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Comparative Review of Battery and Hybrid Energy Storage Systems for Frequency Regulation in Islanded Microgrids

Rudaraiah Yanaganti[1], Kumbajadala Pranathi[2], Habeeb Fathima[3]

[1]Assistant Professor, [2]Lecturer, Department of Electrical and Electronics Engineering, Vaagdevi Engineering College, Warangal, India.

[3]Assistant Professor, Department of Electrical and Electronics Engineering, Vaagdevi College of Engineering, Warangal, India.

E-mail: [1]yanagantirudraiah@gmail.com, [2]pranathi224@gmail.com, [3]sabahabeeb@gmail.com

Abstract

The increasing incorporation of renewable energy sources (RESs) in islanded microgrids has complex frequency regulation problems due to decreased system inertia and unpredictable generation. energy storage systems (ESS), such as battery energy storage system (BESS) and hybrid energy storage system (HESS), have been recognized as potential systems to achieve stable and efficient operation of islanded microgrids. This research study presents a comprehensive comparison of BESS and HESS in frequency regulation in islanded microgrids. In this paper, the hybrid microgrid configurations, operation, energy management, and control strategies such as droop control, hierarchical control, model predictive control, and virtual synchronous generator method are reviewed. Moreover, the performance of BESS and HESS are compared in terms of frequency stability, transient performance, battery lifespan, renewable generation integration, reliability, and complexity of installation. The HESS performs better in terms of transient response and battery lifespan as a result of energy management coordination. Hence, HESS can be regarded as an attractive solution for the future of renewable-powered islanded microgrids.

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Keywords: Islanded Microgrid, Frequency Regulation, Battery Energy Storage System (BESS), Hybrid Energy Storage System (HESS), Renewable Energy Sources (RESs), Energy Management, Hybrid Microgrid.

1. Introduction

The increasing trend of using RESs, namely photovoltaic solar and wind generation, has led to the development of sustainable and low carbon power systems. Microgrids have proven to be a successful tool for integrating RESs and increasing the reliability and flexibility of power systems. A microgrid comprises distributed generation, ESSs and controllable loads which may run in either grid-forming or islanded modes [1], [2]. In these modes of operation, islanded microgrids are highly challenged due to their lack of inertia and reliance on inverter based RESs. Power imbalance arising from intermittent generation and sudden changes in load conditions can cause frequency deviation and instability in islanded microgrids. Thus, frequency regulation is crucial for efficient islanded microgrid operations [1], [3].

To address these issues, ESSs are extensively utilized to deliver fast power support, manage generation and consumption, and reduce renewable power variations. The typical energy storage devices are batteries, supercapacitors, flywheels, and HESS [3], [4], [17]. Among which, BESSs are extensively adopted due to their high energy density, fast dynamics, and mature technology. They play an important role in the regulation of frequency, load leveling, and energy management in microgrids [5], [6], [18]. Nevertheless, the repeated charge-discharge process may accelerate the aging rate of batteries, generate thermal stress, and shorten their lifespan, especially for systems with high renewable integration [7]. To overcome the above problems, HESS adopts batteries as the energy source and high-power-density devices like supercapacitors or flywheels as the auxiliary storage devices. In this way, batteries can supply long-term energy support, and the auxiliary storage devices can regulate the fast variations of power.

The performance of frequency regulation with ESS-based systems also relies on the efficiency of control methods. Various approaches like the droop control method, hierarchical control, model predictive control (MPC), virtual synchronous generator (VSG) control method, and coordinated hybrid control method have been suggested for better stability and optimal usage of the ESS [11]– [13], [22], [23]. Recent researches also involve forecasting and intelligent energy management techniques in order to make the microgrid resilient to any uncertain working situation. This research provides a comparative study of BESS and HESS for frequency regulation of islanded microgrids.

2. System Architecture of Hybrid Microgrid

A hybrid microgrid is an energy system where various kinds of distributed energy resources, ESSs, power electronics, and loads are combined in a control strategy. The main aim of hybrid microgrids is the provision of efficient and reliable power supply, taking into consideration the characteristics of renewable energy resources that include the intermittent nature of the sources. In contemporary power systems, hybrid microgrids have received much interest since they provide the possibility of integrating various RESs like PV panels and wind generators along with other generation units and ESSs.

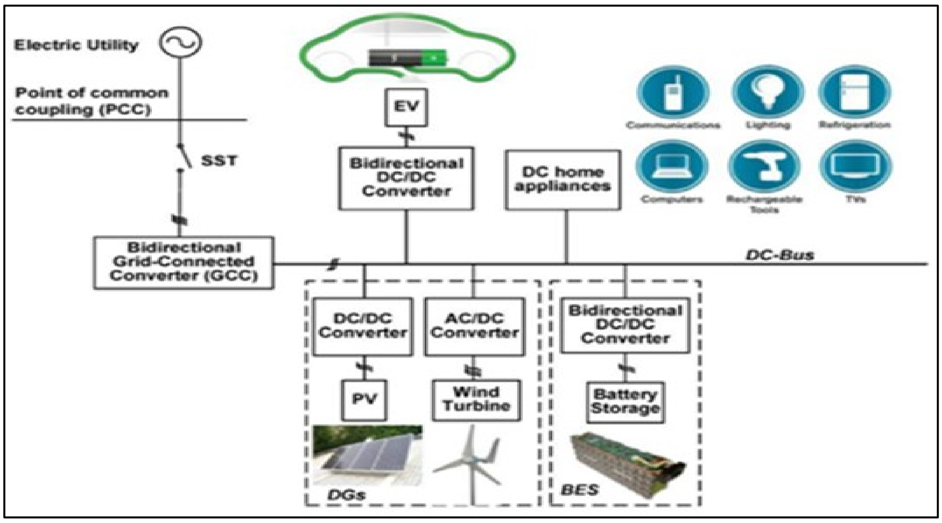

Figure 1. General architecture of a low-voltage direct current (LVDC) microgrid system (adapted from [25])

The architecture of a hybrid microgrid system generally includes renewable energy generation sources, traditional back-up generators, ESS, power electronics converters, and load centers connected via a shared distribution system. The contribution of RESs lies in the provision of environmentally friendly power generation sources; however, these RESs have unpredictable production and their production depends greatly on environmental conditions. This might result in power imbalance and frequency instability in the microgrid, especially in isolated microgrids where there is no access to the power grid. To address these issues, ESS are included to balance the power generated [3], [4].

Among the various types of microgrids, the Low Voltage Direct Current (LVDC) Microgrid system is one that shows great promise due to its high efficiency, simple control scheme, and applicability to renewable energy systems and ESS [2]. The LVDC microgrid connects the RESs, ESS, and the loads via the same DC bus system, which leads to fewer power conversion steps and reduced power loss. The architecture of the LVDC hybrid microgrid, which includes the Photovoltaic (PV) generation, wind energy conversion systems, BESS, HESS, power electronic converters, and local loads, is shown in Figure 1. The PV system is tied to the DC common bus through a DC–DC boost converter for controlling the output voltage and MPPT. Likewise, wind energy conversion systems are interfaced to the common DC bus through AC–DC converters for providing regulated DC power [2], [11].

The ESS ensures balance in the power grid and frequency control in the microgrid. The BESS will provide constant energy supply while the HESS comprises batteries along with high-power-density devices like supercapacitors and flywheels. The LVDC microgrid will be able to improve reliability, renewable energy integration, and stability through coordinated energy control. Energy storage subsystem is the primary element in microgrid structure. BESS are linked through bidirectional DC-DC converters that support both charging and discharging as per need of the system. Whenever there is excess production from renewable resources, energy storage takes place in the batteries, while during deficit generation, energy is supplied from these batteries to compensate for the energy imbalance and maintain stability. In HESS, apart from the batteries, other components with high power density like supercapacitors and flywheels are used [8] - [10], [20], [21].

Point of common coupling (PCC), the microgrid is connected to the utility grid through a voltage source converter (VSC). Bidirectional flow of power can be achieved between the utility grid and the microgrid in the grid-connected mode. The ESS becomes significant when the microgrid operates in the islanding mode because it provides support for regulating both the voltage and the frequency levels of the microgrid system. Control techniques like droop control, hierarchical control, and MPC enable power sharing [11]– [13], [16].

The efficiency of the hybrid microgrid architecture highly depends on the proper operation of renewable energy resources and energy storage technologies. Through the integration of high-energy capacity of the battery with fast-dynamic behavior of supercapacitor or flywheel, transient stability, frequency deviation, and renewable energy usage have been greatly improved by using hybrid energy storage. Therefore, the LVDC hybrid microgrid system is now among the most promising systems for future resilient and sustainable electrical systems due to the presence of high renewable energy penetration [9], [10], [21].

Table 1. Comparative analysis of various microgrid systems.

System Type	Typical Sources	Advantages	Limitations	Typical Applications
Renewable Energy System	Solar PV, Wind Turbine, Small Hydro	Environmentally friendly, sustainable energy generation, low operating cost	Intermittent output, weather-dependent operation, frequency fluctuations	Green energy generation, rural electrification, distributed generation
Non-Renewable Energy System	Diesel Generator, Gas Turbine	Reliable power supply, high controllability, continuous operation	Fuel consumption, greenhouse gas emissions, high operating cost	Backup generation, emergency power supply, base-load support
Hybrid Energy System	Solar PV, Wind Turbine, Diesel Generator, Battery/ Supercapacitor/Flywheel ESS	Improved reliability, enhanced frequency stability, efficient renewable integration	Higher initial investment, increased control complexity	Islanded microgrids, frequency regulation, critical infrastructure, smart grids

Table 1 presents a comparative analysis of renewable, non-renewable, and hybrid energy sources utilized in microgrids. RESs provide environmentally-friendly electricity generation that is characterized by low emissions. Nevertheless, the intermittent nature of RESs makes it difficult to ensure balance in electricity production and frequency control. Non-RESs ensure continuous and controllable generation of energy but at the cost of high consumption of fuel and operating expenses, as well as environmental pollution. Hybrid energy sources include RESs, energy storages, and traditional generating units and provide the opportunity to take advantage of every element and overcome its weaknesses. Therefore, hybrid energy sources have better reliability, frequency control ability, and high level of resilience [1], [3], [8].

2.1 Literature Review and Research Gap Analysis

Many researches have examined the use of BESS and HESS for regulating frequency in isolated microgrid. Studies have been conducted in areas of energy management, smoothing of renewable energy, frequency stabilization, and control methodologies. Though BESS approach is found to be efficient for energy balancing and renewable energy integration, it suffers from problems such as battery wear and tear and lifetime issues [5] – [7]. To overcome these problems, HESS systems which use battery with supercapacitor or flywheel have been suggested [8] – [10], [21]. Advanced approaches like MPC and coordinated control techniques have been proposed for improving the frequency regulation performance and efficiency [13], [21]. However, even though these approaches yield some advantages, issues related to battery degradation, real-time implementation, computational load, and economic viability still remain a hindrance for their widespread application. Table 2 provides a summary of relevant studies along with key research gaps identified through the literature review.

Table 2. Summary of representative studies and identified research gaps

Ref.	ESS Type	Control Strategy	Key Contribution	Identified Research Gap
[5]	BESS	Rule-Based Control	Improved renewable energy dispatch and power balancing.	Battery degradation and aging effects were not considered.
[9]	HESS (Battery–Supercapacitor)	Wavelet-Based Control	Enhanced mitigation of wind power fluctuations and improved power quality.	Limited validation under real-time operating conditions.
[13]	BESS/HESS	Model Predictive Control	Optimized microgrid operation and improved frequency regulation performance.	High computational complexity for practical implementation.
[21]	Battery–Flywheel HESS	Coordinated Control	Improved frequency stability and reduced battery stress.	Higher implementation cost and system complexity.

Table 2 illustrates the list of some representative researches concerning the application of frequency regulation using energy storage in islanded microgrids. From the literature review, it is evident that there have been substantial developments in the area of renewable energy penetration, frequency stability, and energy management using BESS and HESS systems. Nevertheless, there are still many technical issues to be solved concerning the battery aging problem, real-time control, computational complexity, and economic feasibility

3. Battery vs Hybrid ESS for Frequency Regulation

Frequency regulation is an essential requirement for ensuring the continuous stable performance of islanded microgrids. In contrast to traditional power systems whose stable operation depends on the use of the inertia of large synchronous machines, islanded microgrids lack significant inertial contribution because of the increasing use of inverter-based renewable generation. Changes in the intensity of sunlight, wind speed, and load demand may cause fast changes in the system's power balance causing frequency deviation. Hence, ESSs have been recognized as a promising solution for supporting the system frequency [3], [4], [24].

3.1 Battery Energy Storage Systems

BESS is the most commonly used technology for energy storage in modern microgrids due to its high energy density, rapid controllability and mature technology. In particular, lithium-ion batteries attracted much attention due to their high efficiency, quick response characteristics and compatibility with renewable sources [5], [6]. The battery can either consume or generate active power by means of bidirectional converter in case of frequency disturbance, thus balancing generation and load and contributing to primary frequency control. Effectiveness of BESS in frequency regulation was proved in many applications of microgrids. Their quick response ability allows for correction of frequency deviation and balancing of power. Additionally, BESS helps to shave peak load, level load, smooth out renewables, and reserve power [18]. However, despite their many advantages, standalone battery energy storage faces some difficulties in operations. Continuous charge-discharge operations for frequency control contribute to accelerated wear of batteries and higher thermal stresses of battery, thus decreasing system lifetime and increasing cost of maintenance [7]. Additionally, batteries have lower power density than supercapacitors and flywheels, therefore they are not effective in handling high-frequency transients [17].

3.2 Hybrid Energy Storage Systems

To address the problems faced in individual battery storage systems, HESSs have been invented using the combination of batteries and additional storage technologies that possess high power density such as supercapacitors and flywheels [8], [20]. The aim behind HESS is to use the energy density advantages of the battery and power density advantages of the auxiliary storage devices. In the case of battery-supercapacitor HESS, the battery supplies energy over the period of time, but the supercapacitor provides power to compensate for the transient energy demand. Likewise, in the case of battery-flywheel HESS, the flywheel is used to supply immediate power in case of any disturbance, but the battery provides energy continuously [9], [10].

Recent research results, HESS is able to perform better in terms of frequency regulation as compared to the regular BESS especially when the level of renewable energy in the grid system is high [21]. Fast acting storage systems ensure that frequency oscillations are reduced more quickly while providing higher damping characteristics for disturbances caused by changes in either generation or load [9], [21]. Through load sharing in power regulation, battery lifetime can be enhanced.

3.3 Comparative Analysis of BESS and HESS

The primary difference between BESS and HESS is associated with the division of energy and power management processes. In single battery systems, one unit of energy storage needs to address both energy and power demands at the same time, which usually results in higher battery degradation rates and lower energy efficiency. HESS, on the other hand, separates energy and power management into different storage devices and allows the latter to work in their respective optimal regions. From the frequency regulation viewpoint, HESS ensures improved transient performance, greater ability to reject disturbances, minimized frequency excursions, and quick restoration after a disturbance. Despite the fact that the use of several energy storage units makes the system more complex and costlier initially, it improves its dynamic performance, reliability, and lifetime of batteries; therefore, HESS could become an attractive option for future microgrids with high share of renewables [8]– [10], [21].

Table 3. Comparison of battery and hybrid ESS for frequency regulation

Performance Aspect	BESS	HESS
Operating Principle	Performs energy balancing and frequency regulation using a standalone battery [5], [6].	Combines batteries with supercapacitors or flywheels for energy and transient power support [8], [20].
Frequency Regulation Performance	Provides effective frequency support but shows larger deviations during major disturbances [18].	Reduces frequency deviations and enables faster recovery after disturbances [9], [10], [21].
Dynamic Response	Fast response; repeated transients increase battery stress [7].	Near-instantaneous transient response with improved damping [9], [21].
Battery Degradation	Frequent cycling accelerates battery aging [7].	Power sharing reduces battery stress and extends lifespan [21].
Renewable Energy Integration	Suitable for moderate renewable penetration [18].	Better suited for high renewable penetration levels [10], [21].
Control and Implementation	Simple control based on SOC monitoring and power regulation [5].	Requires coordinated energy management and power-sharing control [8], [20].
Economic Considerations	Lower installation cost and simpler architecture [6].	Higher initial cost but lower lifecycle cost due to longer battery life [8], [21].
Overall Suitability	Mature and practical solution with battery limitations [7], [18].	Superior dynamic performance and reliability for islanded microgrids [9], [10], [21].
Operating Principle	Performs energy balancing and frequency regulation using a standalone battery [5], [6].	Combines batteries with supercapacitors or flywheels for energy and transient power support [8], [20].

Table 3 presents a comparison of the performance of BESS and HESS as regulating frequencies in islanded microgrids. Although BESS is relatively easy to design and install with low costs and ability to provide good frequency regulation, its efficiency is hindered by battery aging effects and reduced capabilities with frequent transient events. On the other hand, HESS uses batteries with supercapacitors and/or flywheels in order to improve its dynamic performance, frequency deviations, and system stability. The power sharing function of HESS ensures that the batteries are not stressed hence prolonging their lifespan.

4. Control Strategies for Battery and Hybrid ESS

The performance of Battery BESS and HESS in frequency regulation highly depends on the control approach used. The selected control approaches enable rapid power balance and energy management and improve system stability in diverse operational modes. Classical control approaches like droop control and hierarchical control are applied extensively due to their simplicity and decentralization possibilities [11]. Droop control allows achieving autonomous power sharing between distributed energy sources, while hierarchical control improves overall coordination of the microgrid using primary, secondary, and tertiary control.

In order to increase the dynamic performance, various advanced control strategies including rule-based control and MPC have been extensively studied [5], [13]. The former uses predetermined operating conditions for power sharing between different energy storage devices, whereas MPC improves the system operation by considering the forecast of future load and generation changes. Advanced control allows to restore frequency and reduce the stress of the energy storage. In case of HESS systems, it is essential to consider the coordination strategy since multiple storage systems have to be operated at once. In the battery-supercapacitor system as well as in the battery-flywheel one, the rapid-changing power is provided by supercapacitors or flywheels, whereas batteries deal with energy. Recently, new control strategies based on VSG and synchronverter technologies have been developed. They emulate the operation of synchronous machines in terms of their influence on the system inertia and frequency stability [14], [22], [23]. Thus, advanced coordination strategies are very important for improving the performance and reliability of BESS and HESS operation in microgrids.

Table 4. Control strategies for battery and hybrid ESS

Control Strategy	Description	Frequency Regulation Performance	Application in BESS/HESS	Advantages	Challenges
Droop Control	Adjusts ESS output according to frequency deviation [11], [12].	Fast primary frequency support and autonomous power sharing [11].	Widely used in BESS and HESS microgrids [11], [12].	Simple, decentralized, and reliable [11].	Cannot completely restore nominal frequency; steady-state error may occur [12].

Hierarchical Control	Employs primary, secondary, and tertiary control layers [11].	Improves frequency restoration and system coordination [11], [12].	Applied in coordinated BESS and HESS operation [11].	Better coordination and energy management [12].	Requires communication infrastructure and increases implementation complexity [12].
Model Predictive Control	Predicts system behavior to determine optimal control actions [13].	Improves dynamic response and minimizes frequency deviations [13].	Advanced BESS and HESS energy management [13].	Optimized operation and efficient energy utilization [13].	High computational complexity and accurate system models are required [13].
Virtual Synchronous Generator Control	Emulates inertia and damping of synchronous generators [22], [23].	Enhances transient response and virtual inertia support [22], [23].	Renewable-rich inverter-based microgrids [22], [23].	Improves stability and resilience during disturbances [22].	Requires careful parameter tuning and controller design [23].
Coordinated Hybrid Control	Allocates transient power to supercapacitors /flywheels and sustained power to batteries [9], [21].	Provides superior frequency stabilization and faster recovery [9], [21].	Specifically designed for HESS [8], [21].	Reduces battery stress and extends battery lifetime [21].	Requires advanced power-sharing algorithms and real-time coordination [21].

The control strategies used in the BESS and HESS in terms of frequency regulation are highlighted in Table 4. Conventional methods such as droop control and hierarchical control offer reliable power sharing and coordination in the system, while modern strategies such as MPC control, VSG, and synchronverter control ensure better dynamics and frequency regulation. The coordination of hybrid control is very essential in HESS systems as it offers effective power sharing in batteries and auxiliary ESSs. The choice of a suitable control strategy plays a vital role in system stability and battery life.

5. Performance Analysis and Comparative Discussion

The operation of the ESSs is important for the maintenance of the frequency stability of the microgrid. There are two kinds of ESSs which are widely used to overcome the effects of fluctuating loads and RESs on the frequency stability of the islanding microgrid – BESS and HESS.

Table 5. Performance metrics of battery and hybrid ESS in islanded microgrids

Performance Metric	BESS	HESS
Frequency Stability	Provides effective frequency support under normal conditions [18].	Offers improved frequency regulation with smaller deviations [9], [10], [21].
Dynamic Response	Fast response capability [13], [18].	Faster response due to additional storage technologies [9], [21].
Battery Lifetime	Reduced by frequent cycling [7].	Extended through power-sharing operation [8], [21].
Renewable Energy Integration	Suitable for moderate renewable penetration [18].	Better suited for high renewable penetration levels [10], [21].
Cost and Complexity	Lower cost and simpler control [5], [6].	Higher cost with more advanced control requirements [8], [20].

Table 5 compares the performance of BESS and HESS in islanded microgrids. BESS offers reliable frequency support with lower cost and simpler control, while HESS provides better frequency stability, faster dynamic response, and improved renewable energy integration. Despite its higher complexity and cost, HESS delivers superior overall performance and reliability.

Frequency regulation, HESS exhibits faster responses and better disturbance rejection compared to BESS. With supercapacitor or flywheel storage systems employed for HESS, power variations are more easily controlled, thus leading to enhanced frequency stability and decreased settling time [9], [10]. Battery life is also an important issue to consider. As for BESS, rapid charge and discharge cycles may cause battery degradation. However, with HESS, power variation is taken care of by the auxiliary storage system, thereby enhancing battery life [21].

HESS provides an improvement in integrating renewable energy resources. The high-speed response capability of the technology allows for better balancing the fluctuations and improving the stability of the whole system [8], [10]. However, despite the benefits described above, the fact that HESS needs extra storage components and more sophisticated control systems increases its installation cost and complicates the system. Nevertheless, better efficiency and decreased battery wear can be seen as advantages in the long use. whereas, BESS is an easy-to-install and applicable system to ensure frequency regulation, while HESS provides better dynamics, frequency stability, extended battery life, and better renewable energy integration.

6. Future Research Directions

The increasing penetration of renewable energy resources in islanded microgrids presents various difficulties for their effective frequency and energy regulation. Despite considerable advancements in the design of BESS and HESS technologies, there are still many technical problems to be solved. It is essential that future research concentrates on increasing the efficiency of energy storage, control algorithms, and microgrid resilience.

The primary research directions are the enhancement of advanced battery management algorithms to reduce degradation due to charge and discharge cycles when operating for frequency regulation. As shown by the recent literature review, battery aging continues to be one of the key issues influencing the economic performance of BESS installations in the long term [7]. The future energy management schemes should include such techniques as battery condition monitoring, deterioration-based control, and lifecycle optimization [6], [7]. Another interesting field includes research activities concerning the improvement of HESS, while it can provide better dynamic behavior and frequency control performance than BESS, optimal allocation of different types of storage devices remains problematic [8]-[10], [21].

Incorporation of intelligent control strategies is another potential field for research. The use of control systems such as droop control and hierarchical control is quite effective in achieving satisfactory results under normal circumstances; but these control strategies may prove to be less effective under very dynamic conditions of renewable energy resources [11], [12]. Some new methods, including those of MPC, machine learning, artificial intelligence, and data-driven optimization, may bring improvement to forecasting, decision-making, and performance in frequency regulation [13].

Enhancing virtual inertia is also anticipated to play a significant role in future microgrid operations. The use of inverters interfacing renewable generation sources instead of synchronous generators has resulted in less inertia within the system, making the system vulnerable to frequency variations [22], [23]. Therefore, there is a need for future studies that focus on developing innovative methods in controlling VSG and synchronverters so as to imitate inertial response of the microgrid [15], [22], [23]. Furthermore, the integration of electric vehicles, distributed energy sources and multi-microgrid systems presents new avenues for energy exchange and provision of ancillary services. Future researches should focus on developing frameworks for effective energy management that will utilize energy storage, EV charging systems, and distributed renewable sources. Also, the new standards and protocols of grid interoperability and communication would become crucial for the reliable and secure functioning of the new generation of microgrids [24]. Thus, in conclusion, the research in the future should concentrate on the creation of intelligent ESSs, adaptive control techniques, virtual inertia, and energy management strategies. These developments would become key for increasing frequency stability, using RESs more efficiently, extending the lifespan of the energy storage units, and achieving reliable operation of islanded microgrids in the future [8]–[16], [21]– [23].

7. Conclusion

The increasing penetration of renewable energy resources, the importance of adequate frequency regulation has become significant due to lessened system inertia and intermittent nature of power generation. This review paper evaluates the contribution of BESS and HESS in meeting these requirements through comparisons of the architecture, working principle, performance, and control mechanisms of these systems. It is evident from the literature that the BESS offers an adequate solution to the problem of frequency regulation, but the frequent cycles of charging and discharging of batteries can speed up their degradation. On the other hand, HESS uses batteries along with another storage mechanism of high-power density storage supercapacitors or flywheels to improve the transitory behavior of the system. Hence, the use of HESS appears more appropriate for renewable-based islanded microgrids.

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