Review of energy storage system for wind power integration support

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HIGHLIGHTS

- The principle and characteristics of present EES technologies are reviewed.
- The potential applications of different roles played by EES are described.
- The recent researches about the EES planning problems, including type selection, optimal sizing and siting are summarized.
- The operation and control strategies are discussed.

ABSTRACT

With the rapid growth of wind energy development and increasing wind power penetration level, it will be a big challenge to operate the power system with high wind power penetration securely and reliably due to the inherent variability and uncertainty of wind power. With the flexible charging–discharging characteristics, Energy Storage System (ESS) is considered as an effective tool to enhance the flexibility and controllability not only of a specific wind farm, but also of the entire grid. This paper reviews the state of the art of the ESS technologies for wind power integration support from different aspects. Firstly, the modern ESS technologies and their potential applications for wind power integration support are introduced. Secondly, the planning problem in relation to the ESS application for wind power integration is reviewed, including the selection of the ESS type, and the optimal sizing and siting of the ESS. Finally, the proposed operation and control strategies of the ESS for different application purposes in relation to the wind power integration support are summarized. The conclusion is drawn in the end.

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1. Introduction

Nowadays, as the most popular renewable energy source (RES), wind energy has achieved rapid development and growth. According to the estimation of International Energy Agency (IEA), the annual wind-generated electricity of the world will reach 1282 TW h by 2020, nearly 371% increase from 2009. By 2030, that figure will reach 2182 TW h almost doubling the year 2020 production [1].

Due to the intermittent nature of wind power, the wind power integration into power systems brings inherent variability and uncertainty. The impact of wind power integration on the system stability and reliability is dependent on the penetration level [2]. From the reliability perspective, at a relative low penetration level, the net-load fluctuations are comparable to existing load fluctuations [3], and the Conventional Generators (CGs), such as thermal or hydro units, have sufficient load tracking capability without requiring additional operating reserve. As the wind penetration level increases, the response time of committed CGs should be short enough during sudden and large changes of wind power production and load due to random failures and wind gusts, and more operating reserves will be required. From the stability perspective, different from synchronous generators, Wind Turbine Generators (WTGs) provide only small or even no contribution to frequency stability [4]. The wind power variation can also degrade the grid voltage stability due to the surplus or shortage of power [5]. An Energy Storage System (ESS) has the ability of flexible charging and discharging. Recent development and advances in the ESS and power electronic technologies have made the application of energy storage technologies a viable solution for modern power application [6]. The potential applications mainly cover the following aspects. Through time-shifting, the power generation can be...
regulated to match the loads. The ESS can also be used to balance the entire grid through ancillary services, load following and load leveling [7]. Moreover, it can meet the increasing requirement of reserves to manage the uncertainty of wind generation [8] which can increase the system operation efficiency, enhance power absorption, achieve fuel cost savings and reduce CO₂ emissions. Additionally, the ESS is a potential solution to smooth out the fluctuations, and improve supply continuity and power quality [9].

For a specific application, the first task of an ESS project is planning. It generally includes the type selection and size determination. Sometimes, the ESS siting also needs to be considered. Several factors, such as technical features, economical cost and local wind power characteristics, can influence the ESS selection [10]. Once a specific ESS type is chosen, the optimal sizing needs to be done by balancing the benefits and cost. If there are no geographical constraints, the ESS could be optimally installed to achieve the maximum benefit, mainly in the reduction of transmission system upgrade cost.

The operation and control strategies of the ESS are designed for different application purposes. The recent studies mainly focus on the coordinated control of wind farms and on-site ESSs. The short-term (daily or hourly) dispatch scheme of an ESS and fluctuation smoothing by a wash-out filter are the two attractive areas. It is also proposed to combine many dispersed ESSs as a virtual storage unit and control centrally [10]. Since the ESS is an expensive solution, it is not economically viable for the ESS to work for a single application service. It can also contribute to the system wide control.

This paper is to review the state of the art of the ESS technologies and the applications for the wind power integration support from different aspects. The paper is organized as follows: Section 2 introduces the principle and characteristics of present ESS technologies. The potential different roles played by the ESS for the wind power integration support are described in Section 3. The recent research of the ESS planning problem, including type selection, and optimal sizing and siting, are summarized in Section 4. Finally, the operation and control strategies of the ESS for wind power integration support are discussed in Section 5. The conclusion is drawn in Section 6.

2. Energy storage technologies

The electrical energy can be stored in different energy forms: mechanical, electro-chemical, chemical, electromagnetic, thermal, etc. [3,7]. The classification of energy storage technologies according to the stored energy form is illustrated in Fig. 1.

There are various characteristics of the ESS required to be taken into consideration for different applications, including capital cost, power and energy rating, power and energy density, ramp rate, efficiency, response time, self-discharge losses, and life and cycle time [11,12]. The overview of the capital cost and the technical features of the ESS is listed in Tables 1 and 2, respectively.

The technical details of the ESS have been described in many literatures [10,11,13,14]. A short description of the principles and potential capability of several commonly used ESSs for wind power integration support is presented in this section.

2.1. Pumped Hydro Storage (PHS)

The PHS is the largest and most mature energy storage technology available [15]. It represents nearly 99% of the worldwide installed electrical storage capacity with over 120 GW [10,16]. The conventional PHS consists of two water reservoirs. The water body at the relatively high elevation represents the potential or stored energy. During off-peak hours, it pumps water from the lower reservoir to the upper one, considered as a charging process. In the discharging process, water from the upper reservoir is released and flows through hydro turbines which are connected to generators, producing electrical energy [14].

As illustrated in Table 2, the PHS has the largest power and energy rating, long lifetime, high efficiency and very small discharge losses. The main applications of the PHS for wind power integration are energy management via time-shifting, frequency control and non-spinning reserve supply. Due to the slow response, the PHS is not suitable for suppressing wind fluctuations. The installation of the PHS is dependent on geographical conditions and has an impact on the nature environment. Therefore, the flexibility of its application is low.

The economic benefits of the PHS combined with Wind Farms (WFs) are described and analyzed in [17,18] shows that the hybrid PHS-WF system can meet the hourly energy demand.

2.2. Compressed Air Energy Storage (CAES)

The CAES is a technology known and used since the 19th century for different industrial applications [10]. Electrical compressors are used to compress air and store it in either an underground structure (salt cavern, abandon mines, rock structures) or an above-ground system of vessels or pipes. When needed, the compressed air is released and mixed with natural gas, burned and expanded in a modified gas turbine. Current research on the CAES is focused on the development of systems
with fabricated storage tanks which will remove the geological dependency and the compressed air will be stored with higher pressure. So far, there are only two CAES units in operation. They are located in Huntorf, Germany and MacIntosh in Alabama, USA [19]. There are several CAES units which are either planned or under construction [20].

From Table 2, it is shown that the high power and energy capacity rating makes the CAES another choice for wind farms for the energy management purposes, similarly to the PHS. The storage period can be over a year due to very small self-charge losses [11]. However, the CAES installation is also limited by topographical conditions.

2.3. Flywheel Energy Storage (FES)

The first generation of the FES has been available since 1970s which uses a large steel rotating body on mechanical bearings. In the FES, the rotational energy is stored in an accelerated rotor, a massive rotating cylinder [10]. The main components are a rotating cylinder (comprised of a rim attached to a shaft) in a compartment, bearings and a shaft. The whole structure is placed in a vacuum enclosure to reduce windage losses. During the charging process, the rotor is accelerated to a very high speed which can reach from 20,000 to over 50,000 rpm. The energy is stored in the flywheel by keeping the rotating body at a constant speed. During the discharging process, the flywheel releases energy and drives the machine as a generator.

The main advantages of flywheels are the excellent cycle stability, a long life of providing full charge–discharge cycles, little maintenance cost, high power density and high efficiency. The FES is mainly applied as a power quality device to suppress fast wind power fluctuation, provide ride-through of interruptions of several seconds or bridge the shift between two sources [11]. Besides, it is also designed to provide damping enhancement [21]. The main drawbacks are the short operation duration and high self-discharge losses. They are considered as a support for wind turbines in combination with other ESSs rather than standing alone [13].

2.4. Battery Energy Storage System (BESS)

The BESS stores electricity in the form of chemical energy [22]. A conventional secondary battery consists of a set of low-voltage/ power battery cells connected in parallel and series to achieve a desired electrical characteristic. Each cell is made up of a liquid, paste or solid electrolyte together with anode and cathode [11]. A battery is charged by an internal chemical reaction under a potential applied to both electrodes. The reaction is reversible and let the battery deliver the absorbed energy for discharging. So far, various types of second batteries have been developed for

<table>
<thead>
<tr>
<th>System</th>
<th>Capital cost</th>
<th>$ (kW)</th>
<th>$ (kW h)</th>
<th>$ (kW h-per cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHS</td>
<td>600–2000</td>
<td>5–100</td>
<td>0.1–1.4</td>
<td></td>
</tr>
<tr>
<td>CAES</td>
<td>400–8000</td>
<td>2–50</td>
<td>2–4</td>
<td></td>
</tr>
<tr>
<td>FES</td>
<td>250–350</td>
<td>1000–5000</td>
<td>3–25</td>
<td></td>
</tr>
<tr>
<td>LA</td>
<td>300–600</td>
<td>200–400</td>
<td>20–100</td>
<td></td>
</tr>
<tr>
<td>NaS</td>
<td>1000–3000</td>
<td>300–500</td>
<td>8–20</td>
<td></td>
</tr>
<tr>
<td>VRB</td>
<td>600–1500</td>
<td>150–1000</td>
<td>5–80</td>
<td></td>
</tr>
<tr>
<td>ZnBr</td>
<td>700–2500</td>
<td>150–1000</td>
<td>5–80</td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>10,000*</td>
<td>6000–20,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>100–300</td>
<td>300–2000</td>
<td>2–20</td>
<td></td>
</tr>
<tr>
<td>SMES</td>
<td>200–300</td>
<td>1000–10,000</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Capital cost of ESS.

<table>
<thead>
<tr>
<th>System</th>
<th>Power rating (MW)</th>
<th>Discharge time typical</th>
<th>Power density (W/l)</th>
<th>Energy density (W h/l)</th>
<th>In (years)</th>
<th>In (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHS</td>
<td>100–5000</td>
<td>1–24 h</td>
<td>0.1–0.2</td>
<td>0.2–2</td>
<td>70–80</td>
<td>&gt;50</td>
</tr>
<tr>
<td>CAES</td>
<td>500–1000</td>
<td>1–24 h</td>
<td>0.2–3</td>
<td>0.7–1</td>
<td>70–80</td>
<td>&gt;50</td>
</tr>
<tr>
<td>LA</td>
<td>500–1000</td>
<td>1–24 h</td>
<td>0.2–3</td>
<td>0.7–1</td>
<td>70–80</td>
<td>&gt;50</td>
</tr>
<tr>
<td>NaS</td>
<td>1000–2000</td>
<td>1–24 h</td>
<td>0.2–3</td>
<td>0.7–1</td>
<td>70–80</td>
<td>&gt;50</td>
</tr>
<tr>
<td>VRB</td>
<td>600–1500</td>
<td>1–24 h</td>
<td>0.2–3</td>
<td>0.7–1</td>
<td>70–80</td>
<td>&gt;50</td>
</tr>
<tr>
<td>ZnBr</td>
<td>700–2500</td>
<td>1–24 h</td>
<td>0.2–3</td>
<td>0.7–1</td>
<td>70–80</td>
<td>&gt;50</td>
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<tr>
<td>SC</td>
<td>100–300</td>
<td>1000–20,000</td>
<td>0.2–3</td>
<td>0.7–1</td>
<td>70–80</td>
<td>&gt;50</td>
</tr>
<tr>
<td>SMES</td>
<td>200–300</td>
<td>1000–10,000</td>
<td>0.2–3</td>
<td>0.7–1</td>
<td>70–80</td>
<td>&gt;50</td>
</tr>
</tbody>
</table>

Table 2: Technical features of ESS.
commercial use, including Lead Acid (LA) battery, Nickel Cadmium (NiCd) battery, Nickel Metal Hybrid (NiMH) battery, Lithium Ion (Li-ion) battery and Sodium Sulphur (NaS) battery.

As illustrated in Table 2, as a whole, secondary batteries have very rapid response time (<s) which allows tracking load changes for the system stability enhancement. The self-discharge loss is small and the round-trip efficiency is high. Due to the high power and energy densities, the BESS construction is facilitated by the short lead time, potential convenient sitting and technology modularity [11]. However, most batteries contain metal toxic materials which lead to an ecological problem for disposal. For the inter-comparison, the limited number of cycle lifetime restricts the application of LA batteries as large-scale storage devices. The life span of NiCd batteries is seriously dependent on the cycle depth. A deep cycle can reduce the NiCd battery lifetime significantly.

Besides, this technology suffers from the memory effect [15]. The Li-ion battery has the highest power and energy densities. The research related to the Li-ion battery focuses on its application of electrical vehicles. The high capital cost, shown in Table 1, limits the large-scale use of the Li-ion battery for wind power integration support. The NaS battery is an economical solution for power quality improvement and peak-shaving applications. However, due to the high operation temperature (300–340 °C), the stored energy is partly used for heating which reduces the operation performance. The high cost is another barrier.

The flow battery is another type of battery. The energy is stored in one or more electro-active species which are dissolved in liquid electrolytes [10]. Additional electrolyte is stored externally, generally in tanks and is usually pumped through the cells of the reactor. The energy rating is determined by the quantity of electrolyte whereas the power rating is dependent on the active area of the cell stack [11]. The typical flow batteries are Vanadium Redox Battery (VRB), Polysulphide Bromide (PSB) and Zinc Bromine (ZnBr).

Flow batteries have been built in MW class and can play a more important role for future large scale application. In [5], the ZnBr battery is used to dispatch the wind power based on the optimal control method. In [23], a washout filter-based scheme is adopted to smooth out short-term power fluctuations of a wind farm with VRBs.

2.5. Superconducting Magnetic Energy Storage (SMES)

The SMES consists of superconductive coil, power conditioning system, refrigerator and vacuum [15]. The energy is stored in the magnetic field created by DC current circulating through a superconducting coil [10]. In order to avoid the losses caused by the current flow, the coil is kept in the superconducting state.

The SMES has very rapid response. The power requested is available almost instantaneously [10]. The SMES is very promising as a power storage system for load leveling or a power stabilizer [24,25]. The SMES can be incorporated into a back to back DC link [25]. In this case, a back-to-back system is used as a power conditioning system for the SMES coils. It is also utilized by the coordination with wind farms for power quality improvement [24,26–28] and dynamic stability enhancement [21,29]. However, the superconducting coil is very sensitive to temperature changes. The operational reliability is crucially dependent on the refrigeration system. Up to now, only a few SMES with small capacity are available for commercial use.

2.6. Super-Capacitor (SC)

Great progress has been achieved in the capacitor storage technologies. Instead of the common arrangement of a solid dielectric between the electrodes, an electrolyte solution is placed between two solid conductors for the SC. Compared with conventional capacitors, it has much larger capacitance and energy density, thus enabling a compact design [10,11].

The SC has nearly unlimited cycle stability as well as extremely high power density, and fast charging and discharging due to extraordinarily low inner resistance. Other advantages are durability, high reliability, no maintenance, long lifetime, and operation over a wide temperature range and in diverse environments. They are environmentally friendly and easily recycled or neutralized. The efficiency is typically around 90% and the discharge time is in the range of seconds to hours. The current research for wind power integration support focuses on the power leveling of wind farms [30], coordination with batteries for smoothing fast fluctuations [31].

Other ESS technologies, including Fuel Cell (FC), Metal–Air (MA) battery, Solar Fuel, Cryogenic Energy Storage (CES), Synthetic Natural Gas (SNG) and Thermal Energy Storage (TES) are either still under development or technically developed, but still not widely used. The technical maturity of different types of ESSs is shown in Fig. 2.

Different applications require different technical features of the ESS. Among them, energy and power ratings are the two main factors. In [10], a comparison of several storage technologies based on these factors is illustrated in a double-logarithmic chart (Fig. 3).

3. ESS applications for wind power integration support

The ESS applications related to wind power integration can be summarized and categorized in terms of roles it plays for different stakeholders: the wind farm owner, the grid operator and the energy consumer.

3.1. Generation-side roles of ESS

The main challenges with wind power integration are power intermittency, ramp rate and limiting wind farm output [32]. The generation-side role of the ESS aims to improve the grid-friendliness of the wind farm to dispatch wind energy such that they can be controlled like conventional power plants. Additionally, it shall be controlled to effectively utilize limited transmission capacity.

3.1.1. Time shifting

Due to the stochastic characteristic of wind, wind power production is considered as a non-dispatchable resource and sometimes it demonstrates an anti-peak feature, e.g. high wind power during off-peak demand or low wind power during peak demand. The time shifting is to store extra wind energy during periods of low demand and stands ready to dispatch energy to the grid during periods of high demand [7]. The benefit of storing electricity is expected to be larger with the large gap of demand between peak and off-peak. To fulfill the time shifting function, large quantities of energy for significant periods of time (from hours to days) are required for the ESS facility. Besides, the storage efficiency is another key factor to be considered for the economical operation of time shifting, as significant losses occur for an inefficient storage system.

3.1.2. Output smoothing

The inherently variable nature of wind power can cause fluctuations in frequency and voltage [7]. The ESS can be used to smooth out these fluctuations to keep the system stable. Accordingly, the output power of the ESS needs to be rapidly regulated for absorbing the excess energy during output spikes and releasing energy during output drops. Therefore, the ramping capability is very important for the smoothing function. The output smoothing at
the plant level reduces the need for power quality and ancillary services at the system level [33].

3.1.3. Transmission utilization efficiency

Rich wind resources are often located in rural areas far from existing high capacity transmission lines [34]. Due to the transmission constraints, the energy produced may not be transferred to the load. Additional ESS can mitigate transmission congestion, defer or avoid transmission and distribution upgrades.

3.2. Grid-side roles of ESS

Currently, the ESS is required by the grid operator to provide ancillary services to mitigate the variability and uncertainty of the entire grid, rather than specific loads or wind farms. These applications are listed in Table 3. Due to the geographical distribution of wind resources, the net variability and uncertainty are less. Therefore, the need of the overall service is reduced [7].

3.2.1. Energy arbitrage/load leveling

In the electricity market, the electricity price varies from time to time, normally hourly [14]. The ESS can be used to store low-cost off-peak energy and releases when the price is higher. It can reduce market risk exposure to volatile on-peak prices and manage high cost energy imbalance charges [35].

3.2.2. Frequency regulation

Modern wind farms are required to provide frequency regulation by the grid operator. With high wind penetration level, providing frequency response from a wind farm is technically feasible by utilizing additional droop control. However, it may cause fatigue of wind turbines and instability problem [36,37]. An effective solution is the use of the ESS. For the primary frequency control, a local droop control loop can be added to the active power controller of the ESS. The droop control aims to produce an active power output change which is proportional to the frequency deviation [38]. For the secondary frequency control, the active power command is generated by the centralized Automatic Generation Control (AGC).

3.2.3. Inertia emulation

The grid inertia reduces frequency variability and makes the grid less sensitive to sudden generation changes. The instantaneous inertial response determines the Rate of Change of Frequency (ROCOF) [4]. The addition of the ESS could significantly increase the apparent inertia of a grid. The supplementary loop can be added to the active power control of the ESS.

3.2.4. Oscillation damping

In an interconnected system, sudden changes of power in tie-line might cause oscillations with frequency range between 0.5 and 1 Hz [14]. It may further result in synchronism loss of several machines. Application of a damping controller is an effective control scheme to simultaneously handle the inherent power fluctuations and enhance system stability for a large wind farm [26]. The SMES and FES are utilized in [21,29] to damp the system oscillation. The tie-line power deviation is used as a feedback signal to generate the phase component of the converter control.

3.2.5. Voltage control support

The wind power variability can degrade the grid voltage stability [5]. The installed ESS can provide adequate reactive power to maintain the local voltage level. This service can be obtained by the full scale converter connected to the grid [13].

3.2.6. Low Voltage Ride Through (LVRT) support

WTGs should have LVRT capability to remain connected during severe grid faults specified by grid codes [36]. Furthermore, some grid codes require that WTGs supply up to the maximum reactive current during such faults. The converter should draw real power to compensate for the switching losses associated with provision of the reactive power. During severe faults, no power can be drawn from the grid. As a result, the DC voltage falls and the converter switches are blocked. For such cases, the ESS can support the DC voltage during the faults.

3.2.7. Reserve application

Due to the forecast error of wind power, additional reserves are required for emergency support. Based on the response time, the

<table>
<thead>
<tr>
<th>Application</th>
<th>Time scales</th>
<th>Example of EES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy arbitrage, load leveling</td>
<td>Hours to days</td>
<td>PHS, NaS, CAES, VRB</td>
</tr>
<tr>
<td>Frequency regulation</td>
<td>Seconds to minutes</td>
<td>Li-ion, NaS, FES, VRB</td>
</tr>
<tr>
<td>Inertia emulation, oscillation damping, voltage support LVRT</td>
<td>&lt;1 s</td>
<td>LA, NAS, FES, VRB</td>
</tr>
<tr>
<td>Primary reserves</td>
<td>10 min</td>
<td>PHS, FES, BES</td>
</tr>
<tr>
<td>Secondary reserves</td>
<td>Minutes to hours</td>
<td>PHS</td>
</tr>
<tr>
<td>Efficiency use of transmission network</td>
<td>Minutes to hours</td>
<td>Li-ion</td>
</tr>
<tr>
<td>Emergency power supply, black start</td>
<td>Minutes to hours</td>
<td>LA</td>
</tr>
</tbody>
</table>

Fig. 2. Technical maturity of ESS [11].

Fig. 3. Comparison of rated power energy content of different ESS technologies.

Table 3 Grid-side roles of ESS.
reserves can be generally classified into primary, secondary and tertiary reserves [14].

3.2.8. Emergency power supply/black start

The ESS may be used to restart from a shut-down condition without the assistance from the electrical grid and energize the power system in the event of a catastrophic failure [7,14].

3.2.9. Transmission utilization efficiency

The ESS can help grid operators efficiently use the transmission system capacity, defer transmission system upgrades to reduce transmission costs and mitigate local dependency challenges of wind power.

3.3. Demand-side roles of ESS

Most existing ESS applications for energy consumers are more related to meet the energy needs rather than solving particular challenges related to the integration of large-scale RES [39]. Only one application has a significant support for the wind power integration support: Vehicle-To-Grid (V2G) [7,40].

Due to the aggregation effect of many Electrical Vehicles (EVs) plugged into the grid, these EVs can be considered as a Virtual Power Plant (VPP) with relatively large capacity. This EV VPP (EVPP) has to fulfill the requirements of both vehicle owners and grid operators. Since all the EVs are controlled as a whole, individual vehicles will not be locked in the charging station and its owner has the full convenience. The grid operator can treat this VPP as a provider of ancillary services [41], such as time-shifting, operation reserve, and frequency regulation.

So far, many efforts have been made to investigate the EVPP feasibility and possible architecture [42]. One finished project is the EDISON project financed by the Danish TSO – Energinet, DK. The Danish island, Bornholm, was used as a test site. It aims to coordinate charging and discharging of EVs in order to optimize the utilization of wind energy in the island grid.

Since the ESS is an expensive solution, it is not economically viable for the ESS to work for single application service. In [43], the installed ESS is mainly used for output smoothing. It can also contribute to system wide control such as frequency regulation or oscillation damping. In [36], the applied BESS has the ability to provide both frequency response service and energy time-shifting.

4. Energy storage system planning

4.1. ESS type selection

Besides the aforementioned technical characteristics of the ESS, the wind power fluctuation density at different time scales is another key factor for the ESS selection to satisfy specific application purposes. Low frequency fluctuation, ranged from minutes to hours, is related to the generation reserve and the energy dispatch of the power system, while high frequency fluctuation, ranged from seconds to minutes, affects power system frequency control [44]. Based on the local wind data, the corresponding Power Spectrum Density (PSD) can be derived [45]. Through the PSD analysis, some technical requirements of the ESS, including charging–discharging duration range, power and energy density classes, can be determined. It is observed that the dominant power components concentrate over the low frequency band, especially in the dc and day cycle [46].

Although this observation is obtained from the local data, it has a general implication, and similar results are derived in [11]. The high frequency fluctuations (above 1 Hz) are insignificant which can be absorbed by the turbine generator inertia [47]. In [48], the PSD derived from wind speed measurements from Changi, Singapore, is analyzed. For maximizing the energy capture, the low frequency band is taken into account. The selected storage medium is required to have the capability to fully charge–discharge in hours and have high specific density. Combined with other technical and economical consideration, the NaS is selected for the daily dispatch purpose.

The rated capacity of modern wind farms can reach to several hundred MWs. For the energy management purpose, large-scale storage medium should be applied, such as BESS, PHS and CAES [49]. Since the PHS and CAES are limited by topographical constraints, the BESS is considered as a more competitive option for large-scale ESS application due to high power and energy density, scalability, fast response, simple maintenance requirement and high cycle life for both technical and economical consideration [48,50].

For the power quality improvement purpose, the high frequency band of the PSD should be studied. The response time and ramp rate capability are the main concerns for this purpose. The storage mediums with fast response and small energy capacity, such as FES, super-capacitor, SMES, are potential options.

Since no single storage technology can provide the benefits of both high power density and energy density, a hybrid ESS with the combination of multilevel storage devices can be used to deliver desired power time series [51]. The high energy density storage medium, normally BESS, is adopted for low frequency fluctuation mitigation [31,52,53], and the high power density storage mediums, which can be super-capacitor [31], SMES [53], FES [52], are used for smoothing high-frequency fluctuations.

4.2. ESS sizing

Once the ESS type is determined, the optimal sizing problem can be solved by balancing the benefits and cost [5,54]. The sizing problem includes the determination of both the power rating and the energy rating. The methodologies of the ESS sizing for wind power integration support are summarized and categorized in this section.

Several methodologies for the BESS sizing for short-term (daily) wind power dispatch are developed. In [55], through the spectral analysis of wind and solar resources combined with daily load profiles, a mathematical model is developed for a stand-alone ESS where the storage is calculated for different levels of mean load. The ESS is designed according to the worst case scenario (worst day of the year) to obtain the ESS size. A new method has been developed to obtain a probabilistic density function of wind power forecast error in [56]. Based on the probabilistic density function, the ESS nominal power can be determined. As the follow-up work, the ESS capacity estimation was completed in [57]. A probabilistic methodology is presented which obtains the ESS size as a function of the un-served energy. The ESS sizing aims to compensate forecast errors up to a certain level.

The ESS sizing problem can also be modeled as an optimization problem. The factors related to the sizing of the BESS, including wind power forecast accuracy (error in range between 10% and 30% [58]), application purpose, control strategy and economical aspect, can be quantified and taken into the optimization formulation as constraints. In [59], the cost function is formulated as the power deviation from the next hourly average. The forecast error is considered to be within 10%. Based on the State Of Charge (SOC), current constraints and charging–discharging rules, the power reference of next hour can be generated to minimize the cost. The results show 15–25% of the rated wind farm capacity is a proper ESS size to have an effective hourly dispatch. The same cost function is used in [8]. The hour-long wind power production
scenarios are firstly generated by a probabilistic forecast of the hourly average wind power and the inverse of the joint cumulative distribution. From these scenarios, the ESS characteristics are determined as a function of the desired risk parameter.

The cost function can be formed as the economic benefit obtained from the dispatched power of wind farms against the ESS cost. In [60], the optimal dispatched power level from wind farms is obtained by solving the optimization problem based on the given wind power profile. The DC voltage is another constraint to be considered. The corresponding BESS power and energy ratings can then be determined. With the same procedure [61], aims to minimize the cost of the BESS. Additionally, the ESS output is required to meet the output forecast of a wind farm within 4%, 90% of the time. Besides the economic benefits from wind power dispatch and the ESS cost, a new benefit component related to the voltage stability is introduced into the cost function in [5]. Using the exhaustive search of all possible solution candidates, the method is capable of finding a unique optimum of the ESS sizing. A new planning tool for medium voltage (MV) distribution networks is proposed in [35] based on Genetic Algorithm (GA) and Dynamic Programming (DP). It is able to decide the optimal rating of energy storage plants that minimize the overall network cost.

The cost function can also be formed as the service life of the energy storage system. In [46], the historical long-term wind speed data is assumed to be known. A new dispatch strategy is proposed to ensure the BESS goes through full charging–discharging cycle and thus maximizes the energy storage potential of the BESS. For smoothing the wind power fluctuation, 1 year operation data are analyzed in [28], and it is concluded to choose 20% rated power of a given wind farm as rated power and 4 h charging–discharging time for the ESS. For other applications [21], mentions that according to the accumulated experiences on damping controller design during the past several years, approximate 25% of the system capacity is a general selection.

4.3. Energy storage siting

As discussed before, some large-scale ESS types, such as the PHS and the CAES, are heavily dependent on topographical conditions. Other types can be installed not only on-site with wind farms, but also at different locations in the power system for different purposes [62], like deferring or avoiding transmission capacity upgrade, reducing transmission and distribution losses, and improving system stability [33]. Currently, only a few publications have addressed the optimal placement of the ESS in a power system with large-scale wind integration.

For the on-site installation of the ESS with wind farms, the ESS can either be placed at Point of Common Coupling (PCC) or equipped with WTGs. The former configuration is adopted by the most hybrid wind farm-ESS. The latter configuration is introduced in [30]. Each wind turbine is equipped with a super-capacitor connected to the DC link of back to back converter. This scheme enhances the control flexibility of each wind turbine. However, due to the smoothing effect of power fluctuations of distributed wind farms over a large geographical area, the requirement of power and energy rating is high and not cost-effective.

In [3], a staged procedure is introduced to seek the minimum number of storage nodes and total network storage that can still mitigate the effects of renewable energy fluctuations on network constraints. The interesting result shows that instead of wind power injection nodes, the other nodes at the end or the middle of crucial transmission lines have higher degree of control over congestion. The optimal siting problem is also investigated in [63,64]. The optimal storage location which allows highest wind power penetration is selected based on the calculation for different location scenarios. The simulation results demonstrate that the optimal storage distribution can effectively utilize transmission capacity and eliminate the need for transmission expansion.

5. Energy storage system operation and control

5.1. Operation of ESS for wind power dispatch

The role of the ESS in the wind power trading in the modern power market is analyzed in [65]. A properly designed ESS is proved to bring additional economic benefits. If the wind power output can be scheduled in a manner similar to that of a conventional power plant, the prospect of the wind power will be much improved as the optimal economic dispatch can then be achieved [46].

The operation modes of wind farms with the ESS participating in modern power market are described in [46,66,48,66]. Wind power for next few hours are estimated based on the wind speed forecast. The power dispatch schedule of wind farms has to be submitted in advance to the grid operator. The grid operator adjusts the system operating state to achieve the economic dispatch and power flow regulation. The schedule beyond the certain hours is allowed to be adjusted to compensate the forecast errors. Once the power output of the wind farm differs from the schedule submitted, the wind farm operator will be financially punished. Therefore, a lot of research concentrates on the short-term (daily) optimal scheduling scheme design for wind farms by taking advantage of the flexible charging–discharging ability of the ESS.

In [32], the expected power dispatch is estimated based on the hourly average forecast wind power without consideration of the economic benefit. In [67,68], the generation scheduling is based on the forecast of electricity prices, load and wind generation. It aims to maximize the expected profit from participating in the day-ahead power market. In [58], the wind farm operator is assumed to participant in the Nord Pool Spot market. The wind forecasting error is considered as a stochastic variable. The ESS will be hourly adjusted based on stochastic programming, seeking the maximum benefit of the wind farm and the ESS. Ref. [67] introduces a dynamic algorithm applied for daily scheduling in a power market. The objective of the online operation strategy is to follow a given generation schedule as close as possible. A statistical approach is proposed in [46] to determine the power output of a hybrid wind-BESS system. The developed new dispatch strategy ensures the BESS goes through full charge–discharge cycle to maximize the energy storage potential. Ref. [17] proposes an hourly discretized optimization algorithm to identify the optimal daily operation strategy to be followed by the wind turbines and the PHS, assuming that the wind power is perfectly forecasted.

The aforementioned are the use of single-unit ESS. In [69], a dual BESS is introduced. The latter configuration which allows more flexibility in terms of the design of the dispatch pattern. The dispatched power from the WTG-BESS power station can be treated as a firm commitment. It can be determined based on the long-term historical wind power data, the likelihood of the success of the power delivery and the BESS capacity. With a similar dual-ESS configuration [49], develops an optimal switch-over dispatch scheme for the dual-BESS, by considering the wind speed forecast and the charging–discharging characteristics of the installed BESS. The primary operation objective of the WTG-BES scheme is to harness the energy available in the wind as much as possible.

5.2. Operation of the ESS for fluctuation mitigation

Wind power filtering algorithms are widely applied by means of fast and short-term ESSs to mitigate the output fluctuation of wind
farms. The block diagram of a simplified filtering control of a hybrid WF-ESS is shown in Fig. 4. Through the Low-Pass Filter (LPF) with time constant $T_f$, the high-frequency part $P_{\text{out}}$ of wind power $P_{\text{wind}}$ is filtered as charging or discharging command of the ESS. Since the ESS has a control lag, losses and an output limiter, the actual output does not match the target output. However, due to its simplicity and fast computation speed, it is easy to be implemented and suitable for application in real-time operation.

As proposed in [23,44], the power output reference of the ESS $P_{\text{out}}^\text{bess}$ can be determined by,

$$P_{\text{out}}^\text{bess} = \frac{-sT_f}{1+sT_f}P_{\text{wind}}$$

(1)

While the Remaining Energy Level (REL) of the ESS can be calculated as,

$$\text{REL} = \frac{P_{\text{out}}^\text{bess}}{s} = \frac{T_f}{1+sT_f}P_{\text{wind}}$$

(2)

Eq. (2) shows that the larger time constant $T_f$ has higher smoothing effect but also results in a larger ESS power and capacity. It is very important to select proper $T_f$ for the controller design. Normally, $T_f$ is decided by the local wind profile and the ESS capacity, and is kept constant during operation [23,43,46,70,44]. It proposes a flexible LPF with an optimal $T_f$. $T_f$ is regulated by the Particle Swarm Optimization (PSO) algorithm in real-time. The maximum fluctuation of the combined power in any 1 min and 30 min time window is kept within predefined constraints.

With large output variations of wind farms, it is easy to reach the capacity limits of the ESS by the mere smoothing method without consideration of the charging level. Therefore, the SOC is introduced as a feed-back signal to keep the charging level within its proper range [23,44]. In [46], an additional coefficient $k$ is introduced to protect the ESS from over-limiting, as shown in (3). $k$ is changed according to the predefined curve based on SOC.

$$P_{\text{out}}^\text{bess} = k \frac{-sT_f}{1+sT_f}P_{\text{wind}}$$

(3)

Due to the measurement delay, the phase of the measured power signal is shifted. To compensate this lag, an additional lead-lag compensator is introduced and used for LPF [43].

5.3. Operation of the hybrid ESS

The previous subsections describe the operation of a single type ESS. Since the single type storage technology can hardly meet the requirement of both fast response and large energy capacity [7], the logical solution is a hybrid ESS system, which combines multiple storage devices into several levels that can be used to deliver the required power. In [51], a knowledge-based ANN control with a washout-filter is used for the two-level storage for wind power dispatch.

For the grid with many installed ESS dispersed in a large area, the integration of these ESSs will have much better capability compared with the individual ESS. By gathering them into a virtual assembly and control centrally, they can be used for many utility applications, such as frequency regulation, load leveling and control of transmission power flow. A concrete example of the aggregated energy storage system using the ESS is proposed in Japan, called Battery SCADA [10] and the demonstration of this technology started in 2012 in Yokohama, Japan.

6. Conclusions

The ESS is considered as an effective solution to handle the reliability and stability challenges of future power systems with large scale wind power integration. Various ESSs with different technical features are available in the market.

The ESSs can be used for different applications required by specific wind farms, grid operators or consumers. For the generation-side, it can aim to improve the grid-friendliness of wind farms to dispatch wind energy such that they could be controlled like conventional power plants. For the grid-side roles of the ESS, it can provide ancillary services to mitigate variability and uncertainty of the entire grid. For the demand-side roles, the aggregated EVPP can fulfill the requirements of both vehicle owners and grid operators.

For the ESS planning, it is important to properly select the ESS type, and determine the size and site of the ESS. The size of the ESS, including both power and energy capacity, can be determined by several methodologies, including the method of using historical wind profiles, the probabilistic method based on wind power forecast error, etc. The sizing problem can be formulated as an optimization problem with different cost functions. The siting of the ESS without topographical limitation can be installed either on-site or other locations to achieve high controllability. It shows the nodes at the end or the middle of crucial transmission lines have higher impact on the congestion management.

The recent research of the ESS operation and control focuses on the daily dispatch scheme of the ESS with wind farms and fluctuation mitigation. Different factors, including wind power forecast error, technical constraints, market rules, and energy price, are taken into consideration to determine the optimal operation strategy for single or multiple ESS. For the output smoothing purpose, the high frequency component is filtered and compensated by the ESS. The time constant is the key factor to strike a balance among the smoothing effect, the required ESS power and capacity rating.

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References
