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Review article

A comprehensive review of wind power integration and energy storage technologies for modern grid frequency regulation

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ABSTRACT

Integrating wind power with energy storage technologies is crucial for frequency regulation in modern power systems, ensuring the reliable and cost-effective operation of power systems while promoting the widespread adoption of renewable energy sources. Power systems are changing rapidly, with increased renewable energy integration and evolving system architectures. These transformations bring forth challenges like low inertia and unpredictable behavior of generation and load components. As a result, frequency regulation (FR) becomes increasingly important to ensure grid stability. Energy Storage Systems (ESS) with their adaptable capabilities offer valuable solutions to enhance the adaptability and controllability of power systems, especially within wind farms. This research provides an updated analysis of critical frequency stability challenges, examines state-of-the-art control techniques, and investigates the barriers that hinder wind power integration. Moreover, it introduces emerging ESS technologies and explores their potential applications in supporting wind power integration. Furthermore, this paper offers suggestions and future research directions for scientists exploring the utilization of storage technologies in frequency regulation within power systems characterized by significant penetration of wind power.

1. Introduction

Power systems are currently facing security and stability issues due to rapidly growing electricity consumption around the world. Electricity is essential for development, and innovation in renewable energy is critical for long-term sustainability. The major improvements that must be developed to attain long-term energy development are indeed the decrease of CO_2 emission, the replacement

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of fossil fuel-based energy with sustainable power, and the enhancement of energy efficiency [1]. The utilization of energy from renewable sources to produce electricity has drawn significant attention globally. The prior advancement of renewable energy (RE) is being fueled by a variety of aspects, such as global warming, environmental issues, energy security, reducing costs, and reducing emissions. Ultimately, it is anticipated that the tendency of RE integration will continue to grow. In this respect, renewable energy resources (RESs) such as solar and wind energy are anticipated to generate 50 % of the world's electricity by 2050 [2].

Modern power systems combine traditional rotating machinery, distributed generators with inverter interfaces, renewable energy sources, and energy storage technologies. Furthermore, power electronics-based equipment continues to develop into an essential component of modern power systems. Today, wind power is the most widely used RES, and it has experienced quick growth and advancement. In 2021, the global wind sector had its second-best year ever, installing about 94 GW of new capacity, according to a report by the Global Wind Energy Council (GWEC). The capacity of wind energy globally has increased by 94 GW, bringing the total to 837 GW. Now at 837 GW, the world's total wind power capacity helps reduce carbon emissions by more than 1.2 billion tonnes yearly, which is about equal to South America's annual carbon emissions [3]. Currently, the growth rate is insufficient. To align with the 1.5 °C target and achieve net zero emissions by 2050, it must quadruple by the decade's end [3].

Wind energy integration into power systems presents inherent unpredictability because of the intermittent nature of wind energy. The penetration rate determines how wind energy integration affects system reliability and stability [4]. According to a reliability aspect, at a fairly low penetration rate, net-load variations are equivalent to current load variations [5], and conventional generators (CGs), such as thermal or hydro plants, possess sufficient load-tracking capabilities without needing more operating reserves. The response time of deployed CGs ought to be quick even during rapid and significant fluctuations in wind generations and demand owing to random failures and high winds, and higher operating reserve must be needed as the wind penetration rate rises. Distinct from synchronous generators in terms of reliability, wind turbine generators (WTGs) almost make no contributions to frequency regulations [6]. Due to the excess or shortfall of electricity, wind power fluctuation can potentially impact the reliability of the grid voltage and frequency [7].

A significant mismatch between the total generation and demand on the grid frequently leads to frequency disturbance. It frequently occurs in conjunction with weak protective device and system control coordination, inadequate system reactions, and insufficient power reserve [8]. The synchronous generators' (SGs') rotational speeds directly affect the grid frequency, hence controlling the speed of rotation of the generation plants can directly influence frequency stability. By including a governor, which adjusts the actuator inputs to vary the output power to match the fluctuation in demand and feeds back the generator speed, frequency instability is eliminated. The system frequency is kept near the required rated value in this approach. The dynamic behavior of automated tie-line power and frequency regulation of power systems was investigated and the findings were reported in one of the earliest papers on the subject of power system frequency control [9]. A straightforward two-region power system grid with a single machine for each region served as the study's basis. Through the known dynamics swing equation, the simulations demonstrated the link between rotational inertia, loading damping, and governor features [9]. Furthermore, according to an IEEE study group's definition of automatic generation control (AGC) in Ref. [10], automated tie-line power and frequency regulation were thought to be the primary purpose of AGC. There are also some specific requirements of key terminology and ideas related to the power system AGC [10]. According to Ref. [11], and [12], the initial optimal controller synthesis for megawatt frequency control in multi-area power systems used two equivalent generating plants with non-reheat thermal turbines. A comprehensive review and extensive literature on frequency regulation were offered in Ref. [13].

As decentralized generators (DGs) and loads with power electronics-based technology are increasingly integrated, frequency regulation and stability in today's power system are facing new challenges. As SGs are eventually replaced by power electronics-based Microgrids and RESs, the primary issues are brought on by the lowering of the system's rotational inertia [14]. Decreasing rotating inertia in a power system can degrade traditional frequency control efficacy and seriously impact system frequency responses. This could result in frequency instability, power outages, and potentially dramatic frequency variations [15,16]. Load-power balancing and frequency management are exceedingly difficult due to the power system's reducing inertia caused by the large integration of DGs with power electronic devices. This situation is greatly made worse by the intermittent nature of renewable energy sources [17].

In contrast to traditional generation, the RESs are decoupled from the local AC system and tied to the grid via power electronic-based converters [18,19]. Additionally, the RESs cannot raise their energy production when necessary and often run at maximum power point tracking [6]. Therefore, RESs units are fundamentally unable to offer either inertia response (IR) or frequency regulation (FR) capabilities. Power systems automatically adjust production and demands for safe operation, keeping frequency inside the limits established by grid codes. System failure may result from large frequency fluctuations that trip demands and generators [20,21]. When traditional units are extensively replaced to replace RESs, the system's inertia is reduced, which makes the system more susceptible to higher frequency fluctuations. Even a slight generation-demand mismatch results in a significant frequency nadir and a network with less inertia has a higher rate of change of frequency (RoCoF) [22]. In a system with a significant percentage of RESs, frequency management is a tough issue due to inconsistent production, little inertia, and demand fluctuations. Frequency regulation is often accomplished by load frequency control (LFC) devices installed at synchronous machine-based power units.

Recently, there has been a lot of attention in the industry and academia regarding the applications of ESSs for frequency regulation solutions, such as IR, primary frequency regulation (PFR), and load-frequency control (LFC)—especially when there is a large penetration of intermittent RESs [23,24]. As Wang et al. [25] argue, energy storage can play a key role in supporting the integration of wind power into power systems. By automatically injecting and absorbing energy into and out of the grid by a change in frequency, ESS offers frequency regulations. The ESS improves the existing traditional network resources by offering quick FR capabilities. Several kinds of ESSs are present, providing support with varying features, operational needs, and restrictions that range from a small amount of time to hours [26,27]. In Ref. [28] discussion, the integration of Solar and wind power with energy storage for frequency regulation is becoming increasingly important for the reliable and cost-effective operation of power systems. The fast-responding ESSs—battery energy storage (BES), supercapacitor energy storage (SCES), flywheel energy storage (FES), and superconducting magnetic energy storage (SMES)—as well as their hybrid models the subject of this paper (BES-SCES, BES-SMEs, and BES-FES). The electrochemical double-layer capacitor, which has two electrodes, one electrolyte, and an ion-permeable membrane, is referred to in this paper as a supercapacitor. During the charging and discharging process, no electrochemical action occurs in the supercapacitor; rather than employing electrons as in a battery, ions are utilized, as well as the kind of energy stored is electrostatic. Pseudocapacitors, ultracapacitors, and ultra-batteries are some other technologies that have been created that have characteristics of capacitors and/or batteries. Such innovations are not taken into account in this paper because they are still in the early stages of development. Hydrogen energy storage (HES) technology can help sustainable energy sources improve the challenges encountered with increased wind power penetration [29]. Whenever there is a surplus of electric generation, it can be converted into hydrogen and stored as a compressed gas for future usage [30]. In times of shortages, the stored hydrogen can be transformed back into electricity [31,32]. Hydrogen has many advantages, including the ability to be utilized in industry, transportation, and indoor heating [33]. By having the potential for such gas-based applications, HES differs from other energy storage technologies like batteries, that only offer short-term flexibility services to the power system [34]. An ESS does have the capacity to charge and discharge in a balanced manner. Modern power operations can now benefit from the use of energy storage methods owing to recent developments and advancements in ESS and power electronic technology [35]. Utilizing additional services, load following, and load shifting, the ESS can also be utilized to maintain the power system [36]. Additionally, it can fulfill the rising demand for backups to regulate the fluctuating nature of wind generation [37], which improves power consumption, boosts system operation performance, achieves fuel cost reductions, and lowers CO_2 emissions. The ESS is a possible investment remedy to reduce the variations and enhance reliability and power quality [38].

1.1. Key contributions

This paper analyses recent advancements in the integration of wind power with energy storage to facilitate grid frequency management. According to recent studies, ESS approaches combined with wind integration can effectively enhance system frequency. Additionally, in periods of high demand, it can function as a backup unit and supply electricity to the grid. By providing rapid FR features, the ESS enhances the current traditional system resources. Furthermore, it can satisfy the growing demand for backups to control the fluctuating behavior of wind generation, which enhances energy consumption, boosts system operating efficiency, accomplishes fuel cost reductions, and minimizes CO_2 emissions. ESS is a potential investment remedy in the future power system network to minimize fluctuations and improve system frequency and power quality.

The key contributions in this review paper include as following.

- *Comprehensive Evaluation:* This paper provides a comprehensive evaluation of frequency regulation and energy storage solutions for wind power integration in modern power systems. It offers a thorough analysis of the challenges, state-of-the-art control techniques, and barriers to wind energy integration.
- *Exploration of Energy Storage Technologies:* This paper explores emerging energy storage technologies and their potential applications for supporting wind power integration. It discusses the adaptable charging-discharging capabilities of ESS and their role in enhancing the adaptability and controllability of power systems, particularly within wind farms.
- *Future Research Directions:* The review suggests future research directions to advance the field of frequency regulation and energy storage in systems with significant wind power penetration. It identifies gaps and limitations, providing recommendations for researchers to focus on optimizing storage technologies for frequency regulation in power systems.

1.2. Research gap and motivation

Research Gap: Despite the existing literature on frequency regulation and energy storage solutions for wind power integration in power systems, there is a need for an updated and comprehensive review that addresses the specific challenges, advancements, and potential applications in modern power systems. The review aims to bridge this research gap by synthesizing the latest findings, exploring emerging energy storage technologies, and providing suggestions for future research directions.

Motivation: This review article's primary application area is present power systems that significantly integrate wind power generation and utilize energy storage technologies to regulate frequency. ESS is essential for improving grid stability and streamlining the effective integration of renewable energy sources, especially in wind farms, as this article has highlighted. This paper also explores the difficulties, developments, and possible uses of ESS in assisting with wind power integration for frequency regulation. Additionally, we believe that by offering this in-depth evaluation, this article facilitates addressing the urgent requirements for present-day grid systems making a transition to integrated renewable energy.

The motivation for conducting this review paper stems from the growing importance of frequency regulation in power systems as renewable energy, particularly as wind power integration increases. The evolution of system architecture, advancements in energy storage technologies, adaptive loads, and power electronics have presented new challenges and opportunities in maintaining power system stability and reliability. By consolidating the current knowledge, exploring recent advancements, and identifying research gaps, this review paper aims to provide valuable insights for researchers, practitioners, and policymakers in effectively mitigating system frequency fluctuations and enhancing the overall performance of power systems.

1.3. Searching procedure

A search method was employed to obtain quality literature for this detailed research. In addition to searching the Scopus and Web of Science libraries, the essential key terms were included: “Renewable energy integration and frequency regulation’’, “Wind power integration and frequency regulation’’, “Power system frequency regulations’’ and "Energy storage system for frequency regulation’’. Fig. 1 demonstrates the schematic arrangement used to carry out the bibliometric analysis of the literature about wind power generation, frequency control, and energy storage systems.

1.4. Paper organized

In this paper, we discuss renewable energy integration, wind integration for power system frequency control, power system frequency regulations, and energy storage systems for frequency regulations. This paper is organized as follows: Section 2 discusses power system frequency regulation; Section 3 describes the frequency control methods for the modern power system with energy storage systems; Section 4 discusses regulation policy and incentives; Section 5 discusses challenges, future development, and trends; Section 6 presents the conclusion.

2. Power system frequency regulation: recent review

Power system frequency is a dynamic variable that is determined by both electricity demand and production. A generational shortage leads the frequency to decrease, but a production surplus leads the frequency to rise. To ensure that electrical systems operate steadily, the frequency is regulated within permitted bounds. The synchronous generators used in traditional power production plants have large spinning masses. These synchronous generators instantly increase speed or slow down by inserting or absorbing power into or out of the energy network in the case of whatever variation in load and production [39]. This immediate reaction, or IR, is a feature of synchronous generators that can function without control. Applying the governor’s control, typically enhances the generator’s energy output according to control signals, traditional energy units can provide control FR operations [40–42]. The common frequency variation following an incident is illustrated in Fig. 2, along with the critical control measures that were implemented to mitigate its impacts. The synchronous generators’ immediate response (i.e., IR), is the initial phase. In this phase, the synchronous generators fight against frequency decrease by unleashing the contained kinetic energy in the spinning mass. After this phase, the frequency is stabilized to a novel stable state value via the primary frequency regulation. The LFC is the subsequent stage when the PI control scheme is typically employed to restore the frequency towards its set point [43–45]. Demand response (DR), which entails managing demands

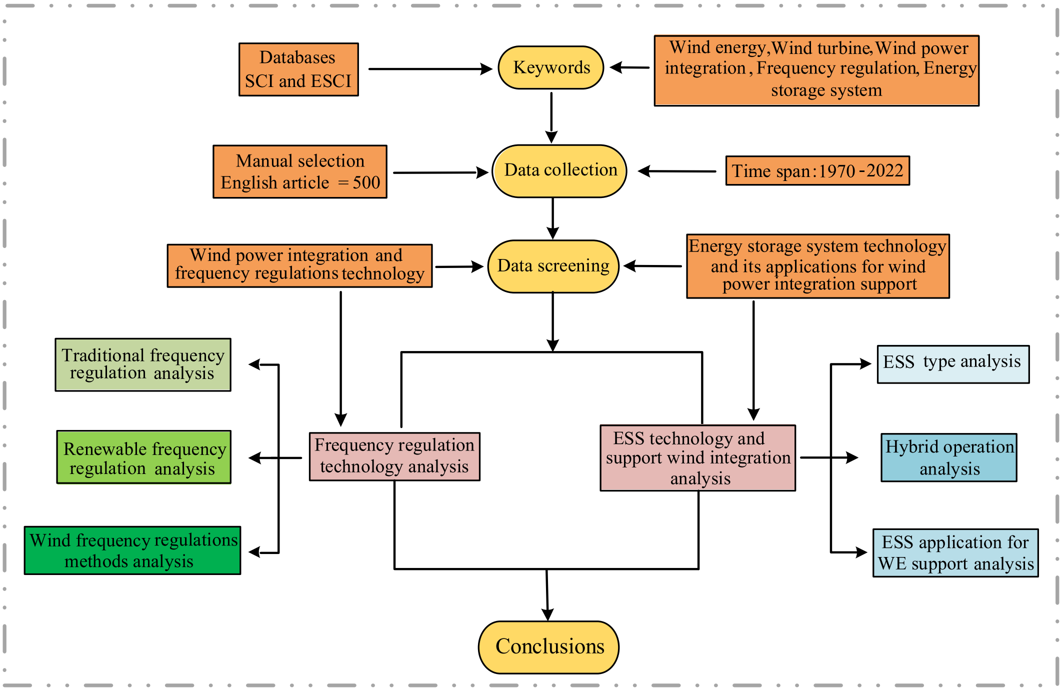

Fig. 1. The flowchart shows how the bibliometric review processes were carried out.

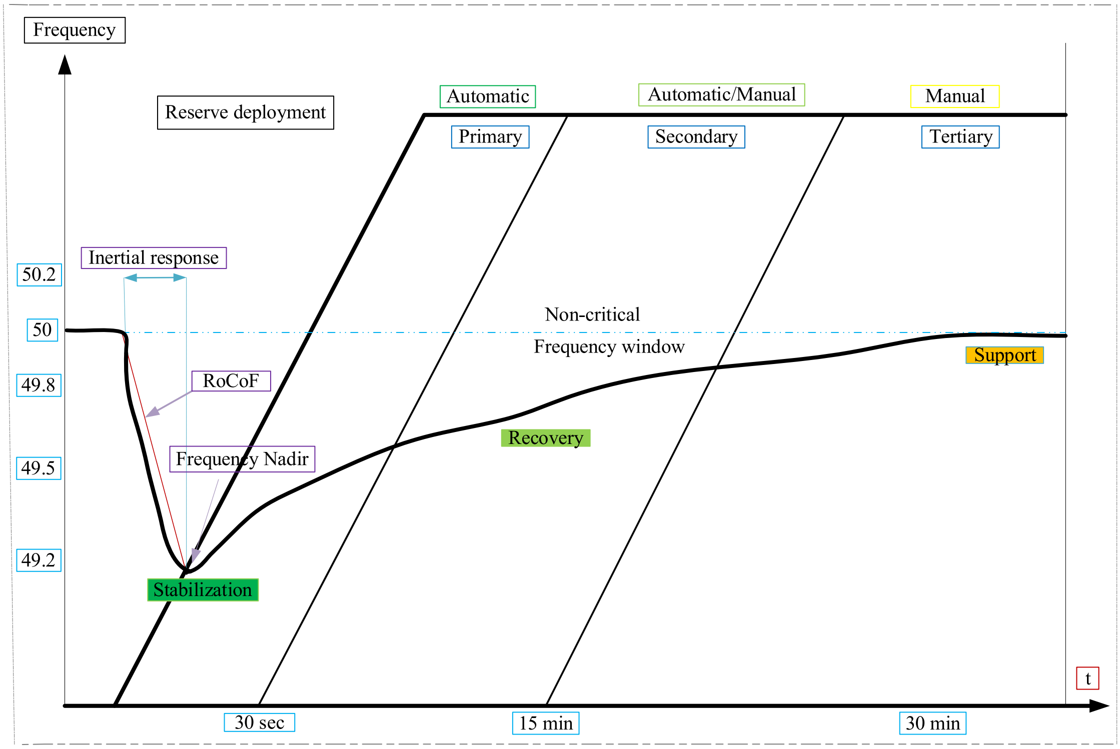

Fig. 2. Various frequency response phases.

and adaptable load side components, also offers a feasible plan for electric utility frequency control [46]. In contrast to traditional SGs, the switched control capability of demands permits the demands to participate in transient conditions rapidly. This adaptation helps load-side machines potential candidates for system frequency management, along with current developments in monitoring, processing, and communications systems.

Instead, the development of power electronics has made it possible for RESs to take part in FR operations. The two RESs that are typically frequently used are photovoltaic (PV) and wind turbine (WT). WTs can be divided into two main types fixed and variable speed. The system is immediately tied to the fixed-speed WT. As a result, it is capable of providing IR [47], though it is considerably less than the IR of synchronous machines. Whereas the power electronic design enables the variable speed WT and PV to be disconnected from the system frequency. They need supplementary power electronic controllers because they are unable to properly deliver FR functions. According to research, the two key controls employed in a wind turbine for FR in energy systems are de-loading and inertial emulation [48]. In Ref. [49] presented the primary frequency regulation technique for a combined wind-storage system using enhanced virtual inertia integrated control. The wind turbine runs below its nominal capacity there in the de-loading approach, and thus its output is regulated during failure to offer FR [50,51]. In inertial emulation, IR is produced using the kinetic energy that is stored in the wind turbine blades [52]. This article addresses the impact of energy storage and wind turbines on system frequency response during frequency regulation [53]. PV units supporting FR solutions can also employ the de-loading approach [54]. The authors established an approach to accurately estimate the damping factor and frequency of real-valued sinusoidal signals [55]. In addition, the development of advanced communication networks and intelligent switching enables the load to use demand-side management (DSM) to contribute to FR operations. DSM's major goal is to help the controlled loads be flexible to power frequency signals. The two types of FR employing DSM are (I) load reduction and (ii) load modulating. To supply additional features, the load reduction DSM method switches the load on and off [56,57]. Depending on fluctuations in frequency, a load-modulating DSM changes the utilization of load [58,59].

To determine all phasors and components' reactance, constant frequency (rated frequency) is utilized as a basis for present study projects in the area of power system stabilization and control. Furthermore, frequency dynamic behavior is getting more changes as a result of the introduction of novel approaches like DGs/RESs and greater load variations. As a result, the straightforward description of phasors and components' reactance could have an impact on how the electric grid relays, manages, and monitors, its power quality, as well as how components based on digital innovations operate. The electrical system's capacity to support microgrids (MGs) is further constrained by localized frequency constraints. To achieve this, a localized frequency estimate is essential in present power systems. Regional frequency prediction in present power systems has recently been the subject of some studies [60,61]. This paper reviewed decentralized energy/voltage control structures and techniques for MGs [62]. In several recent studies [63–65], the concept of estimating low power and the frequency regulation problem has been considered. The idea of robustness in the frequency regulation problem has been taken into consideration in certain recent research [66,67]. These initiatives seek to strengthen system frequency regulation robustness to intrusions and the ensuing manipulations. In many papers [68,69], the ancillary virtual inertias produced by reactive power supplies are also utilized to enhance the basic frequency regulation scheme. This paper introduced an initialization-free distributed approach for dynamic economic dispatch issues in MGs [70]. Other publications [71,72] have nowadays dealt with the development of enhanced frequency regulation for generators with uncertain input operational observers. The authors presented a distributed economic dispatch technique for power and water networks [73].

The energy storage system is among the most attractive choices for offering FR operations (i.e. IR, PFR, LFC) due to its rapid response time and operational flexibility. Rapid response times enable ESS systems to quickly inject huge amounts of power into the network, serving as a kind of virtual inertia [74,75]. The paper presents a control technique, supported by simulation findings, for energy storage systems to reduce wind power ramp occurrences and frequency deviation [76]. The authors suggested a dual-mode operation for an energy-stored quasi-Z-source photovoltaic power system based on model predictive control [77]. This study proposes a coordinated control technique for wind turbines and energy storage devices during frequency regulation to avoid secondary frequency drops, as demonstrated by Power Factory simulations [78]. The energy storage system anticipates upward/downward regulation by injecting/absorbing power into/from the system, much like the fast traditional generation plants that are maintained to update supply PFR by increasing/decreasing their output power in under/over frequency situations [79]. During frequency deviations around 0.02 Hz, the ESS is not used. During frequency variations from 0.02 to 0.2 Hz, the outputs of ESS are linearly enhanced. A 900-s gap is allowed for the ESS to charge batteries after the power has been delivered for 900 s [80]. The specifications for ESS reserve installation, including the operating time (900 s) and linear utilization of the reserve, are mainly obtained from the performance of rapid-responding traditional generators [79]. Energy storage systems exist in a variety of forms, and they all have unique features and operating procedures. According to their quick response times and adaptable operational needs, the presently offered techniques BES, FES, SMES, and SCES are much suited for FR operations [81]. The illustrations of practical BES, SCES, FES, and SMES operations and associated capabilities are shown in Table 2.

Energy storage has been utilized in wind power plants because of its quick power response times and large energy reserves, which facilitate wind turbines to control system frequency [82]. As of recently, there is not much research done on how to configure energy storage capacity and control wind power and energy storage to help with frequency regulation. Energy storage, like wind turbines, has the potential to regulate system frequency via extra differential droop control. According to Ref. [83], the shifting relationship between the energy reserve of energy storage and the kinetic energy of the rotor of a synchronous generator defines the virtual inertia of energy storage. Wind farms are outfitted with energy storage to ensure that wind generators respond to inertia at low wind speeds for coordinated frequency management [84]. The system's frequency change rate reaches its maximum during a load disturbance because of the system's maximum power shortfall, but it still has enough inertia to slow down the frequency change rate. Currently, energy storage has to assess whether it provides inertial support based on the system's frequency requirement and the DFIG's capability for inertial support. The system's specifications for frequency regulation state that the frequency change rate cannot be higher than 0.5 Hz/s. The system can be given inertial support and the frequency change rate can be maintained within a safe range by sensibly allocating energy storage capacity. Energy storage systems provide outputs with rapid response times, huge capacities, and long durations that are effective in suppressing frequency change rates. These characteristics allow the outputs to drastically reduce frequency changes.

2.1. *Traditional frequency control methods for power system*

Traditional frequency regulation Long-term sustaining unexpected frequency changes may be detrimental to the performance, reliability, and safety of the electricity grid. Additionally, this incident can result in component failure and deteriorate the performance of relay and safety systems. Various kinds of frequency regulators are required to stabilize and recover the electric grid frequency based

Table 1
Normalized characteristics of ESS technology [128].

System	Rating		Destiny		Response time	Efficiency (%)	Self-discharging per day (%)	Lifetime	
	Power rating (MW)	Discharging time typical	Power density (W/I)	The energy density (Wh/I)				In (years)	In (cycles)
PHS	100–5000	1–24h+	0.1-0.2	0.2–2	min	70–80	Very small	>50	>15,00
CAES	5–300	1–24h+	0.2-0.6	2–6	min	41–75	Small	>25	>10,000
FES	0–0.25	s-h	5000	20–80	<s	80–90	100	15–20	104–107
LA	0–20	s-h	90–700	50–80	<s	75–90	0.1-0.3	3–15	250–1500
NiCd	0–40	s-h	75–700	15–80	<s	60–80	0.2-0.6	5–20	1500–3000
Li-on	0–0.1	min-h	1300-10,000	200–400	<s	65–75	0.1-0.3	5–100	600–1200
NaS	0.05–8	s-h	120–160	15–300	<s	70–85	−20	10–15	2500–4500
VBR	0.03–3	s-10h	0.5–2	20–70	s	60–75	Small	5–20	>10,000
ZnBr	0.05–2	s-10h	1–25	65	s	65–75	Small	5–10	1000–3650
FC	0–50	1–24h+	0.2–20	600 (200 bar)	s-min	34–44	0	10–30	103–104
SC	0–0.3	ms-1h	40,000–120,000	10–20	<s	85–98	20–40	4–12	104–105
SMES	0.1–10	ms-8s	2600	6	<s	75–80	10–15	–	–

Table 2
Different ESS features [81,133,134,138].

Storage type	Power density (W/kg)	Power density (MW/m^3)	Power cost ($/kW)	Energy density (Wh/kg)	Energy density (kWh/m^3)	Energy cost ($/kWh)	Cycle efficiency (%)	Life cycle (cycles)
Li-ion	150–500	0.4–2	686–4000	70–200	200–600	240–2500	90–97	Up to 20,000
SCES	1000-10,000	0.4–10	100–400	0.5–5	4–110	500–15000	90–97	50,000-1000000
FES	500–4000	1–2.5	150–400	10–50	20–100	1000–14000	90–95	20,000+
SMES	500–2000	1–4	200–500	1–10	0.2–2.5	1000–10000	95–98	20,000-100000

on the magnitude and duration of the frequency deviation [85]. The production and demand unbalance and magnitude of the disruption are shown by the magnitude of Δf, which is the "magnitude" of the frequency variation. For example, $\Delta f = 0.01$ per unit (pu) for a standard frequency of 50 Hz becomes 0.5 Hz. The "length" of a frequency variation relates to its length; for instance, a frequency variation of $\Delta f = 0.01$ pu during 1 s signifies that a one percentile variation is maintained for the period of about 1 s. The duration specified differs from the "period of oscillation" described in the low-frequency fluctuations issue of damp control and rotor angle stabilization.

2.1.1. *Primary frequency regulations*

The primary control system of the present SGs can adjust for minor frequency fluctuations during regular operation. All SGs' aforementioned regulating loops react for a short period after disturbances. The system frequency will eventually settle to a value different from the base frequency because of the proportional feature of SGs droops though. As a result, tie-line energy flow among coupled control regions might reach levels that deviate from those that were originally scheduled.

2.1.2. *Secondary frequency regulations*

The load frequency control or secondary control network is engaged during abnormal operations, depending on the quantity of available regulating energy, the control system will be operated to adjust for the electric grid frequency and restore it to the optimum value. The LFC serves as the foundation of automatic generation control (AGC). A fraction of a second to many minutes can be attenuated by the secondary control in terms of frequency and real power variations. Through allocating adequate power reserves, the control scheme maintains the expected tie-line power and optimum frequency.

2.1.3. *Tertiary frequency regulations*

A considerable generation and demand unbalance can result from a major failure or instability, and frequency variations might not be adequately corrected by the secondary frequency control scheme. In this situation, further control action, known as tertiary control, is needed using the backup power generation to minimize the probability of cascading failures and instability. To restore the system frequency to standard and exchange tie-line power to scheduled quantities, this control method utilizes the immediate support power backup, connects (disconnects) production plants, reschedules the frequency control stakeholders, and manages grid demands. Under-frequency load shedding (UFLS), a safety and emergency control mechanism, should be deployed in the most extreme scenario [86].

2.2. *Frequency regulations methods for power systems with RESs*

Due to their high level of unpredictability, intermittent nature, and nonlinear power system connectivity, RESs such as wind energy bring technological hurdles to energy systems. The need for adaptability in operations and power consumption management is increased by this sort of source. In addition, the network rotational inertia is reduced when SGs are replaced with power electronic-based RESs Network operators deal with major frequencies and tie-line power management issues in electrical networks when RESs are heavily integrated. When there are few SGs and little kinetic energy in isolated power systems, this problem is more serious. In today's electric utility frequency regulation, the unpredictable nature of the demand poses a significant obstacle. Load is becoming increasingly unpredictable, particularly in distribution networks with electric mobility networks. Such networks' only option for such effective modeling of the output of both reactive and active power, in the absence of LFC and a universal frequency management system, is the suitable regulation of power conversion operation conditions [63]. The enormous capability of Renewable generation and microgrids to provide control energy and frequency regulation services must be utilized for a robust and reliable electricity network with massive deployment of Renewable generation. This has demonstrated how highly these essential components of upcoming smart grids can help power system frequency regulation. In actuality, several firms already have made the necessary revisions to existing grid codes, and research has been carried out to create better efficient frequency regulators for the regulation of RESs, Energy storage systems, and microgrids [87]. The network code of some companies presently requires the capacity to contribute to the regulatory power supply. Additionally, certain RESs/MGs are isolated because of flow control, adequate inertia, and backup supply; their power can be utilized to create rising power reserves. Due to the significant fluctuation of RES productions, the distribution of the control capacity by RESs in smart power societies would vary from the similar approach for SGs [88].

2.2.1. *Wind power frequency regulation*

The rapid expansion of fluctuating sustainable power and its implications on electric utility efficiency and regulation pose a substantial challenge to the operation and management of advanced power systems. Nevertheless, this expanding utilization of wind energy also introduces unanticipated risks to the stability of the electrical grid and makes system frequency control more challenging. To simulate fundamental frequency power systems, its emphasis in Ref. [89] has been on modelling wind turbines with direct drive permanent magnet synchronous generators. These two approaches, however, are unable to manage the power system's rapid frequency fluctuation caused by wind generation. In Ref. [90], authors investigated the dynamic scheduling and control schemes (DSCS) of small-scale renewable energy sources in conjunction with the features of renewable energy aggregators (REA). To ensure the electrical system's capacity for frequency control, however, REA needs to deploy ESS. Many studies have proposed various technical methods, such as rotor speed control and variable pitch control, to manage wind energy limitations. Additionally, they explore using the reserve capacity of wind turbines for frequency control. Additionally, researchers suggested a control technique [91], that combines blade pitch angle and rotor speed control to improve the wind farm's capacity for frequency management. However, using these techniques will minimize the wind farm's financial benefits. In Refs. [92,93], it is challenging to ensure the reliability of the frequency maintained by the wind turbine because of the fluctuating and stochastic nature of wind power. The wind turbines, that had contributed to the frequency management of the power system, must be quickly taken back to their ideal speed when the issue has been fixed. As a result, certain active power from the utility grid will be absorbed by the wind turbine, potentially leading to a dual frequency dip. In Ref. [94], authors increase the frequency modulation capability of wind generators by introducing virtual inertia, taking into consideration the frequency control of wind turbines. Furthermore, it is necessary to significantly improve the wind turbines' capacity for frequency response.

Among the most common varieties of wind power generators now available is the doubly-fed induction generator (DFIG). It typically operates in MPPT condition (maximum power point tracking) [95], where the speed of the rotor is uncoupled from the power system. In this condition, DFIG lacks the synchronous generator's inertia as well as droop characteristics. Due to system frequency oscillations, an electric grid including a DFIG would display low stability [96]. To address this issue, the wind power system connection regulations stipulate that grid-connected wind turbines must be capable of inertia response and primary frequency supports [97,98]. The current approaches used by DFIG to participate in frequency control can be divided into different types utilizing rotor kinetic energy, maintaining reserve power, implementing energy storage technology, de-loading control, and pitch angle control.

A. Frequency regulation of wind generation utilizing rotor kinetic energy

The objective of rotor kinetic energy regulations is to add a frequency control interface to the active power control system of a wind farm, which also provides fast frequency regulations power by delivering the rotor's kinetic energy to maintain the system's frequency constant. To further improve the wind plant's capacity for frequency control, they also suggest in Ref. [91] a control technique that utilizes variable pitch angle regulation and rotor speed control. In Refs. [99,100], a control scheme is correctly incorporated into Wind turbines; this control loop boosts the network's capability to react inertial to changes in frequency by enabling WTs to adapt to those changes by employing rotational kinetic energy concealed within the rotors. However, using these techniques will decrease the wind farm's economic benefits. To increase the ability to adapt the rotor kinetic energy regulation, the variables of the suggested control method were optimized in Refs. [101–103]. However, the amount of controlled kinetic energy in the rotor is constrained, and as a result, the controlling ability is inadequate.

To produce rotary inertia related to that of a synchronous generator and respond rapidly to shifts in system frequency, the rotor speed can be adapted quickly. Nevertheless, the rotor speed is dependent on the wind speed, operating conditions, and the rotor speed limit (the speed adjustable range is typically 0.7 p.u. to 1.2 p.u.), which shortens the adjustment process. This procedure may also result in a secondary decrease in frequencies during the restoration of the rotor speed.

B. Frequency regulation of wind generation maintaining reserve power

This control approach can be implemented by a combination of pitching control on one hand and speed control of the wind generator on the other hand. In this control approach of maintaining reserve power, the DFIG keeps a specific reserve power by using over-speed regulation or blade pitch [104–106], allowing the DFIG to offer primary frequency control and long-term power management. Furthermore, this strategy involves the DFIG operating at the load-shedding state under normal circumstances, which significantly wastes wind energy resources. One approach is to maintain a WT's speed at its ideal level while regulating pitch solely to reach de-loaded peak power. In this instance, a smaller pitch angle makes it possible to supply more active power. Another approach is to manage the WT's rotor speed to generate power reserve. In this instance, a slower rotor speed makes it possible to boost the active power delivered while also recovering a significant quantity of kinetic energy from spinning masses. Regarding frequencies control power reserve, only tip-speed ratios that are larger than the ideal tip-speed ratio in optimum operating mode are acceptable. Once frequency excursion happens, the windmill controller adjusts the benchmark rotor speed to its set point. This enhances the efficiency coefficient to its ideal value and, as a result, enhances the active power produced.

The power reserve control technique switches from speed control to pitch control after the optimum wind turbine rotor speed has been attained. In contrast to speed control, pitch control manages pitch angle based on network frequency and power in sub-optimal operating conditions, taking into account the maximum power that a wind turbine can generate. Consequently, a wind turbine does not produce any extra kinetic energy.

C. Frequency regulation of wind generation implementing energy storage technology

It is predicted that renewable energy will share some of the burdens of frequency management in the future power system with a high penetration of renewable energy sources with conventional generators. For accurate and long-lasting frequency control, wind energy and energy storage systems complement each other. As a result, it would be advantageous to combine wind power and energy storage systems to build a real power station or a virtual power station that could supply the industries with both energy and frequency control.

A main frequency control feature for the electricity system is provided by wind turbines and energy storage technologies, according to a study published in Ref. [107]. The analysis demonstration focuses on the wind turbine and energy storage system's maximum economic benefits. There are numerous limitations to simulation, including the power balance of the power system, the wind turbine's control strategy, the energy storage system's participation in frequency control, and the energy storage system's operational limitations. Furthermore, the outcomes of the example evaluation provide the appropriate ESS capability and power. The study also highlighted the significance of the grid firm's regulatory assistance in enabling wind farms and ESS to be profitable. In Ref. [108], it was anticipated that the ESS would offer frequency control services for the power system with a high wind energy integration. This approach will result in a situation where the ESS setup capacity exceeds the actual demand. As a result, those studies' descriptions of the profitability of ESS and wind turbines require to be enhanced.

D. Frequency regulation of wind generation by de-loading control

In typical operation, a wind turbine usually runs in the most economically possible condition for maximum power tracking, known as optimum power extraction. The wind turbine needs, moreover, to operate at the de-loaded optimum power extract curves, in which the active power delivered by each wind turbine increases or decreases as the network frequency varies, in addition to participating in frequency management. It is suggested [109] that WF operate at the de-loaded power harvesting curve so that WF might take part in the frequency regulation of additional services. An approach for wind energy frequency control that combines inertial control with over-speed reducing control was presented in Ref. [110], and while it can significantly enhance the system's capacity for frequency control, it does not apply to high wind speed conditions due to the limitation of the over-speeding de-loading capacity.

The de-loaded control of DFIG can be performed, as per [110–112], by increasing the rotor speed. The only constraints that this control approach can be used are those with moderate and low wind speeds. The research from Refs. [113–115] demonstrates that such wind turbines can also regulate their active output power by changing their blade pitch. However, pitch control is applicable in all wind speed zones, the blade's pitch angle must be activated often. To fully improve the productivity of the wind turbine, a control method based on coordinated over-speed and blade pitch control is presented in Ref. [116]. The coordinate control strategy employs a variety of control mechanisms to respond to fluctuations in wind speed. However, the control input employs wind speed measurements that are unsuitable in real applications.

WT de-loading operations can be accomplished using both over-speed controls and deceleration controls. Although deceleration control has a few minor interfering stability issues, over-speed control is more frequently utilized. Speed increases can cause the output to decrease and the operating curve to shift to the right, leaving some additional capacity. Whenever the network frequency decreases, the WT slows down, and the operating curve shifts to the left, increasing output and preventing the decrease in network frequency. Whenever the network frequency varies, the frequency deviation is presented, and the pitch angle adjusts along with the frequency deviation, adjusting the outputs of WTs and preserving the reliability of the grid frequency. This process involves setting aside a specific pitch angle for power reserve.

E. Frequency regulation of wind generation by pitch angle control

Contributions of wind turbines in primary frequency control, a blade pitch frequency control approach for a doubly fed wind turbine running over the nominal wind speed. Blade pitch control refers to adjusting pitch angles by shifting the rotor blades' route only a little bit away from the wind's flow [117]. This includes the movement of mechanical components, which slows down the responses and, in the event of continuous changes, also could put stress on the components involved [118]. There are several options offered that take into account the pitch angle and rotor speed controls that will be used in a processing step. According to Ref. [119], rotor speed regulation is recommended for under-speed, and above-speed pitch regulation is favored, according to the speed zone.

It is suggested in Ref. [120] to use pitch angle regulation as such an approach to smoothing WT power. By adjusting the blade pitch angle of the wind turbine, the output power of the wind turbine can be somewhat smoothed. Moreover, the vast amount of energy that wind turbines harvest are lost during blade pitching.

In brief, it is the fact that wind turbines offer assistance in frequency regulation and respond to frequency fluctuations effectively has already been mentioned. However, they do have issues with secondary frequency drop and output losses during rotor speed restoration. Additionally, it is unable to provide continuous assistance. To address these issues, an energy storage system is employed to ensure that wind turbines can sustain power fast and for a longer duration, as well as to achieve the droop and inertial characteristics of synchronous generators (SGs). In addition to addressing the aforementioned issues, energy storage devices with wind turbines ensure that they can provide long-term frequency regulation.

3. An updated review of frequency control techniques for modern power systems with energy storage systems

Modern power systems employ a variety of technological advancements, including sophisticated communication systems, energy storage devices, electric automobile charging stations, and distributed renewable energy sources. Due to the penetration of emerging innovative technologies, power systems are undergoing a transformational transition. The term "The Energy Transition," which is frequently used to describe this transformation, primarily alludes to two significant modifications: the expanding integration of renewable energy resources and the growing utilization of electric vehicles [121,122]. When integrating renewable energy into the aforementioned traditional system, challenges arise; as a result, EES was developed to address these issues.

3.1. Brief introduction of different energy storage systems

Energy storage systems are among the significant features of upcoming smart grids [123–125]. Energy storage systems exist in a variety of types with varying properties, such as the type of storage utilized, fast response, power density, energy density, lifespan, and reliability [126,127]. This study's main objective is to analyze BES, SCES, SMES, Hydrogen, and FES applications in frequency regulation utilities. These are rapid-responding energy storage systems. The dynamic response of the Energy storage system may be influenced by several variables, including storage types, charge/discharge ratio, status of charge, and temperatures. Therefore, various ESS approaches have been put forth in the research for frequency regulation investigations that represent their dynamical behavior about frequency responses. Table 1 displays details about various ESS technologies.

3.1.1. Energy storage utilizing batteries

The battery is supposed to be the oldest and most established method of storing electricity in the form of chemical energy [127, 129]. A BES is composed of several single cells coupled in both series and parallel [130]. Every chamber contains electrolytes as well as a cathode and anode [131]. Each battery undergoes specific electrochemical reactions, which are initiated during both the charging and discharging processes. Moreover, these batteries serve a dual function, acting as both consumers and distributors of electricity within the grid [132]. Standby time might be from a few seconds to several hrs with energy storage. There are various battery designs, and they all have unique features [133]. Battery energy storage typically has a high energy density, a low-powered density, and a short cycle lifespan. A battery can be used in operations that demand prolonged continuous discharge. Nevertheless, the battery performance is reduced by regular, fast charging and draining. It is challenging to say categorically that one BES system is superior to others given the wide variety of BES technologies that are now present. A different choice can be made for the relevant scenario according to the user's power and energy requirements, response rate, working temperature, and ambient temperature. Furthermore, an evaluation focused on the power and energy properties of well-known BES techniques has been conducted. The normalizing features of well-known battery storage systems are presented in Table 2. The data is taken from Ref. [134] and references are mentioned there. The flow battery's uses are restricted to large-scale because of its extended service life, weak power, and low energy density. The metal-air batteries have a long cycle lifetime but a low power density and high energy density. Although less expensive, lead acid batteries have poor service lifespan and energy density, which restricts their use to frequency regulation. Additionally, two other developing storage methods are sodium ion and zinc ion. A high energy density (e.g., 200–300 Wh/kg) is a property of the sodium ion [135]. Poor power density and short cycle lifespan are indeed the major challenges to using sodium-ion batteries for frequency regulation. Studies are currently being done to increase service lifetime and power density [136]. Zinc-ion is more affordable, secure, and friendly to the ecosystem. Compared to Li-Ion battery packs, Zinc-ion battery packs have a lower energy density (85 Wh/kg) [137]. It can be stated that Li-Ion is the technology that better matches frequency regulations services out of all the established and widespread ones.

3.1.2. Energy storage using a supercapacitor

Double-layer electric capacitors and ultracapacitors are other names for supercapacitors [139]. A dielectric medium separates the two electrodes that make up the SCES. Instead of transforming it into another type of energy, such as chemical energy in battery packs or mechanical energy in the scenario of FES, the SCES stores electrical energy effectively in the electrostatic field between the electrodes [140]. SCES is independent of chemical processes, allowing for very quick charging/draining with large currents [134,141]. SCES technique has an extremely long lifetime, smaller energy density, high power density, and quick response times.

3.1.3. Energy storage employing a flywheel

Flywheel storage is an electromechanical energy storage system that stores kinetic energy [142]. A spinning wheel and an electrical unit that serves as a generator and a motor while charge and discharge compensate an FES energy storage [143]. The mass and rotational speed of the rotating wheel affect the overall energy of FES. The electrical device functions as a motor during the charging process, accelerating the rotating wheel and boosting the energy stored. The unit functions as a generator when in the discharge cycle

Table 3
A comparison of the energy, power, cost, and technical maturity of various ESS technologies

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

and is propelled by a rotating wheel [144,145]. The FESs features a long lifetime, poor energy density, quick response times, strong self-discharge rates, and low power densities.

3.1.4. *Superconducting magnetic energy storage*

A magnetic field is used to store energy in SMES, an electromagnetic energy storage system [128]. Superconducting coils, power conditioning systems, and cooling systems make up the three main parts of an SMES [146]. The magnetic field that is created across the superconducting coils as a result of the current flowing over it is where the energy is stored during the charging process of the SMES. Underneath the critical temperature for superconductivity, the superconducting coils are cooled down. The amount of stored energy is influenced by the coil's self-inductance and current flow [147]. The SMES's stored energy is discharged into the electricity network via a power conditioning system. The SMES features an increased life span, quick response times, a decreased energy density, and an increased power density. A comparison of different ESS technologies is shown in Table 3.

To acknowledge the diverse states of maturity of various energy storage technologies such as flywheels, supercapacitors (SCs), and superconducting magnetic energy storage (SMES). SMES technology has a lot of potential for energy storage and grid frequency

Table 4
Core issues and solutions for energy storage systems.

	Energy storage system	*Core challenges*	*Techniques to solve challenges*	*References*
1		*Energy Density:* Maximizing the amount of energy stored per unit volume or weight.	*Materials Innovation:* Developing new battery chemistries and materials for improved performance and safety	[154]
	Batteries	*Cycle Life:* Ensuring batteries can undergo numerous charge-discharge cycles without significant capacity degradation.	*Battery Management Systems (BMS):* Implementing advanced BMS for optimal performance and health monitoring.	[155]
		Cost: Lowering the production and maintenance expenses of battery systems	*Manufacturing Processes*: Streamlining production processes to reduce costs.	[156]
		Safety: Mitigating risks such as thermal runaway and fire hazards	*Second-Life Applications:* Repurposing retired batteries for stationary energy storage.	
2		*Energy Density:* Increasing the amount of energy stored per unit mass or volume.	*Materials Innovation:* Developing advanced electrode materials for improved performance.	[157]
	Supercapacitor	*Cycle Life:* Enhancing the durability and longevity of supercapacitors.	*Electrode Design:* Optimizing the structure and composition of electrodes.	
		Cost: Lowering the manufacturing and materials expenses.	*Scalable Manufacturing Processes:* Implementing cost-effective production methods.	[158]
		Self-discharge: Minimizing energy loss over time.	*Electrolyte Optimization:* Enhancing the efficiency and stability of electrolytes.	0
3		*Energy Density:* Maximizing the amount of energy stored within the flywheel.	*Materials Innovation:* Developing lightweight and durable materials for flywheel construction.	[159]
	Flywheel	*Rotational Losses:* Minimizing energy losses due to friction and air resistance.	*Magnetic Bearings:* Implementing advanced magnetic bearing systems to reduce friction.	
		Mechanical Stresses: Managing mechanical stresses to ensure long-term reliability.	*Vacuum Encapsulation:* Using vacuum chambers to minimize air resistance and energy losses.	[160]
		Cost: Reducing manufacturing and maintenance expenses.	*Manufacturing Processes:* Adopting efficient production techniques.	
4		*Energy Efficiency:* Improving the efficiency of energy storage and retrieval processes.	*Cryogenic Cooling:* Utilizing cryogenic temperatures to maintain superconducting states.	[161]
	Superconducting magnetic	*Cost:* Lowering the expenses associated with superconducting materials and cryogenic cooling.	*Superconducting Materials*: Researching and developing high-temperature superconductors.	0
	0	*Cooling Requirements:* Managing the cooling infrastructure required for maintaining superconducting states.	*Magnetic Field Stability:* Ensuring stability and reliability of magnetic fields.	[162]
		Energy Density: Maximizing the amount of energy stored per unit volume.	*Thermal Insulation:* Minimizing heat transfer to enhance efficiency.	
5	0	*Hydrogen Storage:* Developing efficient and safe methods for storing hydrogen.	*Materials for Hydrogen Storage:* Researching novel materials for high-capacity hydrogen storage.	[163]
	Hydrogen energy	*Efficiency:* Enhancing the efficiency of hydrogen production and utilization.	*Electrolysis Efficiency:* Improving the efficiency of electrolysis processes for hydrogen production.	[164]
		Cost: Lowering the expenses associated with hydrogen infrastructure and fuel cells.	*Fuel Cell Efficiency*: Enhancing the performance and durability of fuel cells.	
		Infrastructure: Establishing a robust distribution network for hydrogen.	*Distribution Infrastructure:* Investing in the development of hydrogen distribution networks.	
6		*Energy Density:* Maximizing the overall energy storage capacity of hybrid systems.	*Materials Innovation:* Developing compatible materials for hybrid systems.	[165]
	Hybrid energy	*Cycle Life:* Ensuring durability and longevity across multiple storage technologies.	*Advanced Battery Management Systems (BMS):* Implementing sophisticated control algorithms for optimal operation.	
		Cost: Optimizing the cost-effectiveness of hybrid energy storage solutions.	*Integration of Multiple Storage Technologies:* Combining different storage technologies to leverage their respective strengths.	[166]
		Scalability: Designing systems that can scale to meet varying energy demands.	*Optimization of Hybrid Systems:* Utilizing predictive modeling and control strategies for efficient operation.	

regulation because of its high-power density and quick response times, but it's important to remember that it might not be as developed as other technologies like flywheels or SCs. Even though certain SMES system prototypes have undergone testing and show promise, more research and development may still be necessary to ensure their economic feasibility and widespread implementation. While assessing any energy storage technology's viability for a given grid application, it is crucial to consider its present state and maturity level to make the best deployment decisions and ensure informed decision-making.

3.1.5. Hydrogen energy technology

To mitigate the impact of significant wind power limitation and enhance the integration of renewable energy sources, big-capacity energy storage systems, such as pumped hydro energy storage systems, compressed air energy storage systems, and hydrogen energy storage systems, are considered to be efficient [148]. Because of its vast energy storage time duration, quick response time, and geographical flexibility, hydrogen energy storage systems utilizing water electrolysis are suggested proficiently because the uses of the first two are geographically constrained [149]. However, its cycle reliability is not very excellent whenever the stored energy is transferred back into the form of electricity. As a source of energy, hydrogen is employed in a variety of important approaches, including essentially reusing CO_2 into fossil energy, fueling internal combustion engines, mixing with natural gas in pipelines, and effectively refueling fuel cells [150]. According to Ref. [151], which considered generation and storage techniques, risks, and security concerns associated with hydrogen technology, hydrogen is quite a suitable option either as a fuel for future cars or as a form of energy storage in large-scale power systems. A novel energy storage technique called hydrogen storage has also been created recently [152, 153]. The frequency reliability of wind plants can be efficiently increased due to hydrogen storage systems, which can also be used to analyze the wind's maximum power point tracking and increase windmill system performance. A brief overview of Core issues and solutions for energy storage systems is shown in Table 4.

3.1.6. Hybrid energy storage technology

The attractive features of an Energy storage system include its high-power density, high energy density, extended cycle life, quick response, quick discharge time, extended operating temperature range, and reduced cost. Table 3 provides details on the power,

Table 5
Summary of frequency control techniques with energy storage systems

Strategy	*Important features and applications*	Citations	Year of Publication
1. Battery Energy Storage System	•Chemical energy is converted into electrical power. •Can be employed to provide both primary frequency control and dynamic grid assistance at the same time. •Is capable of providing immediate assistance for both voltage and frequency regulation	[130,132, 135,136], [137].	2018, 2012, 2019, 2019, 2019
2. Super Capacitor Energy Storage System	•possesses a considerably higher rate of electrical energy storage and discharging than Li-ion, Ni–Cd, or flow batteries •It can be employed in combination with BESS for a variety of applications in low-inertia networks. •In responding to rapidly changing power imbalances, it can provide an immediate energy supply.	[134,139], [140,141].	2018, 2015, 2009, 2017.
3. Flywheel Energy Storage System	•Usually consists of three basic components: the spinning cylindrical body, the motor, and the converting interface. •Can store kinetic energy from revolving cylinders. •The quantity of energy stored is determined by the mass and spinning rate of the cylindrical rotor. •Can be employed for frequency assistance, voltage control, black start, maximum shaving, and RES intermittency mitigation. •Because of its rapid reaction and better dynamics, storage technology is seen to be the best option for supporting wind farms.	[142,143], [144,145].	2007, 2021, 2016, 2017.
4. Superconducting Magnetic Energy Storage System	•Has an exceptionally rapid reaction rate, exceptional efficiency, and a massive charge/discharge rate. •Converts the energy stored in a magnetic field created across a superconducting coil into electric power. •can be used as a frequency regulation approach in an isolated microgrid. •can be used in combination with a thyristor-controlled phase shifter (TCPS) to enhance a system's transient responsiveness.	[128,146], [147].	2015, 2010, 2011.
5. Hydrogen Energy Storage System	•Another type of chemical energy storage is hydrogen energy storage. •This energy must be stored before it can be released by utilizing the gas as fuel in a combustion engine or a fuel cell. •Steam turbines, hydrogen fuel cells, and piston engines all can operate on hydrogen as energy, with hydrogen fuel cells having the highest efficiency.	[148,149], [150,151], [152,153].	2014, 2012, 2013, 2012, 2015, 2014.
6. Hybrid Energy Storage System	•To tackle MGs and RES issues, a hybrid energy storage system is a suitable option. •The key benefits of HESS are as follows: reduced storage system costs, increased storage lifetime, reduced reaction time of MG dynamics, increased MG dependability, improved power quality, and pulse demand-supply. •A suitable design is necessary to reap the rewards of HESS.	[167,168], [165,169], [170,171].	2018, 2017, 2021, 2016, 2018, 2016.

energy, budget, number of lifespans, temperature range of operation, and lifetime of BES, SCES, FES, and SMES. It is clear from Table 3 that no storage method demonstrates the perfect storage properties. As an illustration, BES does have a high energy density but a poor power density, shorter life cycles, and a high cost for the power capacity. Even though, SCES, SMES, and FES share practically the same features, namely large power density, low price of power capacity, and long lifetime, in contrast to relatively tiny energy density and high cost of energy capacity. A brief overview of frequency control methods with energy storage systems for power systems is shown in Table 5. The properties of SCES, FES, and SMES techniques complement those of the BES, as can be seen from the diagram. By combining two different storage systems with complementary properties, a HESS can be created. HESS is used to evaluate the viability of BES-SCES in Refs. [167,168], BES-FES in Refs. [165,169], and BES-SMES in Refs. [170,171].

3.2. Applications for energy storage systems that facilitate the integration of wind power

The wind power generation operators, the power system operators, and the electricity customer are three different parties to whom the battery energy storage services associated with wind power generation can be analyzed and classified. The real-world applications are shown in Table 6.

3.2.1. ESS to assist efficient power transportation

Wind energy integration's key problems are energy intermittent, ramp rate, and restricting wind park production [174]. The energy storage system generating-side contribution is to enhance the wind plant's grid-friendly order to transport wind power in ways that can be operated such as traditional power stations. It must also be operated to make the best use of the restricted transmission rate.

3.2.2. ESS to assist system frequency regulation

The utility company requires advanced wind plants to provide grid frequency regulations. Supporting frequency response from wind parks is currently possible with increased wind penetrations by employing ancillary droop control. Nevertheless, it may affect wind turbine fatigue and uncertainty [175,176]. The utilization of the Energy storage system is an appropriate method. A regional droop control could be introduced to the ESS's real power control system for primary frequency regulation. The droop control is designed to adjust the active energy output proportionally to the frequency variation [99]. The central Automatic Generation Control (AGC) generates the real power signal for secondary frequency regulation.

3.2.3. ESS to support system inertia

An electrical utility's total inertia is decreased by large DG/RES connectivity. Reduced inertia may compromise the network frequency's transient efficiency and stability. The network can be strengthened using virtual inertia to address this problem. An Energy storage system with the power-electronics converter and the right control algorithm can be used to create virtual inertia to simulate the essential inertia. Fig. 3 illustrates an interpretation of this idea in the frequency response. In Refs. [177,178] provide more information on internal virtual controls. The transfer functions of a phase-locked loop, K_f (s) used in VSC schemes, and the inertia constants are all examples of virtual inertia loops. Significantly, the K_f (s) supports the dynamics of the inertia control loop by using the state of charge (SOC) of the energy storage system and frequency variation as input feedback control. Although M. is referred to by the power system in Fig. 3's diagram, K_f (s) represents the control of the virtual inertia scheme. In Refs. [178–180] include some pertinent scientific studies on virtual inertia. The M^{ESS}, M^{Conv}, and M^{MG} represent the inertia of energy storage devices, conventional generators, and microgrids respectively.

Power system inertia decreases frequency variations and causes the network less susceptible to abrupt generation changes. The RoCoF is determined by the immediate inertial reaction [6]. The presence of the energy storage system could greatly enhance a system's evident inertia. The ancillary loop could be introduced to the ESS's real power control.

3.2.4. ESS utilization for distributed wind power

In [181], the function of the ESS in dealing with wind energy in the contemporary energy market is reviewed. It has been

Table 6
Real-world energy storage facilities and their applications [133,172,173].

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

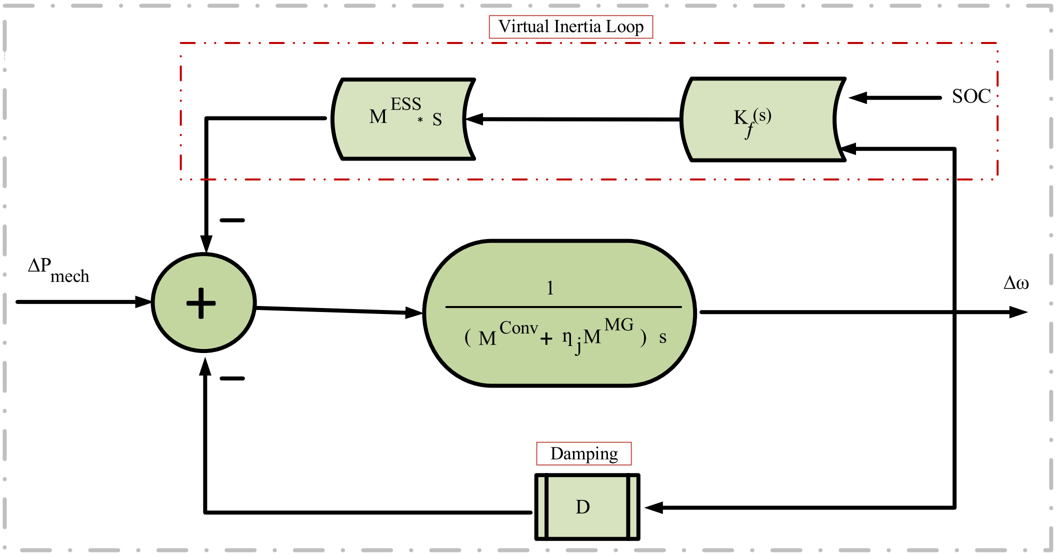

Fig. 3. A basic frequency response model based on virtual inertia.

demonstrated that a well-built ESS offers more financial advantages. The prospects for wind energy will be significantly enhanced if indeed the generation can be managed similarly to that of a traditional plant, as this will allow for the achievement of the best possible financial dispatch [182]. In Refs. [183,184], describes the many ways in which wind parks that use ESSs operate in the current power industry. Based on the forecasted wind speed, wind energy for the upcoming hours is projected. Power from wind farms dispatch plans must be provided in advance to the network operator. To regulate electricity flow and ensure economic dispatch, the network operator modifies the system's operational status. To make up for forecasting inaccuracies, the timeline may be changed after a particular time. The wind energy operator will be penalized economically if the electrical generation of the wind farm deviates from the stated timeline. Because of this, a significant amount of study focuses on designing short-term (daily) efficient scheduling schemes for wind farms that make use of the ESS's adaptable charging-discharging capabilities. In Ref. [185], estimates the predicted electricity dispatching depending on the hourly average forecasted wind energy without taking the financial benefit into account. The production planning in Refs. [186,187] is dependent on estimates of energy prices, demand, and wind generation. It tries to increase the anticipated return on investment from trading in the day-ahead electricity sector. The operators of the wind farms are considered to be a partners in the Nord Pool Spot market [188]. One stochastic factor is wind forecast uncertainty. Stochastic planning will be utilized to update the ESS hourly to maximize the benefits of both the wind farm and the ESS. A dynamical approach used for daily planning in an electricity market is introduced in Ref. [189]. The purpose of the online operational plan is to closely adhere to a predetermined production timeline. To estimate the power production of a hybrid WT-BESS system, a statistical method is suggested in Ref. [190]. A full charge-discharge process of the BESS is ensured by the newly devised dispatching technique, maximizing the energy storage capability. Ensuring correct forecasting of the wind energy, in Ref. [191] suggests an hourly discretized optimization approach to determine the best daily operation plan for the windmills and the PHS. These are examples of individual-unit ESS utilization. In Ref. [192] proposes a double BESS (one in operation and the other in backup), which gives designers of the dispatching strategy additional freedom. The energy from the wind-BESS power plant that was delivered could be considered a firm decision. Based on the long-term historical wind energy data, the tendency for the electricity supply to be efficient, as well as the BESS capability, can be evaluated. The author develops an optimal switchover dispatching system for a dual-BESS (Battery Energy Storage System) based on a comparable dual-ESS setup [193]. This system accounts for the charging and discharging characteristics of the deployed BESS, along with forecasted wind speeds. The WTGBES system's main purpose is to maximize the amount of wind energy that can be captured.

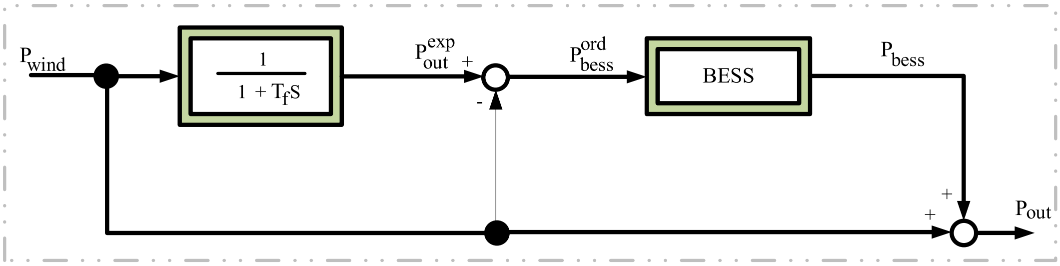

Fig. 4. The basic idea is to employ the LPF algorithm to reduce power fluctuations.

3.2.5. ESS strategies for eliminating fluctuations from wind farms

To reduce the output variation of wind farms, wind energy filtering techniques are frequently used with quick and short-term ESSs. In Fig. 4, a schematic diagram for a hybrid WF-streamlined ESS filtering controls is presented. The high-frequency portion of wind energy P_{wind} is processed as the ESS's charging or discharging instruction by a Low-Pass Filter (LPF) with a timed constant T_f. The real output varies from the desired output due to control delay, loss, and output limitation in the ESS. It is suited for use in real-time operation because of its simplicity and quick processing speed, nevertheless, making it simple to execute.

The power output baseline of the ESS P_{bess}^{ord} can also be established utilizing, as suggested in Ref. [194],

$$P_{bess}^{ord} = \frac{-\ sT_s}{1-\ sT_s} P_{wind} \tag{1}$$

However, the Remaining Energy Level (REL) of the ESS can be considered as,

$$REL = \frac{P_{bess}^{ord}}{S} = \frac{T_f}{1+sT_f} P_{wind} \tag{2}$$

According to Eq. (2), a bigger time constant T_f leads to a greater smoothing effect as well as bigger ESS energy and capability. The appropriate T_f must be chosen for the control algorithm. T_f is usually determined by the regional wind profiles and ESS capability, while it is maintained constant throughout operations [194–196] suggesting an adjustable LPF with an optimum T_f. The Particle Swarm Optimization (PSO) approach controls T_f in real-time. Every 1-min and 30-min time duration max power variation is limited within predetermined limits. It is simple to exceed the ESS size limits when wind farms have considerable output changes by using the simple smoothing approach without taking the state of charge into account. To maintain the charging levels inside the allowed limits, the SOC is provided as a feedback signal [194]. To prevent the ESS from over-limiting, a supplementary factor k is added in Ref. [181], as illustrated in (3). According to the predetermined curves based on SOC, k is modified.

$$P_{bess}^{ord} = k \frac{-\ s\ T_f}{1+sT_f} P_{wind} \tag{3}$$

The amplitude of the calculated power signal is altered as a result of the measuring lag. Further lead-delay compensation is developed and utilized for LPF to make up for this delay [197].

3.2.6. Operations of the hybrids ESS

The aforementioned subsections illustrate how the individual form of ESS operates. The logical approach is a hybrid ESS scheme, which integrates various storage systems into different layers that can be utilized to provide the required energy because a singular stored storage system can barely match the requirements of both fast reaction and enormous power capability [198]. In Ref. [199], the two-level storage for wind energy dispatching is controlled by a knowledge-based ANN control with a washout filter. The combination of several ESSs will provide considerably higher capacity compared to the single ESS for the power system with multiple deployed ESSs distributed over a vast region. These can be utilized for a variety of utility applications, including frequency control, load variations, and management of transmit power supply, by arranging them into a virtual assembly and central controlling it. The deployment of this method began in Yokohama, Japan, in 2012, and it is known as Batteries SCADA [200] in Japan. This system is an actual example of an aggregate energy storage unit that uses the BESS.

3.3. Energy storage systems' tertiary utilization in the integration of wind Power

ESS have important tertiary applications that help improve the integration of wind power into contemporary grid systems, in addition to their principal function of regulating frequency. In addition to primary and secondary frequency regulation, tertiary applications include grid support services such as voltage support, peak shaving, time shifting for renewable energy, and ancillary service providing.

3.3.1. Voltage support

ESS can offer dynamic voltage support, which helps lessen fluctuations in voltage brought on by intermittent wind power generation and helps stabilize voltage levels. ESS can increase voltage stability and dependability by injecting or absorbing reactive power as needed, especially in regions with a large concentration of wind farms.

3.3.2. Peak shaving

Peak shaving is another crucial use for ESS. It involves releasing stored energy during spikes in demand to lessen the burden on the grid and eliminate the requirement for traditional peaking power units. In areas with an abundance of wind, ESS can even out variations in wind speed and guarantee a steady supply of electricity when demand is maximum.

3.3.3. Time-shifting of renewable energy

ESS facilitate the development of renewable energy by storing and utilizing excess wind power produced during off-peak hours during periods of increased demand. This adaptability improves the overall performance of wind-integrated grid systems, minimizes curtailment, and maximizes the consumption of renewable energy.

3.3.4. Ancillary services

Moreover, ESS is capable of offering ancillary services including improved grid stability, reactive power support, and frequency response. These services are essential for preserving the resilience and dependability of the grid, particularly in those where variable renewable energy sources like wind power are heavily incorporated.

These ESS tertiary applications when combined with primary and secondary frequency control, can optimize energy storage's advantages in facilitating wind power's dependable and effective integration into contemporary grid systems.

In summary, wind power integration with energy storage technologies for improving modern power systems involves many essential features. Firstly, energy storage systems play a crucial role in mitigating the intermittent nature of wind power generation by storing excess energy during periods of high production and releasing it during low production or high demand. This helps to ensure a more reliable and consistent power supply. Additionally, energy storage systems enable better frequency regulation by providing instantaneous power injection or absorption, thereby maintaining grid stability. Moreover, these systems facilitate the effective management of power fluctuations and enable the integration of a higher share of wind power into the grid. Overall, the deployment of energy storage systems represents a promising solution to enhance wind power integration in modern power systems and drive the transition towards a more sustainable and resilient energy landscape.

4. Regulations and incentives

This century's top concern now is global warming. By the Paris Agreement, attempts are being made to keep the increase in global temperatures "just under" 2 C° and, preferably, to 1.5C° above pre-industrial levels during the current century [201]. A significant change in the world's energy sector is required to achieve the ecological goals of the Paris Agreement. The rapid adoption of low-carbon technology in place of traditional fossil energy production and utilization would enable such a transition. The concern is whether countries would establish longer-term goals for achieving net zero in 2050 (or 2060 in China's scenario), but short-term goals will be left undefined or will be ignored. This will essentially move the issue into the "high grass" for future governments and, ultimately, result in a scenario where it will be too late.

The first step is to instill a feeling of urgency by being open and transparent regarding where we are present currently and the discrepancy between objectives and actual progress. Regulators and lawmakers need to understand that our ability to achieve net zero relies on the steps we take today. Next, we must put up prompt and workable ideas. Contrary to a decade ago, there is a lot of money attempting to move into wind power and renewable technologies, but bureaucracy and out-of-date management and regulatory procedures are dragging down the Energy Transformation globally. Therefore, GWEC is pushing for decision-makers to engage institutional policies and procedures with a genuine "Climate Emergency" perspective. Furthermore, encourages governments to take steps immediately to ensure that the social costs of CO_2 emission are covered and that the utilization of harmful energies is removed from the system. Research over the past ten years demonstrates that the corporate sector would make the appropriate judgments once authorities issue unambiguous indications. Finally, as the shift to sustainable power grows increasingly about assisting harder-to-transform industries like heavy industry, pharmaceuticals, transportation, and agriculture to decarbonize, it needs to seek new allies, consumers, and supporters. The keywords "Powerto-X″ and "Sector Coupling" may quickly transition from buzzwords to new industries, areas, and technological innovations. This leads to the last conclusion. Researchers need to collaborate to accomplish this resetting and the larger vision that has been stated. This entails working collaboratively to quickly resolve planning and permitting obstacles on the part of the authorities, localities, and businesses. It entails combining innovations like wind, photovoltaic, storage, and next-generation distribution and transmission to make the transformation as smooth and effective as feasible. It requires combining renewable energy sources with totally unrelated techniques, each of which has various difficulties and follows a different course. It also implies cooperating to develop the diversified and professionally competent workers necessary to implement a genuine paradigm shift in the way society organizes its energy market. Therefore, this is an opportunity for all researchers as well as a challenge.

Several different policy strategies have promoted wind energy. Such supports for onshore wind have typically appeared in the form of feed-in tariffs (for reference, in Europe), tax subsidies, and quotas and duties (for instance, in India and the US), however, it is shifting more and more towards auctions worldwide. Offshore wind is currently mainly dominated by bids, with the state assisting companies mainly by offering locations, resource assessments, network connections, and other regulations that encourage cooperation. Three essential factors should generally be taken into account while selecting effective tools and prototypes: Regulations should be adapted to the situations and goals particular to each state, guarantee long-term security to encourage investors, and take into account all pertinent expense trends factors (2019b).

To encourage investment and set long-term, accurate, and consistent wind power goals. Additionally, make sure that the tools of approach are long-lasting, and promote the utilization of a variety of energy sources. Enhancing predictions of the weather should also be employed to reduce the unpredictable nature of wind power. Moreover, implement initiatives for the nearshore and offshore regions, including change policies to reflect changing market dynamics. The Beijing Manifesto, which targets 50 GW of yearly installation from 2021 to 2025 and 60 GW from 2026 ahead, was endorsed by more than 400 enterprises in China's wind market in October 2020. As a result, China's total wind potential is projected to achieve 800 GW by 2030 and 3000 GW by 2060.

5. Challenges and future directions of research

5.1. Challenges

To achieve a worldwide energy transition by the Paris Climate objectives, wind power is one of the essential renewable energy sources. The technology is currently available, may be rapidly utilized on a wide scale, and therefore is reasonably priced (especially onshore). Wind energy developments even so encounter significant challenges that prevent additional growth and industrialization despite the tremendous progress. Challenges stemming from various project requirements, regional settings, and maturity levels have varying levels of impact on renewable energy sources. In the coming thirty years, the installation of wind energy may be restricted by current constraints in several dimensions (technological, economic, political social, and environmental). These challenges are further illustrated in Fig. 5. To encourage further installation, it is essential to eliminate such obstacles right away through a variety of support legislation and implementation techniques.

To tackle the problem of the uncertain impact of wind power's fluctuating nature, and to ensure the stability and uninterrupted operation of the power system during periods of low available resources, an approach could be to integrate wind technologies with other sustainable products such as Photovoltaic, hydropower, or energy storage systems, either with developing technologies such as hydrogen. Through 2025, the industry for hybrid solar-wind energy systems is predicted to have grown from more than 0.89 billion dollars in 2018 to even more than 1.5 billion dollars, representing a CAGR of around 8.5 % over the preceding seven years (Zion Market Research, 2019). During 2020, China dominated the global market in hybrid energy technologies, and it is anticipated that it will continue to do so in the next years.

Wind power has been regarded as a tendency and the resource of the future due to its ability to overcome all existing barriers presented by traditional sources, such as fossil energy scarcity, rising greenhouse gas emissions, and climate change. Considering this, it has been determined that utilizing wind power has serious limitations, such as load-increasing penetrating existing systems, which leads to network instability, low network inertia, frequency instability, and ultimately rising cost. A challenge in widely integrating wind power is caused by several issues, and these issues must be kept in mind. Due to the aforementioned problems, public and private entities have been compelled to support the widespread use of renewable power (wind power). ESS are utilized in stabilized power systems to smooth out the integration of wind power and maintain network inertia and frequency. Furthermore, when the energy transformation is to take place as rapidly as feasible, then still significant battery and storage issues in the twenty-first century that must be resolved in the following years. However, ESS faces other obstacles, like prices and ESS's expected service. For instance, lithium-ion batteries have low energy density and a short life span. Regarding the development of new techniques, the new materials

Fig. 5. Wind energy challenges.

that can be used would increase battery lifespan and performance. Integrating renewable energy sources such as wind and solar energy with the support of a microgrid is essential for the ecosystem to become clean and more effective. Transitioning to technological innovation is indeed tough due to its difficult challenge.

5.2. Discussion on future development

Appropriate research initiatives and upcoming projects are as follows, based on existing issues involving frequency regulation and the influence of distributed renewable energy sources and microgrids.

- Electricity grids with high levels of wind energy integration require an efficient control strategy, especially island networks given their low relative inertia, large power fluctuations, and numerous uncertainties. The effective planning of the generating plants and energy storage devices is essential in this regard. Utilizing the storage units can enable efficient coordination methods that support primary and secondary control.
- The majority of previous research attempting to minimize wind energy fluctuation did not evaluate the efficiency of the suggested strategy using a numerical index. In these papers, comparisons are made when non-smoothed wind energy is taken into consideration. Therefore, future research should evaluate the effectiveness of their techniques using the already-existing criteria or even recommend brand-new indices. Additionally, it is important to note the absence of a proper comparison of the approaches used in the literature using a uniform benchmark.
- Due to the enormous quantity of data obtained and the expanding advancements in computers, communications, smart electronic devices, and control techniques, efficient and quick data filtering and processing methods are needed. Predicting loads and assessing the frequency regulation industries of upcoming grids are two examples of frequency regulation difficulties where artificial intelligence and machine learning can be very helpful. The cyber-security of frequency control schemes must also be emphasized in this area.
- Even though ESS prices are going down, they still require a significant investment. Therefore, scientists should investigate this utilization combined with other additional services whenever considering wind energy smoothing approaches that demand ESSs. Furthermore, because of its high prices, future research should focus more on factors that are related to the ESSs' state of life. Additionally, investigate hybrid energy storage technologies and compare the technological, financial, and smoothing capabilities of these combinations with wind energy.

5.3. Future trends

By analyzing the aforementioned discussions, the related future direction trends have been determined. As a result of technology improvements, current grids are becoming "smart grids," which securely store and analyze information to improve system performance. To sustain a stable and cost-effective transformation, large wind integration needs advanced control and energy storage technology. In recent years, hybrid energy sources with components including wind, solar, and energy storage systems have gained popularity. However, to discourage support for unstable and polluting power generation, energy storage systems need to be economical and accessible. Additionally, long-term storage technologies would be necessary for system transformation. According to the latest study, decarbonizing the California grid could need up to 55 GW of long-term storage by the year 2045, which is more than 150 times the region's present storage capacity. China made public its ambition to reduce emissions by 2030 and turn the country carbon zero by 2060. The below enhancements are the great steps that the goal could be achieved.

- larger turbines are being designed.
- blades getting longer.
- better productive material and manufacturing techniques.
- lower expenses and shorter cycle durations.

In the future, researchers need to investigate ways to save expenses by also ensuring ease for ESS and wind energy integration. Considering DG schemes are simple to build and can minimize the environmental consequences of coal- and fossil-fuel power plants, it would be important to talk about their integration.

- *Hybrid Energy Storage Systems:* Explore the concept of combining multiple energy storage technologies, such as batteries with flywheels or compressed air energy storage, to leverage their complementary characteristics and enhance overall system performance. Discuss the potential for hybrid systems to address the limitations of individual storage technologies.
- *Integration of Renewable Energy Sources:* Investigate the integration of other renewable energy sources, such as solar photovoltaics, into the frequency regulation framework. Analyze the synergies and challenges of combining wind power integration with other renewable sources, considering their complementary generation patterns and potential benefits for system stability.
- *Advanced Control Strategies:* Examine advanced control strategies that can improve the performance and flexibility of energy storage systems for frequency regulation. This includes the integration of machine learning algorithms, predictive control, and advanced power electronics techniques to optimize storage operations and enhance system stability.

- *Grid-Forming Inverter Technologies:* Discuss the role of grid-forming inverters in wind power integration and frequency regulation. Explore the potential of these inverters to provide stable grid support and maintain system frequency under varying wind conditions. Highlight ongoing research and development efforts in this area.
- *Market Mechanisms and Policy Support:* Analyze the evolving market mechanisms and policy frameworks that incentivize energy storage deployment for frequency regulation. Discuss the role of ancillary service markets, capacity markets, and regulatory support in promoting the adoption of energy storage technologies in modern power systems.
- *System Flexibility and Demand Response:* Explore the potential of demand response programs and flexible load management to enhance system flexibility and support frequency regulation. Discuss the integration of smart grid technologies, real-time monitoring, and control systems to enable dynamic demand response and improve overall grid stability.
- *Grid Resilience and Cybersecurity:* Address the challenges and considerations related to grid resilience and cybersecurity when integrating energy storage systems for frequency regulation. Discuss the need for robust security measures, grid hardening strategies, and backup systems to ensure the reliability and resilience of power systems.

6. Conclusion

This review paper has provided a comprehensive evaluation of frequency regulation and energy storage solutions for wind power integration into power systems. The analysis highlights the significance of these solutions in ensuring the reliable and cost-effective operation of power systems while promoting the broader use of renewable energy sources, based on an analysis of existing literature. The review highlights the accomplishments, challenges, and prospects in this field.

The analysis reveals that ESS play a crucial role in addressing the efficiency and safety concerns associated with integrating large amounts of wind power into future grid systems. Various ESS technologies have been explored, each with its advancements and capabilities to meet the diverse demands of wind farms, grid operators, and consumers. The impact of sustainable energy penetration, DGs, and MGs on network frequency dynamic stability and efficiency have been thoroughly discussed in the literature. The review has identified promising avenues for frequency regulation, such as regulatory support for RES/MG, virtual inertia, and load control. Furthermore, the literature emphasizes the importance of careful planning for ESS deployment, including considerations of storage requirements, size, and location. Different techniques, such as historical wind profile data and stochastic approaches, have been proposed to determine the optimal size of the ESS. However, the literature acknowledges that uncertainties in wind energy forecasts and grid dynamics can impact the accuracy of these predictions. The review has also underscored the need for tailored operational strategies for ESS in conjunction with wind parks and variation mitigation. Factors such as wind energy forecast errors, technology considerations, industry regulations, and electricity rates have been identified as crucial aspects to be considered when designing effective operational approaches for ESS installations. While the literature review has provided valuable insights into frequency regulation and energy storage solutions, it is important to note that the findings are subject to the limitations and specific contexts of the reviewed studies. Future research should aim to address these limitations and provide further insights into the optimal integration of wind power into power systems.

In summary, this review paper has synthesized the existing literature on frequency regulation and energy storage solutions for wind integration. The findings highlight the significance of ESS in ensuring the efficiency and reliability of future grid systems with significant wind power penetration. The review also identifies areas for further research, ultimately contributing to the development of sustainable and resilient energy systems.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Farhan Ullah: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Xuexia Zhang:** Writing – review & editing, Supervision, Resources, Methodology, Data curation, Conceptualization. **Mansoor Khan:** Writing – review & editing, Visualization, Data curation. **Muhammad Shahid Mastoi:** Visualization, Data curation. **Hafiz Mudassir Munir:** Formal analysis. **Aymen Flah:** Writing – review & editing, Formal analysis. **Yahia Said:** Writing – review & editing, Formal analysis, Data curation.

Declaration of competing interest

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

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