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REVIEW

ENERGY STORAGE WILEY

A review of key functionalities of battery energy storage system in renewable energy integrated power systems

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Abstract

Renewable energy sources (RES), such as photovoltaics (PV) and wind turbines have been widely applied as alternative energy solutions to address the global environmental concern and satisfy the energy demand. The large-scale amalgamation of intermittent RES causes reliability and stability distress in the electric grid. To mitigate the nature of fluctuation from RES, a battery energy storage system (BESS) is considered one of the utmost effective and efficient arrangements which can enhance the operational flexibility of the power system. This article provides a comprehensive review to point out various applications of BESS technology in reducing the adverse impacts of PV and wind integrated systems. The key focus is given to battery connection techniques, power conversion system, individual PV/wind, and hybrid system configuration. The application of BESS is categorized into three areas, active, reactive, and active-reactive power features. The key findings of the existing research of BESS application are summarized and discussed along with several simulation results. By taking a thorough review, this article identifies the key challenges of BESS application including battery charging/discharging strategy, battery connection, power conversion efficiency, power converter, RES forecast, and battery lifetime and suggests future research directions that could be explored during the design, operation, and implementation of BESS technology in the power system.

KEYWORDS

battery energy storage system, BESS application, PV, renewable energy, wind systems

1 | INTRODUCTION

The installation of renewable energy source (RES) has grown remarkably and is foreseen to expand expeditiously in upcoming years. Integrating RES in the power network can minimize grid losses and reduce carbon footprint. However, with inconsistent and little predictable nature, RES can generate serious lapse that may create difficulty in maintaining normal grid balance, that is, load and generation equilibrium.[1,2] Rapid fluctuations, especially from large-scale photovoltaics (PV) and wind farms put more stress in power system[3] such as voltage fluctuations, reverse power flow, frequency deviations, and so forth. In extreme cases, these phenomena can lead to a catastrophic collapse of the entire system, that is, "a complete blackout." The adverse impact of RES farm originates from variable solar radiation and wind speed that changes seasonally, monthly, daily, hourly, and even in seconds.

Harmonic distortions and voltage flickering are a few of the other problems that arise with the large-scale penetration of PV and wind generating plants.[4,5] As the level

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of RES penetration increases, frequent fluctuations in RES power output may impose additional stress on conventional generation (CG) units in order to maintain voltage and frequency within the acceptable limit. This will minimize the lifespan of CG units and also increase operational cost in CG units.[4] Moreover, an increment in RES penetration reduces accessible inertia in the system that increases the need for additional spinning reserves and eventually imposes extra costs.

In order to minimize the harmful effects of RES in the grid, many countries are already maintaining compulsory grid codes guideline considering such unpredicted situations to ensure controlled fluctuations and reliable renewable energy operation within the acceptable operating range.[6,7] The grid codes range from limits in ramp-rate, fault-ride-through (FRT) capability, voltage and frequency regulation capability, dispatchability, and so forth. Few countries like Italy,[8] Germany,[9] and United Kingdom[10] have already imposed financial penalties in the case of RES farms do not maintain the promised output power schedule. If auxiliary power reserves are not arranged as RES penetration increases, the power system may encounter severe system failure, that is, blackout can be more frequent in the future.

Energy storage technologies have the capability to regulate their output and thus minimize the adverse impact of RES indeterminacy. Among many existing energy storage technologies, such as a flywheel, pump hydro, capacitor, supercapacitor, and compressed air energy storage, battery energy storage system (BESS) offers better flexibility in terms of capacity, siting facility, and fast response to fulfill the requirements of storage system application.[11,12,13] BESS can store energy and is able to control active and reactive power flow independently at the point of common coupling (PCC) and provides various services. BESS services may include transient frequency stability,[14] enhanced reliability,[15] peak shaving,[16] transmission congestion management,[17] output power leveling,[18] ramp rate control,[19] and dispatchability.[20] BESS can also provide black start (BS) and energy arbitrage facilities.[21] The mitigation of output power fluctuation, frequency regulation, peak shaving and plant dispatchability can be improved by regulating the active power output of BESS. Conversely, reactive power reinforcement, voltage regulation and low voltage ride-through (LVRT) can be realized by regulating BESS reactive power output.

The earlier studies have presented a detailed discussion on thermal management[22] and the application of storage technologies.[23,24] Authors in References 22 and 24 presented an overview of various energy storage technologies in terms of power/energy density and efficiency. Various application modes of BESS application for the last decade are briefly outlined by Zhang et al.[25] The implementation of Lithium-ion batteries in Europe, the Middle East, and Africa region are elaborately presented in Reference 26 to highlight its technical services vs revenue and future market potential in the region. However, these studies did not provide an in-depth discussion of the particular application of BESS and the identification of BESS application in an order in which the in and out of BESS application can be perceived. On the contrary, the study in Reference 27 has provided a brief discussion on BESS application. Nevertheless, in-depth analysis and the identification of key challenges are not given careful consideration in the study.

The key objective of this study is to provide an extensive investigation of active and reactive power contribution of BESS in PV and wind renewable energy integrated system. Compared to previous works, this study aims to put forward an in-depth analysis of the BESS application. In addition, several simulation-based case studies are carried out to highlight BESS applications in the grid. The mitigation of output power fluctuation, frequency regulation, peak shaving, and plant dispatchability improvement by the active power regulation of BESS are demonstrated. Conversely, reactive power reinforcement, voltage regulation, and LVRT are realized by reactive power supervision of BESS. The consideration of the aforementioned issues contributes in the identification of various objectives, control strategies and battery storage technologies. Furthermore, key findings of the previous studies are summarized to bestow an overview of existing BESS application and their relevance in grid applications. Additionally, the key challenges and their viable reasons are discussed in order to present the existing challenges of integrating BESS in the grid. Finally, the rigorous analysis aims to bring forth the idea of future research opportunities on BESS for integrating into the grid.

The rest of this article is organized ass follows. Section 2 provides brief discussion of energy storage technologies. Section 3 discusses BESS structures and types of battery storage technology employed in wind and PV studies. Section 4 presents applications of BESS in PV and wind integrated power systems. Section 5 presents key findings and key challenges in the applications of BESS. Concluding remarks are provided in section 6.

2 | ENERGY STORAGE TECHNOLOGIES

Energy storage technology is subjected to the type of storage, short-term and long-term operating time frame, power and energy ratings and applications.[28,29]

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2.1 | Storage technologies-general consideration

The available energy is possible to be stored for later use in various energy forms including mechanical, magnetic, and electrical natures which can be summarized as shown in Figure 1.[30,28,29] These storage technologies are already extensively discussed in earlier studies and hence these will not be further elaborated in this article. Interested readers are encouraged to consult the earlier studies[30,28,29,31,23,24,27] for more details.

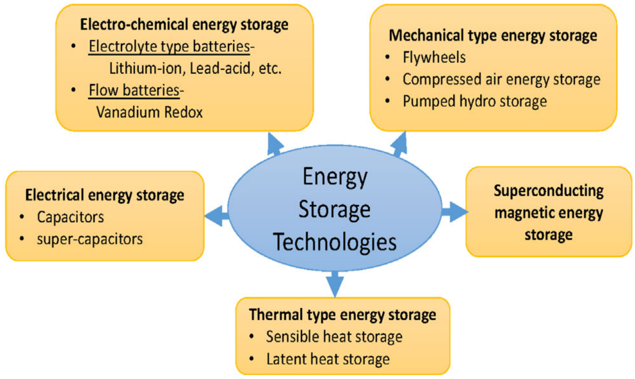

FIGURE 1 Types of energy storage technologies

2.2 | Operating time frame, power, and energy rating

The application of energy storage technologies in the power industry has existed for more than 150 years. Many storage technologies with high potential have been advanced and further research is ongoing for their application to large-scale power systems. The application of available energy storage technologies can be classified in terms of the short-term and long-term periods as shown in Figure 2.

As indicated in Figure 2, several battery storage technologies are available in MW power and MWh energy capacity.

However, mechanical storage systems are still at the forefront in the course of higher power and energy rating. Recent technical advancements in battery technologies are set in motion for large-scale battery storage installation ever than before.

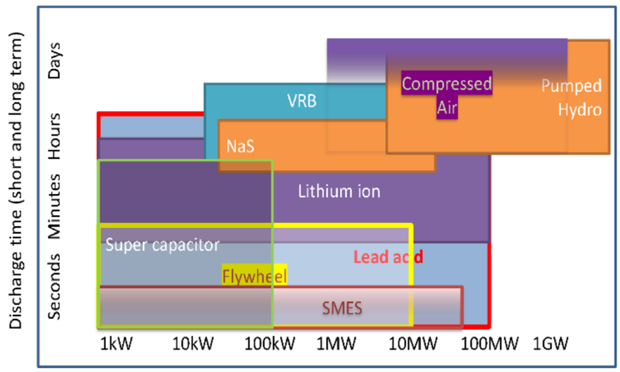

FIGURE 2 Energy storage technologies capability-operating time frame

3 | BESS TECHNOLOGY AND BATTERIES

The battery technologies have been in practice for more than 100 years. However, only rechargeable or secondary batteries are preferred in power system applications. The battery technologies are gaining popularity in power system applications due to their ability to provide operational flexibility, rapid response, reduction in price/kWh[32] and technological advancement in recent battery technologies. The batteries are widely used at all voltage levels in power systems.[33] Their application can ensure operational flexibility and environmental benefits. However, large-scale application of battery storage systems is not widely used because of their low energy density and power capacity. Nevertheless, recent advancements in battery technologies, especially in lithium-ion batteries have increased the interest in their application to large-scale power systems.

3.1 | BESS connection diagrams

The basic structure of BESS mainly depends on the voltage level it is intended to be connected. A typical BESS structure may consist of battery banks (typically stacks of batteries in parallel), DC/AC power conversion system (PCS). A transformer might be needed to convert BESS output voltage level to the grid voltage level if BESS is planned to be connected with local distribution or transmission system. Very often, BESS absorbs and delivers power to and from the grid which requires a bi-directional voltage source converter (VSC),[34] current-source converters,[35] with its choice mainly depending on the purpose of BESS in that particular case study. Commonly used BESS-PV configurations are shown in Figure 3. Each configuration has its own advantages and disadvantages. In the case of Figure 3A, an additional DC/AC converter will increase system cost. In addition,

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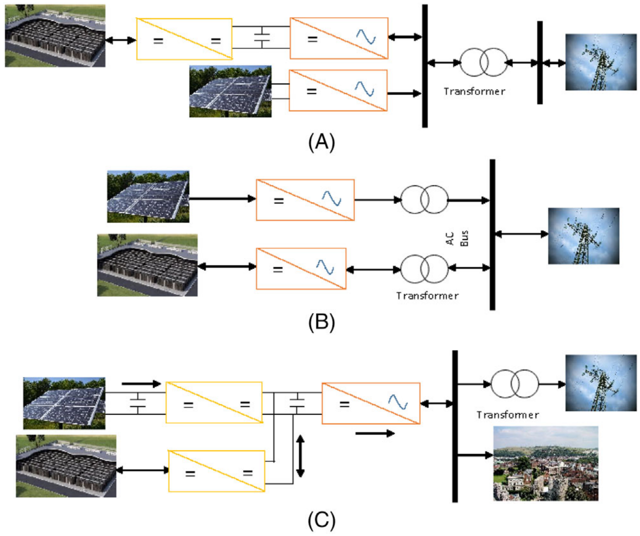

FIGURE 3 Typical battery energy storage system (BESS) connection in a photovoltaic (PV)-BESS energy system

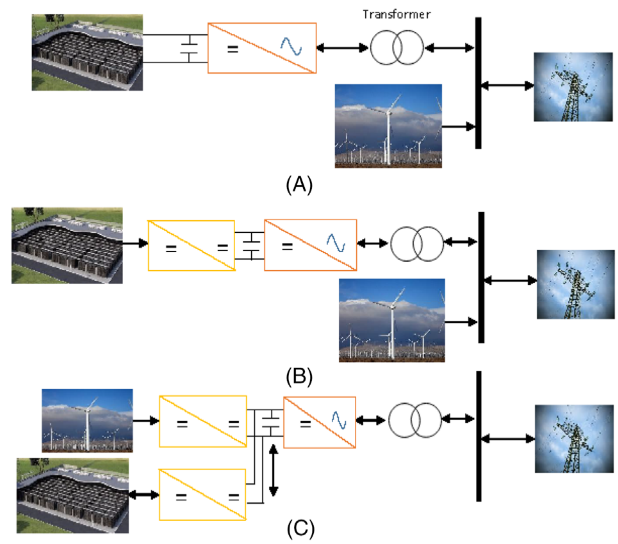

FIGURE 4 Typical battery energy storage system (BESS) connection in a wind-BESS energy system

as BESS is directly connected to the PCC, it requires an added circuit protection system that further increases cost to the system. However, the main advantage is that BESS can be regulated as a separate storage system for grid service. The intermediate DC-DC inverter with BESS in Figure 3B provides the flexibility to be connected with various DC-link voltage level as it allows to increase the battery voltage to the high DC-link voltage. The block diagram in Figure 3C eliminates the need of a DC-DC converter. This architecture is only suitable for a battery voltage equal to the DC-link voltage. The battery cannot be controlled and this requires proper inverter control with the varying DC-link voltage as battery SOC varies for grid synchronicity.The classical BESS structure in a wind farm comprises a very similar structure as employed in a solar PV system; a battery bank, PCS, and a transformer, if needed. Most importantly, BESS application in the wind farm is to store excess energy from wind power and deliver it during low or no wind period. General schematic diagrams of a wind-BESS combination are shown in Figure 4. The battery is connected in such a way that BESS can be regulated as an independent storage system as shown in Figure 4A,B whereas a battery can be connected to the DC-link in some cases as shown in Figure 4C.

In the case of a hybrid energy system, the battery can be coupled either to DC or AC bus, depending on design constraints and preferences. The battery banks may be integrated directly[36,37] or with a DC-DC PCS to DC bus.[38] Another option for the BESS connection is a battery bank with a DC/AC PCS to be connected with the AC bus. A transformer can be installed at BESS output before local AC bus[39,40,41] or after local AC bus[42] to finally being connected with the grid. A few possible PV-wind-BESS structures are shown in Figure 5.

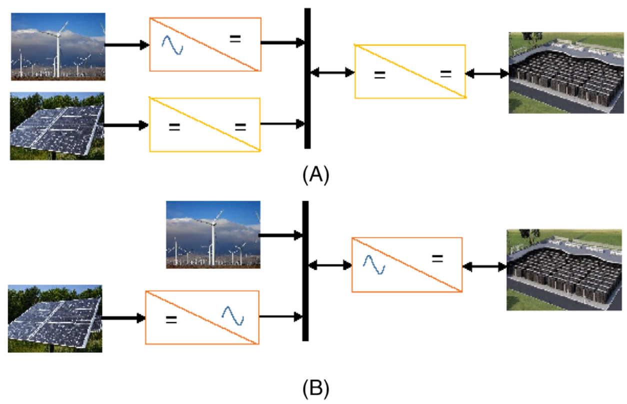

FIGURE 5 Typical battery energy storage system (BESS) connection in a photovoltaic (PV)-wind-BESS energy system

3.2 | Power conversion system and converter technologies

PCS is a power electronics-based interface to connect the storage system with AC. As a battery storage system employs a DC interface, the battery can be incorporated with DC terminal of PV, sharing the same DC bus. However, in a wind farm terminal, such a possibility does not exist. Therefore, PCS is necessary to connect a BESS with the AC grid. With high efficiency, fast response and control design, PCS perform both instantaneous active and reactive power regulation, as demanded in the present-day grid applications. The PCS comprises of two-level

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control-primary and secondary control.[43] Primary control generates gate drive signals to control power converter depending on reference charging mode and state of the system. The secondary control receives active and reactive power command and selects appropriate operation mode based on the SOC, electricity tariff, and so forth.

- Most trivial primary control approach is:
  - Proportional-integral (PI) control.
- Secondary control determines the operation mode of the power converters. Three frequent practices are:
  - Charge mode.
  - Discharge mode.
  - Standby mode.

The direction of power flow denotes BESS power output, that is, charging (negative) and discharging (positive) as shown in Figure 6. In an ideal condition, the BESS output is zero. However, there will be a small amount of power flow in BESS in reality due to the self-discharge of batteries and converter losses.

The most common PCS design topologies are-

1. Single-stage converter (DC/AC).
2. Dual-stage converter (DC/DC and DC/AC).
3. Single-/dual-stage multiport converter (multiple DC/DC or DC/AC converters in parallel).

Single-stage converter (DC/AC) is one of the less complex power electronics technologies for converting battery DC voltage into a three-phase AC voltage.[44] Many batteries are connected in parallel and series for high voltage-high power application. The addition of a medium frequency transformer-isolated AC/AC converter with BESS DC/AC converter eliminates the need for DC-link capacitors, reduces the size of grid filter.[45] However, this increases the total harmonic distortion in the output voltage resulting from the non-idealistic nature of switching.

A limitation of direct battery connection to DC-link voltage is the wide operating range of DC-link voltage as battery voltage alters according to its SOC status and so as the DC-link voltage. Therefore, to accommodate these broad voltage operating ranges, semiconductors need to be oversized for safe operation. The DC-link voltage can be controlled by incorporating a DC/DC converter between the battery and DC/AC converter that allows maintaining a constant DC bus voltage regardless of battery SOC status.[46] In contrast to a non-isolated DC/DC converter,[46] an isolated bidirectional DC/DC converter enhances converter efficiency, provides smoother power flow control and reduces costs.[47]

In order to connect BESS to the medium voltage grid without a step-up transformer, the modular converter can be designed in cascaded order. In a single-stage cascaded H-bridge converter type connection, each series-connected cell can contain equally distributed battery modules with smaller battery strings (distributed) and each full-bridge converter can control battery modules to regulate the power flow.[48] In the modular multilevel converter, long battery strings can be connected to the common DC-link (centralized) with submodules (SMs) in series to form converter arms. However, a centralized battery connection hinders the advantage of a cascaded structure.[49] In a dual-stage multiport converter, each SM consists of DC converter with battery and DC/AC converter.[50]

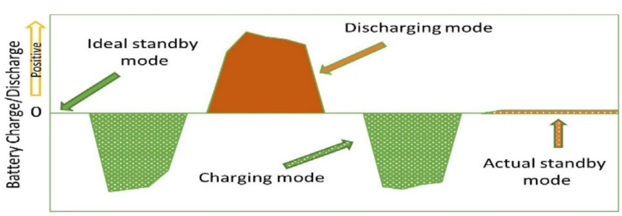

FIGURE 6 Various operation modes of battery energy storage system (BESS)

3.3 | Quantities for battery SOC calculation

The SOC is the accessible battery capacity to participate in charging/discharging cycles that is possible to define from the perspective of power and energy application. The measurable quantities for battery SOC estimated calculation are as follows:

- Cell/electrolyte temperature.
- Ambient temperature.
- Ampere-hour counting.
- Battery age.
- Cell voltage.
- Concentration of the electrolyte.

In model free approach, Coulomb counting method[51] and open-circuit voltage[52] methods are reasonable ways to determine a battery SOC but the accuracy is debatable as the estimation results are dependent on the initial error and accumulated noise in voltage and current measurements. An intelligent recurrent neural networks (RNN) method based on battery voltage/current and ambient temperature is another way of estimating SOC.[53] Nevertheless, RNN is a training-dependent method that may not perform satisfactorily for unseen data sets and

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also as this ignores the internal parameters of the battery, the error may persist in SOC estimation.

On the contrary, model-based method comprises of closed loop approach that uses estimation algorithms for correcting SOC error regularly from the voltage, current and temperature measurements to provide more accurate SOC calculation. A dual fractional-order extended Kalman filter[54] or other types of Kalman filter has been one of the most preferred algorithms for estimating SOC. Battery surface temperature often varies by a great number than the battery internal temperature and hence battery shell temperature is added for better SOC estimation.[55] Nevertheless, as the battery parameters change with battery aging and operating conditions, model-based approach still faces difficulties in providing reliable SOC estimation.[56] Few adaptive estimation approaches are available in the literature for estimating SOC accurately and reliably.[57,58,59] The errors in measurement and model result in incorrect SOC estimation[60] and it can be said that there are ample space for developing an accurate, robust, and reliable SOC estimation technique.

3.4 | Battery types

Rechargeable batteries are the most mature method of energy storage[61,62] as chemical energy[63] and are preferred in the power system application. A battery comprises numerous electrochemical cells coupled in series and/or in parallel based on appropriate voltage and capacity requirements.[64] Individual cell is composed of positive and negative electrodes, separated by liquid, paste, or solid electrolyte.[65] The important characteristics of rechargeable batteries are that transformation of electrical energy to chemical energy (charge) and vice versa (discharge) should be energy efficient and of minimal physical changes.[66]

Rechargeable or secondary batteries can respond very quickly (<s)[67] which allows BESS to be a popular and widely used option for steady-state and dynamic stability enhancement in power systems. Some important features or performance characteristics of batteries[68,69] that are intended for power system applications are exhibited in Figure 7:

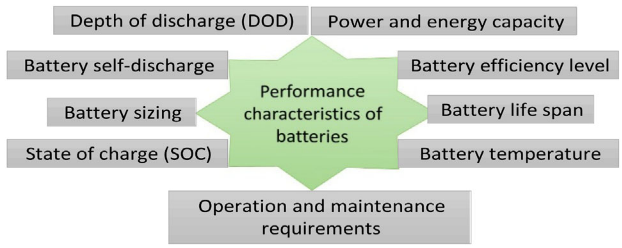

FIGURE 7 Typical battery energy storage system (BESS) connection in a photovoltaic (PV)-BESS energy system

The duration of energy storage ranges from hours to months.[65] Various battery technologies[66,28,70,71] used in the renewable energy system are briefly discussed in the following subsections.

3.4.1 | Lead acid

Since the beginning of the practical application of lead-acid batteries in 1860, it has been the most sophisticated and frequently adopted rechargeable battery technology in the power system. The lead-acid cell comprises a lead oxide positive electrode and a sponge lead negative electrode which are isolated by a microporous substance.[28] It has 70% to 90% efficiency but a limited life cycle span (5-15 years) which restricts its large-scale storage application.[70] Flooded battery and valve regulated (VRLA)[72] types are the most common types of the lead-acid battery.

3.4.2 | Lithium-ion (Li-ion)

With nearly 50 years of technology development, Li-ion is well recognized in a hybrid electric vehicle or plug-in hybrid vehicle and in power grid application.[73] The anode of Li-ion batteries is comprised of lithiated graphite or lititanate and the cathode is Li metal oxide or a Li metal phosphate separated by electrolyte made of lithium salts.[74,28] With an efficiency of nearly 100%,[70] this technology is lucrative for 3Cs (computer, communication, consumer) market applications. However, the problem with Li-ion batteries is their high capital cost ($)/kWh. In Li-ion polymer batteries, electrodes are separated by microporous poly-olefin.[75] These batteries are becoming more attractive in renewable energy and EV as a result of higher power and energy density and less memory effect.[75,76]

3.4.3 | Sodium sulfur

Sodium sulfur (NaS) has four times higher power and energy density compare to a lead-acid battery with nearly a similar energy efficiency.[28] The electrodes are composed of molten sulfur (positive), molten sodium (negative) and separated by a strong ceramic electrolyte, sodium alumina.[28] A study in Reference 77 shows that expensive NaS is more economical compare to cheap lead-acid for a long-term period.

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3.4.4 | Nickel cadmium

Nickel cadmium batteries have over 100 years of matured technology. Nickel hydroxide is used as cathode and metallic cadmium is used as an anode, separated by an alkaline electrolyte.[28] Nevertheless, NiCd is a robust alternative to lead-acid batteries, with higher energy density (two times) and power density (six to seven times).[28]

3.4.5 | Zinc hybrid cathode

With a development of 13 years, zinc hybrid cathode battery technology by Eos Znyth R technology is a low cost DC battery system with a price of $160/kWh which is almost 50% cheaper than that of current lithium-ion battery technology.[78,79]

3.4.6 | Vanadium redox battery

Vanadium redox battery (VRB)[28] accumulates energy by exchanging (accepting/donating) electron between electrolytes during the charging/discharging process. They have a really large cell voltage which is beneficial to acquire large power and energy than that of other redox flow batteries.[80] The fast responsive VRB[81] has a round trip efficiency, including several losses, of 75% in their life time.[82]

3.4.7 | Polysulfide bromide

Polysulfide bromide technology is a regenerative reversible electrochemical reaction between sodium bromide and sodium polysulfide electrolytes, a polymer membrane that works as a separator between electrolytes.[83] Positive sodium is allowed to pass through and the efficiency of this battery is about 75%.[84]

3.4.8 | Zinc bromine

Zinc bromine (ZnBr) is of hybrid form,[28] a combination of Zinc and Bromine, two electrolytes flow through two electrodes, microporous polyolefin membrane as a separator and an efficiency of about 75%.[84] With a high energy density and low cost, ZnBr is pondered as striking for large-scale application.[82]

4 | BESS APPLICATION IN RENEWABLE ENERGY SYSTEM

The application of BESS in the electric grid has started several decades ago. However, with the growing level of intermittent RES penetration, BESS is becoming one of the dominant energy storage technologies in the modern power system application as shown in Figure 8. BESS improves reliability and provides operational adaptability to wind/PV farms. Owing to complementary behavior, a hybrid combination of solar PV and wind has drawn much broader attention globally in recent years. However, regardless of an interconnected system or hybrid islanded system, the stable operation requires support from auxiliary energy sources. The choices of the BESS application are presented in Figure 8 in that reflects the various application modes in terms of active, reactive and both the active and reactive power application. These three aspects are considered since BESS can provide all three services at the grid level. A comprehensive study of existing researches on different types of BESS applications in PV, wind, and hybrid (PV-wind) integrated power systems are analyzed and summarized in this section (Table 1).

4.1 | Output power smoothing with BESS

PV generation is mainly affected by solar radiation, ambient temperature, panel temperature, cloud coverage and operating characteristics. A consistent power flow to the grid from PV is always desirable and certainly, it is possible to attain such expected stable power output.[85] However, this can result in rapid charging and discharging of batteries, thereby, affecting the battery life cycle. On some occasions, battery storage energy management strategy allows to purchase/sell electricity to and from the grid.[86] However, this does not reduce peak-to-mean ratio (PMR) and hence an optimized energy management

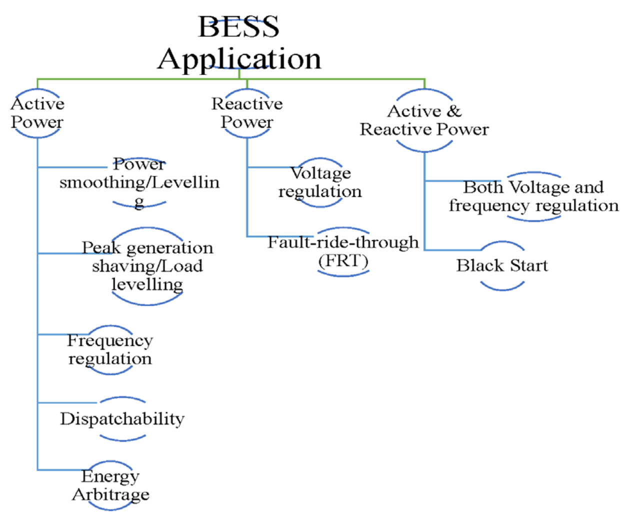

FIGURE 8 Typical battery energy storage system (BESS) applications in renewable energy integrated system

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TABLE 1 Summary of the battery storage system application in a photovoltaic (PV)/wind energy system

Applications objective	Battery types	Control algorithm	Duration	References
Output power smoothing	VRLA	Simple moving average	8760 h	88
	Lead-acid	Simple moving average	10 s	85
	Li-ion	ANN and grid-exchanged power profile	8760 h	87
	—	Exponential smoothing	24 h	89
	—	Discrete Kalman filter	—	94
	—	Fuzzy-based discrete Kalman filter	—	95
Peak generation/load shaving	Li-ion	Algorithm for the management of the power flows	1517 h	96
	—	An efficient method of finding the potential peak shaving	8 h	97
	—	PSO-based multiobjective planning approach	8 h	99
	Li-ion	Stochastic optimization-based battery operation framework	24 h	100
	$LiMn_2O_4$	Joint optimization framework	15 h	101
Voltage regulation	—	Coordinated local droop and distributed consensus algorithm	24 h	109
	$LiFePO_4$	Coordinated control of distributed ESS with tap changer transformers	8 h	113
	—	Bang-bang controller using a hysteresis current controlled technique	0.25 s	117
	—	Coordinated active and reactive current control strategy	24 h	118
	—	Indirect feeder voltage control scheme	1.8 s	119
Frequency regulation	—	Central power plant controller	9.7 h	123
	Lead-acid	Step-wise inertial control method	100 s	130
	Ni-Cd	PID regulator control scheme	16 s	41
	—	H_∞ controller-based wind-BESS coordination strategy	30 min	128
	Ni-Cd	Distributed control system coordinated control	12 s	129
	Lead-acid	Step-wise inertial control method	100 s	130
	Li-ion	State-machine-based coordinated control	24 h	130
Voltage and frequency regulation	—	Optimized operating scheme	3 s	137
	—	SMO master/slave control	15 s	138
	—	PI controllers-based control strategy	3.2 s	139
	—	Three-level hierarchical power quality control strategy	25 min	141
	—	Control coordination strategy of hybrid operation	10 s	143
	Li-ion	Fuzzy logic-based intelligent control technique	18 s	144
	—	FLC and PI control scheme	6 s	146
PV plant dispatchability	—	Parametric study of simplified imbalance settlement	8760 h	147
	NaS	Stochastic coordinated predictive controller scheme	60 h	154
	—	Two-stage optimization algorithm	24 h	155
	—	Adjustable robust power dispatch	24 h	156
	Li-ion	Optimal power control strategy	72 h	158
Fault-ride-through	—	Two-stage power conversion system	14 s	161
	—	Bidirectional DC/DC converter OFF/ON operation	5 s	162
	—	Coordinated PV/battery control strategy	1 s	163

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TABLE 1 (Continued)

Applications objective	Battery types	Control algorithm	Duration	References
	Li-ion	Master slave control mode	18 s	166
	Lead-acid	Supervisory control system	240 s	164
Black start	Lead-acid	A copula selection and goodness-of-fit-based method	80 min	167
	Li-ion	Stratified optimization strategy	60 min	168
	—	Systemic approach for restoration and black-start	17 min	169
	Li-ion	Mixed integer	60 min	171
Energy arbitrage	—	Cooperative hybrid storage model	24 h	172
	Li-ion, VRF	Multiobjective mixed integer linear programming	168 h	173
	Li-ion	Classification-based scheme	21 mo	174
	Li-ion, VRF	A techno-economic model	24 h	175
	Lead-acid	Dynamic program approach	720 h	176

Abbreviations: BESS, battery energy storage system; FLC, fuzzy logic control; NaS, sodium sulfur; PDI, proportional-integral-derivative; PV, photovoltaic; SMO, single master operation.

strategy is suggested in Reference 87 that reduces PMR in accordance with the variable sizes of integrated battery capacity. The moving average method determines the average generation of the system, compensates the error with less storage capacity and ensures better load supply.[88] However, this method has a memory effect that results in frequency switching of BESS producing an increased energy loss and thus reduces battery life cycle compared to the ramp-rate control method.[89] The value of window size defines the degree of smoother output (ramp-rate in Watt/min), that is, longer window size reduces the change of ramp/min. An approach for PV output smoothing with BESS is shown in Figure 9. BESS operates in charging or discharging mode depending on the surplus or shortfall in PV energy to smooth out PV power and meet the desired load demand. One of the main drawbacks with this kind of approach is that BESS undergoes huge number of charging/discharging cycle that affects lifespan of a battery.

Battery storage plays the foremost role to secure power leveling following wind variations. SOC status of battery is a crucial measure of providing the capability of output power smoothing at the desired level and duration. While providing fluctuation smoothing service, an SOC feedback method is presented in[90] to avoid overcharging/discharging. In favor of maintaining a constant wind power output at its terminal, a battery storage system can store/supply surplus/shortfall in the wind power system.[42,91] In order to maintain proportionate economic expenditure and smoothing performance, an optimal sized and fuzzy controlled charging/discharging strategy for BESS is proposed in[92] that concluded BESS as a cost-effective solution for wind farm owners. A constrained charging/discharging of multiple battery sets can prolong

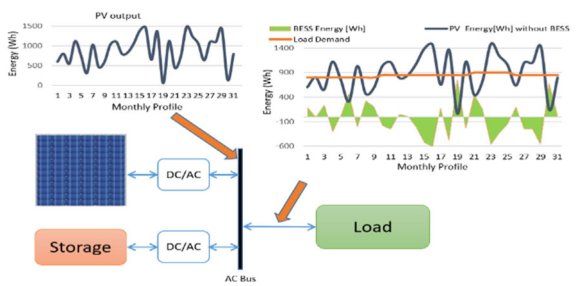

FIGURE 9 Photovoltaic (PV) output smoothing with battery energy storage system (BESS)

the battery's lifespan[93]; however, the actual implementation is essential for validating the proposed method.

A discrete Kalman filter is incorporated for eliminating the bias errors and predicting the actual power of PV and wind that reduces the requirement of BESS power for providing smoothing service.[94] Battery state-of-health can also be incorporated for improved battery health while smoothing output with the coordinated regulation of battery power output.[95]

4.2 | Peak generation/load shaving

Peak generation and peak load demand in industry, commercial, and residential buildings do not often coincide. The battery storage system can store excess energy during peak generation and supply the stored energy throughout the peak demand period at a later time of the day. Additionally, a battery can further be charged from the grid following a low price period.

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BESS installation facilitates the maximum use of available PV generation by peak demand smoothening.[16] BESS can store excess energy during the daytime and utilize stored energy in the evening to support peak load demand[96] and significantly reduce the peak power flows in the network.[97] The battery charging/discharging rate is updated in response to the actual SOC with the desired SOC level[98] and with minimized cost and power loss.[99] In some cases, peak load demand in a feeder may not align with the utility-wide peak demand and customer owned BESS can perform satisfactory peak reduction if sufficient battery capacity is available.[100] A typical BESS operation for peak generation shaving is illustrated in Figure 10. BESS can store the surplus PV energy during the daytime that can be used later on in the evening to facilitate peak load demand reduction.

Demand peak-cutting is extremely important to reduce a definite point of peak power consumption in commercial buildings, factories and residential buildings that might cause an extra cost to consumers and the adoption of BESS can considerably reduce users' electricity bills.[101] However, in response to a deregulated and competitive electricity distribution system, peak time energy price may not be much higher than that of regulated price, thereby affecting the economic benefit of a battery storage system in such cases.

4.3 | Voltage regulation

To ensure nominal voltage remains within the operating limit, fluctuating renewable energy generations must follow strict voltage regulation rules. Battery storage responds quickly by charging/discharging the battery by following voltage sags/swells and taking the initiative of maintaining a steady voltage source in the power system. Voltage surge arises during PV peak generation periods with little or no load demands resulting in a power flow in a reverse direction to the network. However, a large-scale distributed generation unit at a single connection point can also result in voltage violation.[102] A variety of solutions have been proposed to overcome such undesirable effects of large PV infiltration in low voltage distribution networks.[103-107] PV curtailment can be one of the solutions but this will reduce maximum use of PV generation capacity with the consequence of minimizing financial benefit.[103] Other adopted solutions are PV converter reactive power compensation,[104] installations of voltage regulator[105] and transformer tap adjustment.[106] Grid reinforcement may be another solution that can reduce feeder losses but it is a costlier solution.[107] BESS can be used to consume surplus PV energy during the peak generation and thus reducing the voltage rise impact of PV in grid[108] as shown in Figure 11. According to the network requirement, BESS can be designed to regulate grid voltage within the allowable limit by consuming surplus energy or regulating reactive power.

To deal with voltage rise/drop that emerges at peak PV generation or peak load demand, the battery storage system plays an important role.[109-115] Battery charging/discharging can be controlled by local droop method in regard to battery SOC,[109] monitoring PCC voltage[110] and using measurements from distributed controllers.[111] Battery storage system may support increased PV penetration while maintaining allowable voltage limit,[112] reducing transformer operational stress and resistive power losses[113] and to achieve the most functional combination of PV and BESS in mitigating voltage regulation constraints.[114] BESS active power[111] or priority on BESS reactive power coordinated with BESS active power can be designed for providing voltage regulation.[115]

The overvoltage is possible to be controlled considering wind power operation below maximum power point (MPP) but this will incur unwanted energy loss. Few research is available in wind farm voltage support utilizing a battery storage system. Battery charge/discharge is

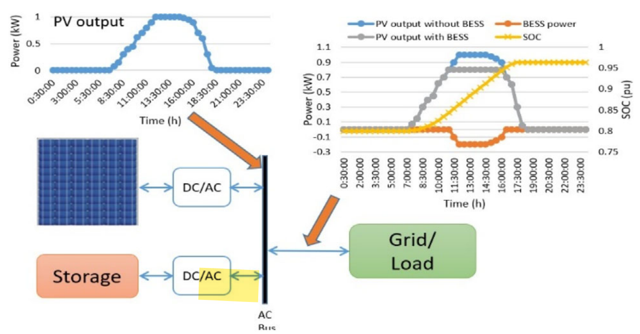

FIGURE 10 Photovoltaic (PV) peak generation shaving with battery energy storage system (BESS)

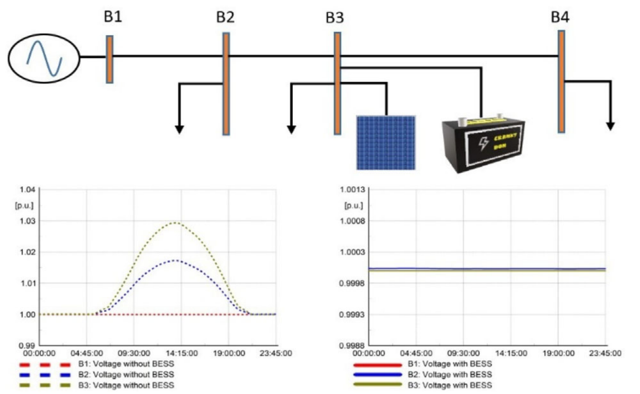

FIGURE 11 Voltage regulation with battery energy storage system (BESS) in a photovoltaic (PV) integrated system

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regulated to control DC-link voltage in a wind farm at varying wind speed conditions while maintaining overall system efficiency and increase the lifespan of the battery.[116] Voltage regulation is achieved by controlling both real and reactive power[117] and SOC-based active power and dead band-based reactive power control.[118]

Peak generation associated with PV during daytime and wind at nighttime may create voltage stability issues (voltage rise/drop) for outreaching the power limit. Typically, battery system is integrated with a separate conversion system to store and supply energy. However, in a PV-wind-BESS hybrid system, based on the configuration, PV inverter can be utilized to charge/discharge a battery at night to control voltage rise issues that arises from wind farm surplus energy.[119] An optimum placement and size of BESS is imperative for improved voltage regulation and prolonged life of the battery.[120]

4.4 | Frequency regulation

The power system inertia decreases reciprocally with an increased share of renewable energies. Hence, renewable power plants must adjust their output power proportionally to respond against frequency deviation. The PV controller can be exploited in order to provide frequency control which is subjected to overfrequency support through PV curtailment.[121] Underfrequency support is possible to carry out but this requires PV to be operated at a point other than the MPP.[122] Since PV output is intermittent in nature and weather dependent, PV plants need to arrange dispatchable auxiliary energy source to support system frequency whenever needed. Batteries are widely studied storage arrangements to support system frequency in a PV plant. The battery can be charged during peak generation and power can be supplied back to the system whenever low PV output is available. Battery storage system reduces power fluctuation and provides a fast response to a frequency deviation.[44] The combined control of PV and BESS can also be an alternative for frequency regulation in which BESS injects active power in the case of PV power deficit.[123] The power-frequency droop (P/f) characteristics as in Equation (1) can be fixed type[123] or adaptive type; nevertheless, an adaptive P-f demonstrates smoother transitions in various control strategies.[124] Coordinated optimized control of frequency control and self-consumption for battery recharge can be technically and economically demanding which requires a trade-off between them.[125] The amount of active power regulation of BESS (P) is determined by the droop value $R_{P\text{-}f}$ with respect to the changes in frequency deviation (df) from the nominal set point as in Equation (1).

$$P = \frac{df}{R_{P-f}} \tag{1}$$

BESS not only reduces the frequency drop but also diminishes frequency oscillation compared to without a BESS, as shown in Figure 12. Conventional generators are getting replaced by large-scale wind power plants and therefore wind power plants must commence the duty of frequency regulation support in the future. The participation of Wind farm in frequency regulation has been evidenced via inertial control[126] and pitch control.[127] Mainly, low frequency support is controlled by integrating a pitch control mechanism and high frequency support is controlled by battery charging/discharging accordingly.[128] Battery storage system can provide system frequency support on the basis of power imbalances[129] for the severe underfrequency situation.[130] To regulate system frequency, battery stores surplus energy thereby providing a peak shaving facility, supplying stored energy throughout the low wind period.[41] However, it is argued in Reference 131 that the coordinated control provides better frequency regulation compared to individual BESS or wind turbine control due to the need for large power in the short-term. Nevertheless, in a coordinated control approach, the wind farm can regulate its output for regulating frequency and battery storage will compensate if regulation demand is not satisfied.[132] The effective utilization of BESS allows reducing the amount of unexpected energy consumption while preventing wind fluctuations and provide additional regulation services without affecting the lifespan of the battery. However, extra benefits and economic advantages are subjected to accuracy in wind power estimation, market price and battery technology.[133]

The shortcoming associated with wind and PV are dependent on unpredicted wind speed and irregular solar radiation. Thus, intermittent natural renewable

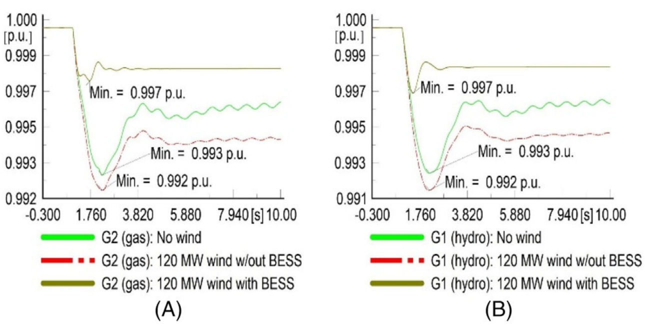

FIGURE 12 Frequency regulation with battery energy storage system (BESS) in a wind integrated nine-bus system

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generation often results in difficulty to meet load demand that greatly affects system frequency. In addition, rapid oscillation in hybrid power output might lead the system to instability. Frequency is possible to be controlled by sliding mode regulated wind turbine pitch control and battery system.[134] Battery storage (overfrequency/underfrequency) and PV (overfrequency) may provide primary frequency support and diesel generator can be used to provide secondary frequency support for long-term frequency regulation service.[135] Adaptive SOC can be incorporated in the feedback control for regulating high frequency oscillations where generators provide low frequency oscillations that minimizes stress on the conventional generators providing frequency control.[136]

4.5 | Voltage and frequency regulation

Referring to temporary or permanent island operation, following a fault in the system and passing clouds, BESS, as an active and reactive power contributor is much more reliable compared to other available conventional energy sources, for instance, diesel power source, to satisfy generation-load balance. An optimized operating scheme,[137] single master operation master/slave control[138] and PI controller-based control[139] strategy is suggested to support ancillary services such as voltage and frequency to a PV system considering dynamic behavior of the network and connected loads.[137,139] The batteries can be charged either from PV surplus energy[137,139] or grid following a low energy price period.[137]

In a grid-connected mode, MG operation might be needed in case of a grid fault. Therefore, an isolated system must be able to maintain nominal voltage and frequency to guarantee reliable operation. Battery storage system improves dynamic performance by scaling down system voltage and frequency fluctuation.[140] VSC tracks the active and reactive power following the grid demand, the available battery energy[141] and wind speed changes to regulate voltage and frequency of the studied network.[142] In some cases, an additional dump load might be useful to dump excess energy beyond the battery capacity to be stored.[143] BESS for voltage and frequency regulation in nine-bus system is shown in Figure 13A,B which demonstrates that BESS can improve grid voltage and frequency by regulating its active and reactive power as illustrated in Figure 13C.

Intentional or unintentional islanding operation requires voltage and frequency stability to serve the loads continuously. Considering the intermittent nature of PV/wind in an islanded hybrid system, fluctuation in voltage and frequency in response to load-generation imbalances, a battery storage system may enhance the power quality of the system. The controller will detect the power deficit and control the battery to maintain DC-link voltage and system frequency by providing the required power.[144] A combination of frequency control by BESS and reactive power control by the PV/wind converter is an alternative to maximize BESS use for frequency regulation and PV/wind regulated voltage control in an MG.[145] Different controller may have a technical benefit over another such as fuzzy controller may outperform PI controller under different scenarios with advanced dynamic response and minimum overshoot.[146] However, rigorous assessment of operational complexity, technical benefits and so forth. need to be addressed clearly to draw any conclusion.

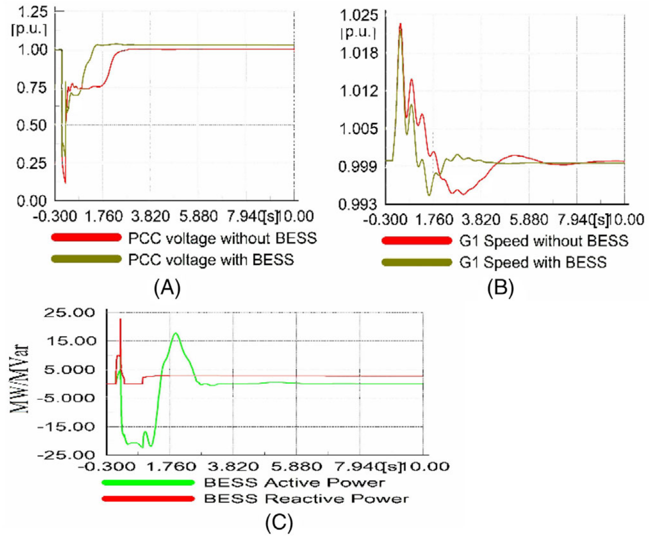

FIGURE 13 Voltage and frequency regulation with battery energy storage system (BESS) in a wind integrated nine-bus system

4.6 | PV/wind plant dispatchability

Non-dispatchability of RES in comparison to dispatchable conventional power plants; acts as the main hurdle for RES to be integrated in a large scale. RES dispatching ability influences estimated power production to manage load demand in real time. RES plant output power is estimated from weather forecast on intrahour to up to 39 hours.[147] RES should have sufficient feasibility of dispatchability due to forecasting error and storage systems are recognized as the utmost solution in such circumstance. Moreover, electricity authorities in some countries, such as in California in the United States,[148] United Kingdom,[149] and Italy[150] are impelling incentives and obligatory specifications to ensure RES penetration

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without impacting system reliability by means of encouraging storage system establishment.

Battery storage improves PV plant dispatchability by facilitating peak demand management, minimizing losses and charge/discharge cycles of the battery.[20] Dispatchability schedule to determine battery charging/discharging operation at a minimum cost may be based on forecasts generated 1 day ahead[20] or 1 hour ahead[151] which largely depends on the dispatch period and renewable generation types. A large size of BESS capacity is required in order to minimize the error between the forecasted PV and actual PV power dispatch. BESS can be dispatched to constrain PV output within the allowable maximum and minimum limit as shown in Figure 14.

Battery storage system, as a simple charging/discharging scheme, provides the flexibility to store surplus energy that can reduce forecast error in real time wind power and contribute in dispatchability improvement of wind farm.[152] Dual BESS can provide added safety to BESS operation.[153] However, dual BESS may bring additional costs compared to a single BESS topology. Optimal coordinated planning provides efficacious handling of non-Gaussian wind power unpredictability[154] and economic dispatch as opposed to battery cost through effective coordination and optimization.[155] BESS not only can minimize overall costs but also contributes to reducing carbon emissions from the CG units by supporting higher wind penetrations without raising the stability concern.[156]

The ultimate purpose of BESS usage in wind farm dispatchability improvement is to smoothen wind farm output power at a given dispatch period, that is, 30 minutes or hourly dispatch and so forth.[157] Battery SOC plays a key role in power mismatch compensation by using battery storage to improve the dispatchability of the wind farm.[158] When SOC is the primary objective for dispatch scheduling, dispatchability is largely reliant on battery capacity. Battery charging/discharging efficiency also acts

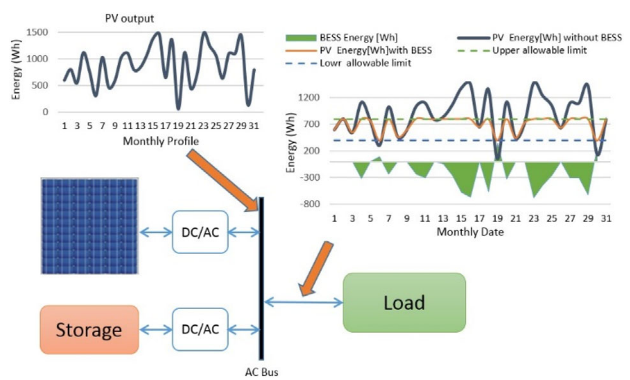

FIGURE 14 Dispatched photovoltaic (PV) power with battery energy storage system (BESS)

as a major determinant of dispatchability improvement.[159] To match load demand by hybrid system output, BESS contributes to increasing dispatchability of the hybrid system, reduce the spillage rate of PV/wind energy when participating in dispatching event and thus reducing the costs of the system.[160]

4.7 | Fault-ride-through

Typically, following grid faults, DG units are removed for safe operation but the removal of large size PV plants will affect negatively in such situation. Therefore, PV generation plants need to have an adequate FRT or LVRT capability to remain connected during faults period and provide active power immediately following fault clearance. Unlike in a wind power plant, a few studies are available on PV FRT capability because of small capacity of PV and thereby neglecting the negative impact on the grid.

In order to provide FRT service during the fault period, battery storage is designed to consume surplus active power during the fault and the possibility to contribute to reactive power support to control DC-link voltage.[161] The DC/DC converter operates in buck mode to charge a battery from available extra charge at DC-link.[162] However, if DC-link voltage exceeds the DC bus threshold or if SOC limits exceed the allowable limit, the battery system should stop functioning.[163]

With the increment of large-scale DG units, disconnection of DG units tend to increase the vulnerability of an electric grid. Therefore, recent grid codes considered such conditions and included FRT requirements for the wind farm to be connected to the existing electric grid. To enhance the response of faults in wind turbine, the coordination of a battery storage system and wind turbine is essential.[164] Battery storage reduces overcurrent during a transient fault in the system and supports DC-link voltage converters to improve dynamic stability.[165]

Following a transient disturbance in the system, distributed renewable energy should remain connected to avoid catastrophic failure of the system. Thereby, PV and wind farms must ensure FRT capability to avoid possible instability in the system. FRT capability improves the overall system stability.[166]

4.8 | Black start

BS is defined as the ability of the grid to regain its operating state after shutdown conditions resulting from catastrophic failure without any grid support. To be eligible for a BS source, the system must be capable of self-starting,

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provide adequate power to start a non-BS generating unit and maintain voltage and frequency stability. BESS with VSC-based active and reactive power regulation capability to regulate voltage and frequency makes it one of the ideal solution to form and adjust the grid voltage and frequency.

BESS in wind[167] and PV[168] farms can be exploited to start up these units as a BS source because BESS is capable of providing the necessary excitation voltage that other non-BS units require.[169] This will enhance the BS ability of the grid and widen the prospective application of PV/wind generation. However, proper sizing[167,168] and allocation of start-up sequence of BESS and other generating units[170] are imperative for enhancing the resiliency of the grid.

4.9 | Energy arbitrage

In day-ahead and real-time electricity markets, the price varies throughout 24 hours which implies the possibility of energy arbitrage as a part of the business strategy. In a deregulated market, BESS can be engaged in energy arbitrage to exploit the price differential between the peak and off-peak hours[171] and shift the energy from expensive to the inexpensive hours[172] and minimize the operating costs.[173]

However, in order to maximize the benefit of energy arbitrage, it is extremely important to have an insight into the price alteration of forthcoming hours in the day-ahead and real-time market. A proper optimization platform can significantly increase the profit of BESS for energy arbitrage.[174] BESS can be designed to provide multiple services and in that case, synergies can maximize the techno-economic benefit of BESS, that is, minimum revenue reduction during frequency response to maximize energy arbitrage benefit.[175] Nevertheless, the maximum benefit from energy arbitrage is subjected to battery degradation and price.[176]

5 | DISCUSSION ON KEY FINDINGS AND CHALLENGES OF BESS APPLICATION

5.1 | Key findings of BESS application

Thorough review of existing literatures unfolds the importance of BESS application in renewable energy system to provide required active and reactive power support. The key finding of these studies is summarized as follows:

- The damping of active power oscillation is generally provided by tracking output power as a reference and BESS supplies the required power imbalances. In other cases, voltage/frequency or both is used as an error signal for BESS contribution.
- Direct integration of batteries on DC side of the DFIG back-to-back converter or on a DC converter terminal of a PV may eliminate the necessity of an additional PCS, associated losses and thus minimize costs. However, this may require the complex design to improve the converter's robustness with high power/energy transfer capability.
- The adoption of a battery storage system to reduce forecast error may not be always a cost effective approach.[147] The main determinants of cost-benefit are the investment costs of battery, round trip efficiency, and service life.
- A large capacity of BESS is essential for reducing the error between the forecasted and the actual generation from RES which requires techno-economic justification for the mandatory investment.[151]
- The performance of smoothing is ameliorated by battery charging/discharging rates and thereby smoothing of high ramp rates may result better output profile but at a cost of quicker battery aging.
- Several minutes/hourly based dispatch strategy improves the charging/discharging profile of batteries than that of a constant output power smoothing and thus improves the life span of the battery.
- Dual-BESS combination may significantly improve battery charging/discharging management and is capable of reducing the number of charge/discharge cycle; however, this will incur more cost due to additional battery set to maintain enough capacity of BESS.[153]
- SOC-based battery control design is crucial to avoid battery overcharging/discharging and adversely affecting battery lifespan.[177] However, with high forecast error, SOC feedback-based control strategy could be unsuccessful in maintaining desired to smooth performance[90] over the long period.
- Coordinated and adaptive control algorithms always provide robust performance and better power tracking.[154]

5.2 | Key challenges of BESS application and future directions

Disregard of progressive research in this field, ample opportunities are available to accomplish further research in the applications of BESS in renewable energy systems. A comprehensive study of BESS application in

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renewable energy systems reveals the potential challenges associated with BESS installation, the efficiency of BESS components and energy regulation policy. The key challenges are summarized as follows:

- Optimal sizing of battery in PV smoothing is greatly affected by the maximum level of ramp-up and minimum ramp-down boundary and an inappropriate size will result very low and high capacity of BESS.[19]
- Battery energy efficiency and lifespan play a key role in the optimal sizing of BESS. Thus, an improvement in battery technology is imperative to bring down battery costs.
- Sometimes a simple control approach can be effective for smoother PV output but it may be subjected to memory effect and result in reduced life cycle due to persistent battery switching.[89]
- The constant charging/discharging of an individual battery in a dual BESS system can be economically advantageous but the actual implementation through a single PCS is a demanding and complex task that requires validation.[93]
- The installation cost of BESS is quite high so far which impedes the attraction of BESS adoption by RES farm owner. Therefore, a cost-efficacious and high efficient BESS technology is required to minimize the impediment of BESS implementation.
- BESS can be directly connected to the DC-link but this lacks the control of the battery. To provide the regulation capability, the battery can be coupled to the desired bus via DC/DC or DC/AC converter. However, this will add to the converter's cost.
- An appropriate selection of DC-DC converter (unidirectional/ bidirectional) is needed to handle the required power conversion (low/high-power/energy capacity) efficiently.
- In the case of multiple BESS structure, a proper power allocation between individual batteries is always a demanding and complex task. Decentralized battery sets with multiple SMs provide better operational flexibility than the centralized converter module. Nevertheless, an array of converters will incur higher costs.
- Accurate forecasting is able to alleviate proper planning of battery charging/discharging to ensure an achievable unit commitment to the grid with economical battery operation. However, it is often difficult to predict accurately and hence, improvement in predicting irradiance and wind speed is essential.
- The inaccuracy between the forecast and real-time production of RES power output varies by a large margin in 24 hours ahead market than 1 hour ahead market. This results in the commitment for large BESS capacity in a day-ahead market that increases the capital cost for installation and hence, techno-economic feasibility is demanding for participating in such dispatchable market.[151]
- The requirement of battery power is highly unpredictable than that of battery energy which causes troublesome in real-time BESS operation.
- Dynamic impact of battery conversion efficiency to the grid support is often ignored. There is a need to consider the converter's conversion efficiency including variable charging/discharging resistance with respect to battery SOC in real time.
- The impact from the failure or disturbances in battery storage systems to the connected network is open for investigation.
- BESS can be adapted for various applications by modifying its closed loop feedback control strategy and incorporating a suitable battery SOC management and SOC recovery strategy. A convenient battery SOC recovery is pivotal for ensuring sufficient battery capacity for participating in the energy market or stability enhancement. This is particularly challenging in terms of stability performance requirements vs the economical charging of the battery.

6 | CONCLUSION

With the proliferating nature of RES penetration, the urgency of minimizing the adverse impact of RES has drawn significant consideration in recent years. Considering this, an attempt has been put forward to present BESS application in RES integrated power system and how they have been adapted for diminishing the adverse impact of RES. The study has focused only on the transmission and distribution levels.

The literature survey points out that BESS is mostly used to regulate active power or simultaneous active and reactive power while participating in minimization RES impact in grid voltage and frequency. In addition, as compared to smaller window sizes for smoothing, the larger window provides a better ramp profile per minute but this requires a larger battery capacity to be installed. On the contrary, BESS employment for reactive power management is not yet widely acknowledged both in practice and academic research mainly due to the financial reasoning of BESS installation. The concern arises because the fractional use of BESS (reactive power can be provided by any other shunt devices with lower cost) is not economical as compared to the use for active and reactive power. While regulating power output, battery SOC needs to be accurately calculated and considered in the design to avoid any damage to battery life.

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Integrating battery to the DC-link of DFIG generator/PV can be a cost-effective solution to control the active/reactive power supply. However, this has a shortcoming of DC-link voltage to be regulated by battery SOC that needs to be large-sized or limited SOC operating range for safe operation. Remembering this, a separate DC/DC converter can provide better operational flexibility but this will incur an additional cost. The improvement in converter efficiency requires further attention to minimize conversion losses and reduce the requirement of battery power and energy capacity.

The development of a software program that allows the user to choose an optimal BESS technology in terms of grid conditions, costs, lifetime and power and energy capacity. In the same token, the improvement in battery technology is imperative to thrive in the energy industry.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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