Wind Power Generation with Battery as Storage: A Review

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***Abstract*— When it comes to renewable energy sources, wind power has the biggest potential and is also the best developed technology. The unpredictable and sporadic character of wind, on the other hand, makes it difficult to plan, schedule, manage, and exert effective control over the generation of wind power. Integration of large-scale wind farms into the grid might potentially provide substantial issues to the administration and operation of the electricity system. A battery energy storage system (BESS) that is synchronized with a wind turbine offers a significant amount of potential to tackle these issues. In this work, we investigate many research publications with an emphasis on utilizing BESS for applications relating to wind farms. Challenges associated with active power management and reactive power management are discussed in detail in separate sections of the text. Concerning topics include the lessening of power fluctuations, the regulation of frequency, the enhancement of dispatch capacity, the provision of help for reactive power, and the preservation of stable voltage. The viability of low voltage ride through is being investigated as part of this study. An extensive number of potential solutions, such as control tactics and developments in battery technology, are presented in this article. The anticipated future research issue has been investigated, and the primary difficulties associated with the combination of wind and batteries have been uncovered...**

Keywords*— *Active power management; battery energy storage system; grid integration; reactive power management; wind power

I. Introduction

Wind power is notoriously difficult to integrate into the established protocols of power system operations, planning, and scheduling due to its highly variable and intermittent output. The installed capacity of wind power in India has increased noticeably over the course of the previous few years and is anticipated to increase even more quickly over the course of the following few years. This ever greater degree of integration has raised significant worries over the impact that such a significant scale of wind penetration will have on the dependability, security, and stability of the power system. The influence that integrated wind turbines will have on the stability of the power system, particularly in regards to frequency regulation and voltage stability, is one of the primary issues that are associated with high-level penetrations of integrated wind turbines [1]. The amount of active power generated by a wind farm is contingent on the amount of wind flow as well as the design of the wind turbine generators, but the amount of reactive power required is dependent on the conversion devices. The wind farm is often situated in a remote region, and the reactive power needs to be transferred across a long distance, which leads in power loss. Consequently, the wind farm's power output is reduced. Wind farms that are linked to the grid can produce power fluctuations and the redistribution of reactive power, both of which can occasionally result in voltage that is not properly balanced. This presents a significant risk to the reliability and safety of the system. As a result, it is essential to preserve the dynamic stability and continue the dependable functioning of a power system that has a significant proportion of wind power incorporated into it.

As a result of recent advancements in energy storage technology, it is now possible to deploy energy storage devices in order to compensate for the intermittent nature of renewable energy resources (RES). Flywheels, super capacitors, SMES, compressed air systems, batteries, and hydro pump stations are some of the energy storage methods that may be used in conjunction with wind power [2]. Battery storage allows for the most efficient integration of wind farms in terms of cost. The battery storage device is able to store and manage both active and reactive power while it is connected to the grid. As a result, they are able to preserve the integrity of the system.

The management of active and reactive power in wind farms that store energy in batteries is the focus of this particular piece of research. Active power management brings to a reduction in power fluctuations, improves frequency control, and enhances dispatchability. The management of reactive power covers difficulties relating to voltage stability and LVRT capacity, as well as problems with reactive power support. A reduction in power fluctuations, regulation of frequency, and improvement in dispatch are all benefits of active power management. When each issue is studied on its own, one gains a deeper comprehension of the control tactics, methodology, and battery technology utilised to address it. We investigated and resolved the most significant problems associated with the combination of wind power and batteries. The publication will continue in the following manner. The challenges of active power management are discussed in Section II. In Section III, we will talk about the reactive power components of the wind farm. The most important findings are broken down and discussed in Section IV. Coordination concerns between wind turbines and BESS are discussed in Section V. The final section of the paper is Section VI..

II. Active power Management

The primary goal of the operation of a power system is to maintain the right generation-demand balance. Power fluctuations, frequency excursions, and dispatchability issues can result from a power generation-demand mismatch. Operational planning and reserve capacity address wind power output variability. System operators plan for wind output and load changes and maintain an adequate margin on thermal (coal and gas) and hydro power facilities. This strategy is costly since it often necessitates the development of more expensive coal or gas to compensate for wind energy.

BESS is helping researchers solve these issues. BESS provide active electricity when wind is low or load demand is high. When load demand drops or the wind generator has excess active power, it can charge the batteries. Thus, BESS can help maintain the generation-load balance, which reduces power oscillations and frequency deviations and improves wind power dispatchability, benefiting wind farm owners. The following sections address related research.

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A. Power Oscillation Damping

The scenario in which the amount of electricity that is put into the system does not fluctuate would be the one that best meets our needs. Wind power generation facilities have a variable output, hence it is conceivable for there to be power fluctuations as a result of this. This is one of the disadvantages that wind energy has. Combining a wind power generation plant with an energy storage device, such as a battery, is one approach that might be taken to address this issue. The goal of the power oscillation damping method is to set a baseline power output for the wind farm, and it is imperative that this output be preserved. When the active power that is produced by the wind turbine and the active power that is stored in the batteries are synced, reference tracking is accomplished.

Within the academic literature, a number of different strategies for the coordinated control of wind turbines and battery systems are presented. Several of these approaches make use of learning algorithms in order to achieve more accurate reference tracking. The authors of [3] provide a technique for power tracking that is based on Adaptive Linear Neurons. In order to accomplish optimization, they use a particle swarm optimization-based computation of a variable learning rate. This process is optimized via particle swarms, which allows for very precise adjustments. Additionally, a method for charging and discharging the BESS has been suggested for use. By maximizing the effectiveness of the switching capabilities of the BESS, the strategy extends the lifespan of the BESS. The authors of [4] provide a fuzzy logic-based adaptive Kalman filter that takes into account feedback from the battery's state of charge. This filter was developed with the help of fuzzy logic. This makes it possible to smooth out the output power based on the degree of charge that the battery currently has. The use of coordinated controllers that are based on fuzzy logic has also been covered in [5]-[7]. In the paper [6], fuzzy logic is applied in order to optimize the state-of-charge (SOC) of a battery energy storage system (BESS) that is based on a vanadium redox battery (VRB). In [8,] researchers used bacteria foraging in conjunction with synchronized tuning of wind turbines and batteries in order to keep the amount of power generated by the grid at a steady level. As part of this investigation, a BESS was inserted in the generator converter in place of the dc link capacitor in order to get rid of oscillations that were caused by the dc link voltage.

Several scholarly articles demonstrate how frequency domain analysis might be utilised to achieve more accurate output power regulation. According to the results of the spectrum analysis of the output power that was carried out in [9], the oscillations change depending on the position of the power injection. The spectrum response of the system may be bent to generate the appropriate response thanks to the coordinated controller for the wind farm and the BESS. This is possible because to the fact that the required response can be created. This method is comparable to the one that is outlined in [10], which makes use of a neural network model to maximize the efficiency of a HESS that consists of a super capacitor and a lead-acid battery. The use of HESS that makes use of super capacitors has also been utilized in [11-13] with the purpose of enhancing the performance of batteries. When they are put to service, super capacitors are capable of handling power fluctuations occurring at very high frequencies. Battery energy storage systems (BESS) and superconducting flywheel energy storage systems (SFES) have both been installed at [14] in an effort to reduce the frequency and severity of power outages. Two time scale coordinated control has been established by researchers [15–17] in order to eliminate power fluctuations that occur during periods of one minute and thirty minutes respectively. We make use of hybrid energy storage, which is a combination of several distinct forms of energy storage that are effective at being used for various time durations.

We are given a hierarchical, three-tiered system for managing power quality in [18]. This technique is supplied to us to improve power quality. The active and reactive power references are generated in accordance with the specifications of the grid at the most advanced level of the grid demand computation. At the next level of energy management, the modifications that are made to the active and reactive power reference signals are informed by the charge level of the battery and the output capacity of the converter. The third layer is responsible for monitoring not just one but two different sources of electrical power. Grid power levelling is covered in [19], where it is explained how to alter the rotor side converter (RSC) and the grid side converter (GSC) to achieve a more constant output power. Grid power levelling is important for maintaining a stable electrical grid. [20] describes the design of a state-machine based supervisory control that is intended for use with wind turbines and lead-acid battery energy storage systems (BESS).

B. Frequency Regulation

The reliability of the electrical supply is significantly impacted by frequency. The power quality of the grid is impacted by the system frequency. Therefore, it is of the utmost importance to keep the frequency within the range that is both safe and useful for electrical equipment. The grid benefits from conventional generators' inertial response capabilities as well as their ability to regulate both primary and secondary frequency. Wind generators are anticipated to perform the same function, despite the fact that they do not possess inertia and are instead linked to the grid by means of power electronic converters. [21]. By synchronising the energy storage system with the wind turbines, this research provides a compensation for the inertial support provided by the wind farm. The addition of superconducting magnetic energy storage (SMES) results in an increase in inertia.

The topic of frequency management with the help of the SOC feedback control system and pitch angle control is discussed in [22]. Using this method of control, the battery will be connected to the grid, and its SOC will be maintained close to its ideal operating point. Batteries can deal with fluctuations in the grid's frequency. A synchronized system frequency management is present in both a battery storage system and a generator for a wind turbine [23]. This controlled the frequency of the system. The H-controller can modify the pitch angle, which in turn lessens the strain on the turbine blades and the size of the battery. BESSs have been constructed using sodium supplied batteries. The wind farm is able to adjust wind frequency thanks to the spilling wind. The article [24] suggests utilizing energy storage from wind farms to spill wind energy. Within the scope of this investigation was VRB. A specialized controller is used to regulate the state-of-charge of the batteries and to smooth out the output of the wind power...

C. *Dispatchability Improvement*

Wind power cannot be used at full capacity like other conventional generating resources. Load components may be predicted 24 to 36 hours in advance, unlike wind power. Thus, substantial wind power use in electric grids may undermine system reliability and stability. Researchers use the BESS to control wind farm output. Better wind power forecasting methods also boost dispatchability. In [25], the top layer stochastic coordinated predictive controller (SCPC) optimized the power reference for the wind and BESS subsystems, taking into account non-Gaussian wind prediction errors. After optimization, references are provided to subsystems for bottom layer controllers to track. Using wind power estimates and prior data, [26] proposes a coordinated operational dispatch strategy.

[27] proposes stochastic model predictive control (MPC). Predictive control uses a probabilistic wind forecasting model. This model quantifies non-Gaussian wind forecasting uncertainty. The controller will optimism the BESS while considering the system's limits to increase wind and battery power generation to dispatch levels. The dual battery energy storage system built between [28] and [30] is designed to offset the wind power output-to-dispatch level mismatch. Depending on their SOC levels, the two BESS must prevent a power mismatch. BESS's wind power dispatch capabilities was assessed using a sequential Monte Carlo simulation [28]. BESS was evaluated to improve.

In [31], artificial neural network control algorithms determine the appropriate energy storage device size. Using a zinc–bromine flow battery energy storage technology can enhance wind power production predictability, dispatchibility, and reserve cost integration. In [32], a hybrid energy storage system with batteries and super capacitors was demonstrated to be the cheapest way to dispatch wind power with reasonable accuracy. A cost-optimized wind-hybrid energy storage system [33] improves short-term dispatch efficiency. The control algorithm regulates the battery's charge and smoothies power variations between one-hour dispatch intervals. BESS optimizes energy for shorter-term markets [34]. This method uses two-scale dynamic programming based on long-term and short-term wind power estimates to compute battery SOC. In [35], the NaS energy storage system was explored to move wind power generation from off-peak to on-peak and restrict wind farm output ramp-rates, allowing the wind farm to participate in the energy market and as operational reserves...

III. Reactive Power Management

The control of wind farms' reactive power assures that there will be little power loss during the transfer of energy to the main grid, that grid code connection requirements will be met, and that the wind farm's voltage profile will be preserved. The Indian Electricity Grid Code (IEGC) outlines a number of grid requirements that must be met by wind farms in India, including the following:

• VAR taken from or injected into the grid at a level lower than 97% of the nominal voltage will be penalized/rewarded, whereas VAR levels higher than 103% would be rewarded.

• Wind farms at 33 kV must be able to function normally over a voltage range of +5% to -10%, while those at 66 kV must be able to run normally over a voltage range of +10% to -9%. There is a possibility that wind farms with voltages lower than 220 kV might only have a voltage imbalance of 3%.

• Wind farms should be able to maintain a power factor at the grid connection that ranges from 0.95 lagging to 0.95 leading; • Indian wind turbines must output power at a frequency that falls between 49.9 and 50.05 hertz. Wind farms can withstand frequencies between 47.5 and 51.5 hertz. Wind farms are required to be able to endure changes in frequency of up to 0.5 Hz every single second.

Many methods for controlling voltage and reactive power have been developed by the academic community. Researchers may make use of FACTS Devices, STATCOM, SVC, DVR, OLTC, SDBR, UPFC, UPQC, or any combination of these and other devices [2]. In recent years, researchers have been making use of BESS in order to regulate reactive power in wind farms.

A. *Reactive Power Support*

It is typically important for the operation of converters on both the rotor side and the grid side of a wind farm in order for the farm to be able to provide a reactive power supply. Through the use of a flywheel energy storage system (FESS), the authors of [36] were able to increase the quality of the active as well as the reactive power. A fuzzy logic based supervisory controller is used to manage both the functioning of the FESS and the voltage at the dc bus. This is done in order to make the active power that the wind generator provides as smooth as possible. A separate control approach for the smoothing of reactive power has also been implemented in addition to that. BESS was utilized in [37] to exchange regulated real and reactive electricity to the grid. The power was traded, which allowed this to be done. Control of the converter is achieved by the utilization of the hysteresis current control mode, which makes it possible to achieve more rapid dynamics. Research on the use of synchronous machine-based ESS for dynamic reactive correction for transient grid stability was carried out by the authors of [38], who cited their findings.

B. *Voltage Stability*

Wind power is fraught with a number of severe problems, one of the most notable being fluctuations in voltage. It has a direct connection to the fluctuations in the real power as well as the reactive power, and it acts as a factor that limits the amount of wind power that can be deployed. The phrase "voltage sag" refers to a drop in voltage, while "voltage swell" refers to an increase in voltage [2]. Voltage fluctuations may also be broken down into short term interruptions and long term interruptions. However, studies are presently being done to evaluate the viability of employing energy storage systems for the management of reactive power and voltage stability applications. BESS has historically found its usefulness in the active power regulation of wind farms. The authors of [39] discuss a number of different control strategies that are based on supervisory control for the functioning of GSC and RSC combined with the adjustment of pitch angle in order to ensure voltage stability. These control solutions are offered in order to accomplish the goal of maintaining a constant voltage. In order to establish whether or not the findings of the study can be trusted, a number of cases of voltage sag and phase-to-ground failures were analysed..

C. *Low Voltage Ride Through (LVRT)*

In an effort to mitigate the potential damage to the natural environment that may be wrought by large-scale wind farms, a number of countries' governing bodies have mandated severe grid criteria to which all wind power generation facilities must adhere. As a result of this, it is absolutely necessary to give the fault ride through (FRT) capabilities of the wind turbines the attention that it is necessary for them to have. The LVRT requires that the generators must preserve their connections to the grid and maintain transient stability even in the event that fault circumstances occur.

In the paper [40], which was authored by the people who developed FRT, a comparison of numerous different FRT approaches is presented. BESS is not included into any of these designs in any way, shape, or form. Recent research has demonstrated that wind farms may increase their FRT capabilities by making better use of the benefits that BESS has to offer. Researchers were the ones responsible for carrying out these researches. The authors of [24] present the control strategy for an IGBT-based Static VAR compensator (SVC), which is employed when the BESS is also being used. This is done so because the SVC is used while the VRB-based BESS is delivering the active power that is essential during fault conditions. The authors of [41] investigate the capabilities of ESS to promote fault riding through augmentation and output power smoothing when linked to the dc connection through a bi-directional converter.

TABLE I. APPLICATION OF ESS FOR ACTIVE POWER MANAGEMENT: SUMMARY

Objective	Paper Reference	Technique/ Algorithm	ESS type	Time frame
Power Oscillation Damping/ Power Fluctuation Mitigation/ Output Power Smoothing	[3]	Tracking power using an adaptive linear neural network	BESS	Steady state
	[4]	The Adaptive Kalman Filter is based on Fuzzy Logic.	Li-ion battery	Steady state
	[5]-[7]	Fuzzy logic	SMES, VRB, Ultra-capacitor	Steady state
	[8]	Bacteria Foraging	BESS	Dynamic
	[9]	Spectral analysis, MPPT technique	Lead-Acid battery	Steady state
	[10]	Neural network	Super-capacitor, lead-acid battery	Steady State
	[11]-[13]	tracking of the reference waveform for the output power	BESS with Super-capacitors	Steady state
	[14]	Control of HESS via Coordination	BESS with SFES	Steady state
	[15]-[17]	Two time scale coordinated control	Super-capacitor hybrid system	Steady state
	[18]	The control is based on a hierarchical structure.	BESS	Steady state
	[19]	RSC and GSC regulate respectively	BESS	Dynamic
	[20]	Based on a state machine Regulatory and auditing oversight	Lead-acid battery	Steady state
Frequency Regulation	[21], [24]	Fuzzy Logic	SMES [21], VRB [24]	Steady state
	[22]	Feedback control from the SOC	BESS	Steady state
	[23]	Control of the pitch angle for the turbine as well as the H- controller for the BESS	NaS battery	Steady state
Dispatchability Improvement	[25]	Controller with a stochastic coordinated predictive model	NaS battery	Dynamic
	[26]	An examination of the statistics behind the wind power prediction	Li-ion battery	Steady state
	[27]	Stochastic model predictive control	NaS battery	Steady state
	[28]-[30]	Feedback control from the SOC	Dual Battery ESS	Steady state
	[31]	Dispatch determined by an artificial neural	Zinc–bromine flow battery	Steady state
	[32]-[33]	network based on the wind power forecast	Super-capacitor HESS	Steady state
	[34]	A dynamic programming approach with two scales	Li-ion battery	Steady state
	[35]	The shifting of wind power generation and the restriction of ramp rates	NaS battery	Steady state

TABLE II. APPLICATION OF ESS FOR REACTIVE POWER MANAGEMENT: SUMMARY

Objective	Paper Reference	Technique/ Algorithm	ESS type	Time frame
Reactive Power Support	[36]	Fuzzy logic based supervisory control	Flywheel ESS	Steady state
	[37]	Hysteresis current control	BESS	Dynamic
	[38]	Stall-controlled wind turbines	Synchronous machine based ESS	Dynamic
Voltage Stability	[39]	Hybrid control strategy	Lead-acid	Dynamic
Low voltage ride through (LVRT)	[24]	Fuzzy logic	SVC with VRB	Dynamic
	[41]	Bi-directional control converter	-	Steady state

IV. Concluding Remarks

This study presents a thorough analysis of current attempts towards integrating wind energy systems with battery energy storage systems (BESS). The review covers a broad spectrum of recent advancements that have been made in the sector. BESS has found a broad variety of applications in wind power systems, one of which is the control of both active and reactive power. BESS is able to offer frequency support, alleviate power fluctuations, and maintain constant local grid voltage during the transient situations. As a consequence of these capabilities, it contributes to the preservation of the system's overall stability and security.. The improved dispatchability brought about by the additional active power assistance provided by the BESS makes the system more dependable and resilient.

Several different battery technologies are now in various stages of development for the purpose of large-scale energy storage for wind applications. Because of the quick dynamics of sodium-sulfur (NaS) batteries, their use is advantageous for the increase of wind power dispatch ability. The use of flow batteries in frequency control applications has demonstrated significant potential. The vanadium redox battery now holds the lead among them. Nevertheless, the cost of installing a BESS is comparable to the cost of installing a wind turbine with the same rating. The ongoing research in this area has the potential to lower the cost of the BESS down.

The level of charge remaining in the battery and the amount it has been discharged both have a role in how the BESS manages energy. In the literature, the same purpose is being served by the application of supervisory control techniques. When it comes to optimizing battery SOC, PSO-based optimization approaches are extremely common; nevertheless, there are alternative optimization strategies that may be investigated. The accuracy of wind power forecasts is very important to the dispatchability of wind power. A more accurate forecast of the wind will ensure that the system is more reliable. There is still a need for significant effort to be put into reducing the wind forecast inaccuracy. The ability of wind power to be dispatched can be improved with a more accurate short-term wind forecast that is coupled with model predictive control.

BESS controls reactive power, although research is ongoing. Some research suggest using STATCOM with BESS to manage active and reactive power, however this is not cost-effective. Other study links the BESS to the wind generator through a power electronic converter and proposes several control algorithms for the converter. However, buying a converter makes this procedure expensive. The BESS can be connected to the generator converters' DC link. The BESS may give voltage and current support to the GSC, increasing its reactive power support, and it can be controlled by either generator converter (GSC or RSC)..

As a result of this review study, a better knowledge of the integration elements of wind turbines with battery energy storage systems has been provided. Even though there has been steady progress in research over the past few years in this area, there is still a significant amount of room for expansion.

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