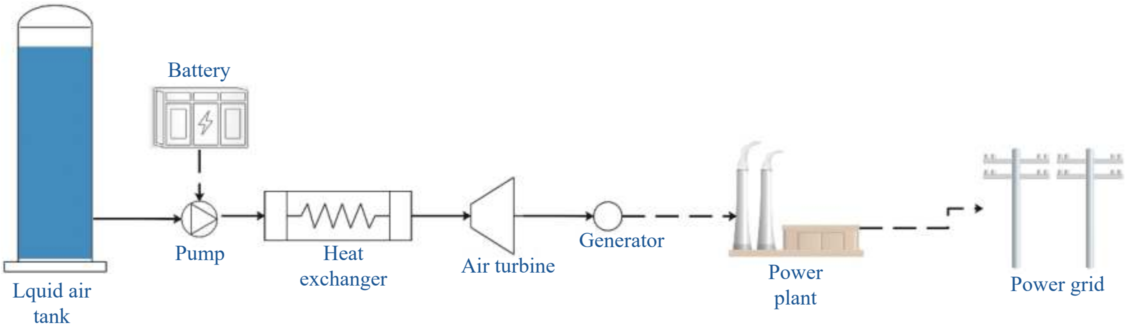

Fig. 15. Configuration of the combination of LAES and battery for black start and frequency regulation.

The integration of two or more different energy storage methods is an effective solution to provide fast-response and large-scale power supply, which can successfully meet the black start requirements. However, relevant research in this field is rare. Exploring the different combinations of electrochemical, thermal, mechanical, and thermomechanical methods for black start applications will be of considerable interest.

4. Conclusion and outlook

Overall, this study comprises a review of energy storage-based black start services and the different energy storage methods employed for the black start. The outcome of this study provides guidelines for the development of energy storage-based black start restoration systems, especially with integrated renewable plants. The feasibility of utilizing different energy storage systems as black start sources has been analyzed and compared. The pumped hydro and LIB methods are currently the most promising technologies, with their most significant advantages of large capacity (storage and power) and short response time, respectively. Other energy storage methods have the potential to be utilized for black start services (e.g., flow battery and FES have quick response times, HT-TES has high energy density, LASE has 100% depth of discharge, and CAES has large storage capacity and high power capacity). The comparison results of different energy storage methods reveal the advantages of a hybrid energy system that integrates large-scale storage and power capacities (HT-TES, LAES, and CAES) and a small-scale energy storage system with quick ramping speed (LIB, flow battery, and FES). The system can begin the black start process within seconds and provide a high-power and long-period resilient supply, eventually achieving the total power restoration. Other grid applications, including frequency regulation, peak shaving, and voltage control, can also be achieved with a hybrid energy storage system, thus making the system profitable.

For further work, first, conducting additional research to examine the feasibility of hybrid energy storage systems in grid applications, such as superconductor magnetics energy storage with high power capacity, sodium–sulfur batteries with 1 ms fast response time, and hydrogen energy storage with high energy density, is suggested. Second, the energy storage system model depends on the external characteristic and the control mode. Thus, additional extensive studies of the system model should also be performed to identify the black start capacity and program the system restoration plan. Characteristics of different stages of the black start event should be extracted and associated with the energy storage system. Third, the smart grid is aspired to be self-healing and resilient to system anomalies. Thus, the inclusion of artificial intelligence-based smart energy storage systems into the smart grid could further complement the smart grid system, which should also be investigated.

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Conflict of Interest

The authors declare there is no conflict of interest.

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