Advancements and Challenges of Battery Energy Storage Systems (BESS) in Modern Power Grids: A Review

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Abstract: *Battery Energy Storage Systems (BESS) have become indispensable in modern electric power systems, particularly with the increasing integration of renewable energy sources such as solar and wind. This review paper comprehensively explores the evolution, architecture, and core components of BESS, emphasizing their crucial role in enhancing grid stability, reliability, and efficiency. By mitigating the intermittency of renewables, BESS offer solutions such as peak shaving, time shifting, and grid stabilization. Despite their numerous benefits, BESS encounter challenges when connecting to medium voltage grids due to voltage compatibility issues. This paper highlights the importance of BESS in both Low Voltage (LV) and High Voltage (HV) power grids, outlining their applications, advantages, and the critical role of power quality in ensuring uninterrupted operations across residential, commercial, and industrial sectors.*

Keywords: *Battery Energy Storage Systems (BESS), renewable energy integration, grid stability, power quality, LV power grids, HV power grids, energy management.*

I. INTRODUCTION

Battery energy storage system (BESS) have been used for some decades in isolated areas, especially in order to supply energy or meet some service demand. There has been a revolution inelectricity generation. Today, solar and wind electricity generation, among other alternatives, account for a significant part of the electric power generation matrix all around the world. However, in this scenario of high level of renewable energy, BESS plays a key role in the efforts to combine a sustainable energy source with a reliable dispatched load and mitigates the impacts of the intermittent sources. Therefore, the installation of BESS has increased throughout the world in recent years. Despite their benefits, the implementation of such systems faces considerable challenges. The nominal voltage of the electrochemical cells is much lower than the connection voltage of the energy storage applications used in the electrical system. For example, the rated voltage of a lithium battery cell ranges between 3 and 4 V/cell, while the BESS are typically connected to the medium voltage (MV) grid, for example 11 kV or 13.8 kV. The connection of these systems in MV grids can contribute with various services, such as peak shaving, time shifting and spinning reserve [1]. Therefore, it is common to connect several cells in series to form a bank of batteries that is capable of delivering a minimum recommended voltage on the dclink. In several applications, this voltage is usually 600 V, which is converted into ac for the grid connection through an inverter. Furthermore, a controllable dc-link voltage can be achieved by inserting a dc/dc stage, between the battery bank and the dc-link. Under such conditions, it is possible to increase the degree of freedom to control the battery state of charge (SOC). The dc/dc converters also allow using less batteries in series, since the converters can boost the voltages to the grid connection.

Structure and core elements of BESS
To understand what a BESS is and how it works, it helps to learn about its structure and core elements:

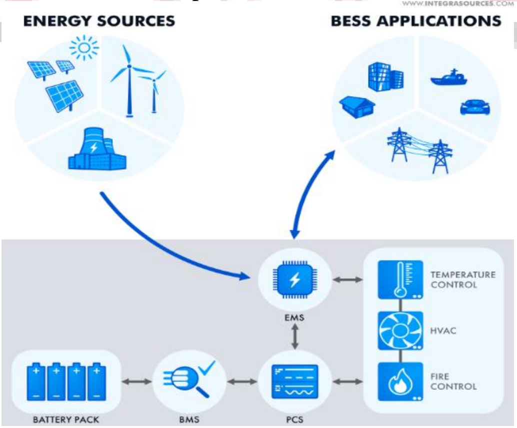

Figure 1 Typical BESS structure. (Image source: Integra Sources LLC)

Battery

Electrical energy supplied from different sources such as solar, wind, or power stations is converted into chemical energy during battery charging. The energy released by batteries during discharge can power homes, vehicles, commercial buildings, and the grid. The battery is composed of battery cells, which can be arranged to form battery modules, battery packs, and battery boxes.

Battery Management System (BMS)

The BMS provides assurance for the safe and correct operation of the battery. Each type of battery has specific charging and discharging conditions. The BMS ensures that the battery remains within the required current, voltage, and temperature ranges. A BMS monitors the battery's parameters and estimates its remaining capacity (SOC) and state of health (SOH), ensuring reliable and long-lasting battery performance.

Power Conversion System (PCS)

BESS uses a power conversion system that converts direct current (DC) into alternating current (AC) and vice versa. When the battery is charging, alternating current flows from the power source and is converted to direct current. As the battery discharges, it generates DC power, which is converted back to AC power for the BESS application.

Electric Energy Management System (EMS)

EMS is a control unit of the battery energy storage system. The EMS manages the power available in the BESS, i.e. when, why and in what amount it is accumulated or released. EMS combines the individual elements of the BESS and optimizes its overall performance.

Security System

There can be a series of security systems, each responsible for a specific task. For example, the HVAC system keeps the BESS at the desired temperature and humidity through HVAC. Fire protection systems can detect smoke and prevent fire accidents.

II. LITERATURE REVIEW

Lawder et al., 2014 [14]: This study provides an overview of Battery Management System (BMS) modeling advancements, emphasizing sophisticated models tailored for vanadium redox-flow and lithium-ion batteries. It discusses system architecture and potential applications in control and monitoring, proposing improvements to enhance BESS effectiveness in grid-scale applications. The research underscores the importance of precise BMS modeling for optimizing energy storage systems and ensuring reliable grid integration.

Narayanan et al., 2019 [15]: This research introduces a standalone microgrid system integrating Photovoltaic (PV), Battery Energy Storage (BES), and Distributed Generation (DG). Key functionalities include PV maximum power extraction, harmonics elimination, reactive power compensation, and DG current balancing. It highlights BES integration with the DC link for Voltage Source Converter (VSC) control, optimizing power flow management within the microgrid. The study emphasizes renewable energy and storage technologies for enhancing microgrid stability and reliability across diverse applications.

Xu et al., 2013 [16]: Addressing challenges in grid-integrated solar and wind systems, this paper reviews mitigation technologies for intermittency and fluctuations in renewable energy sources. It explores strategies like energy storage systems to manage peak production periods and stabilize supply variations. The study advocates for integrating renewables into grids to enhance energy security, reduce emissions, and promote sustainable development, contributing to reliable and efficient grid operation.

Nair & Ilango, 2018 [17]: Focused on a smart microgrid system with PV generation, battery storage, and load optimization, this study validates a pseudo State of Charge (SOC) method for accurate SOC estimation. It discusses MATLAB/Simulink simulations confirming SOC estimation reliability and battery health maintenance through controlled discharge. The research showcases practical advancements in smart microgrid technology, emphasizing SOC estimation's role in enhancing energy storage management and system reliability.

Undre et al., 2019 [18]: This paper proposes using Battery Energy Storage Systems (BESS) for mitigating voltage sags and underfrequency events in islanded microgrids. It develops algorithms to optimize battery lifespan while enhancing microgrid performance without costly power conditioning equipment. The study demonstrates the feasibility of BESS in injecting active power to improve power quality, enhancing microgrid reliability and operational efficiency.

Jain et al., 2013 [19]: Introducing the FL-BESS controller, this study focuses on load balancing, harmonic elimination, and neutral current minimization within a microgrid. It highlights the fuzzy logic-based controller's adaptability to varying loads and fault conditions, enhancing microgrid reliability and efficiency despite computational complexities. The research illustrates the controller's effectiveness in achieving stable and optimized microgrid performance.

Soni & Pandya, 2018 [20]: Investigating a household PV and BESS system in islanding mode, this study evaluates a novel control strategy ensuring IEEE 519 power quality compliance. Simulation results demonstrate effective voltage and current harmonic control, supporting stable energy supply to households under different conditions. The research emphasizes PV and BESS integration for reliable and efficient energy management in standalone microgrid settings.

Praiselin & Belwin Edward, 2017 [21]: This paper explores solar PV and battery storage integration within a microgrid using MATLAB/Simulink simulations. It develops a battery converter control strategy to mitigate voltage and current harmonics during grid operation. Simulation results validate the controller's effectiveness in improving system stability and ensuring reliable microgrid performance through enhanced energy management.

Kaushal & Basak, 2020 [22]: Proposing a controller integrating Battery Energy Storage (BES) with protective relay systems in a three-phase AC microgrid, this study emphasizes power quality management and safety. It introduces a Fuzzy Inference System (FIS)-based controller for voltage, frequency, THD, and power factor regulation, demonstrating its effectiveness through real-time simulations. The research highlights the controller's practical application in enhancing grid stability and reliability while complying with international standards.

Wang et al., 2013 [23]: Examining a microgrid configuration with centralized Battery Energy Storage System (BESS), DG units, and load management, this study implements an energy management system with Model Predictive Control (MPC) algorithms. It validates the microgrid's ability to manage operations such as load balancing, reactive power compensation, and peak shaving under varying conditions. Simulation results confirm the system's effectiveness in optimizing energy utilization and enhancing microgrid stability through centralized BESS integration.

III. IMPORTANCE OF POWER QUALITY IN LV AND HV POWER GRIDS

Battery Energy Storage Systems (BESS) have emerged as versatile tools in modern electric power systems, offering solutions to enhance grid stability, reliability, and efficiency. These systems utilize rechargeable batteries to store electrical energy, which can be discharged when needed to support grid operations. BESS find applications across both Low Voltage (LV) and High Voltage (HV) power grids, albeit with varying functionalities and benefits tailored to each voltage level.

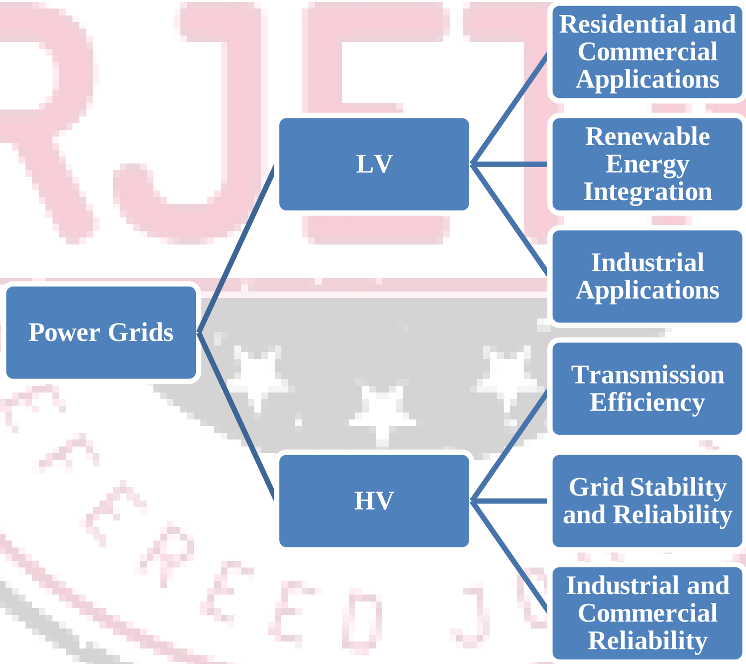

Figure 2 Importance of Power Quality in LV And HV Power Grids

In Low Voltage (LV) power grids, ensuring high-quality power supply is essential for residential, commercial, and industrial applications. LV grids serve as the backbone for homes, offices, and small businesses, where a wide array of sensitive electronic devices, such as computers and appliances, rely on stable voltage and frequency. Poor power quality in LV grids can result in equipment malfunction or damage, disrupting everyday operations and potentially leading to costly repairs. Consistent power supply not only ensures uninterrupted operation of these sensitive devices but also enhances reliability by minimizing downtime due to failures. Moreover, as LV grids increasingly integrate renewable energy sources like solar photovoltaic (PV) and wind farms, maintaining stable power quality becomes critical. Smooth integration of distributed energy resources relies on stable grid conditions to prevent instability and voltage fluctuations. Additionally, in industrial settings, LV grids power essential manufacturing processes where precise voltage and frequency control is paramount. Inconsistent power quality can cause production losses and damage to industrial equipment, impacting overall productivity and increasing operational costs. Therefore, ensuring high power quality in LV grids not only safeguards equipment and enhances operational efficiency but also supports the seamless integration of renewables and sustains reliable industrial operations.

In High Voltage (HV) power grids, maintaining high-quality power supply is crucial for efficient transmission, grid stability, and reliable operation across industrial and commercial sectors. HV grids are designed for long-distance transmission of bulk power with minimal energy losses, making stable voltage and frequency essential to optimize transmission efficiency. This stability not only ensures efficient energy delivery but also reduces operational costs associated with transmission losses, enhancing overall grid economics. Grid stability in HV systems relies on precise frequency and voltage regulation. Stable frequencies are critical to preventing cascading failures and maintaining the reliable operation of interconnected systems. Voltage variations can significantly impact grid stability and the performance of connected equipment and machinery, underscoring the importance of consistent power quality in minimizing disruptions and ensuring reliable grid operation. HV grids serve large industrial consumers with heavy electrical loads, providing essential power to maintain operational reliability and productivity. For these industries, consistent power quality is indispensable to avoid production interruptions and mitigate potential financial losses due to downtime. Similarly, commercial facilities relying on HV power grids for continuous operation require stable power supply to uphold customer satisfaction and operational efficiency.

IV. 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/kWh32 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 [2].

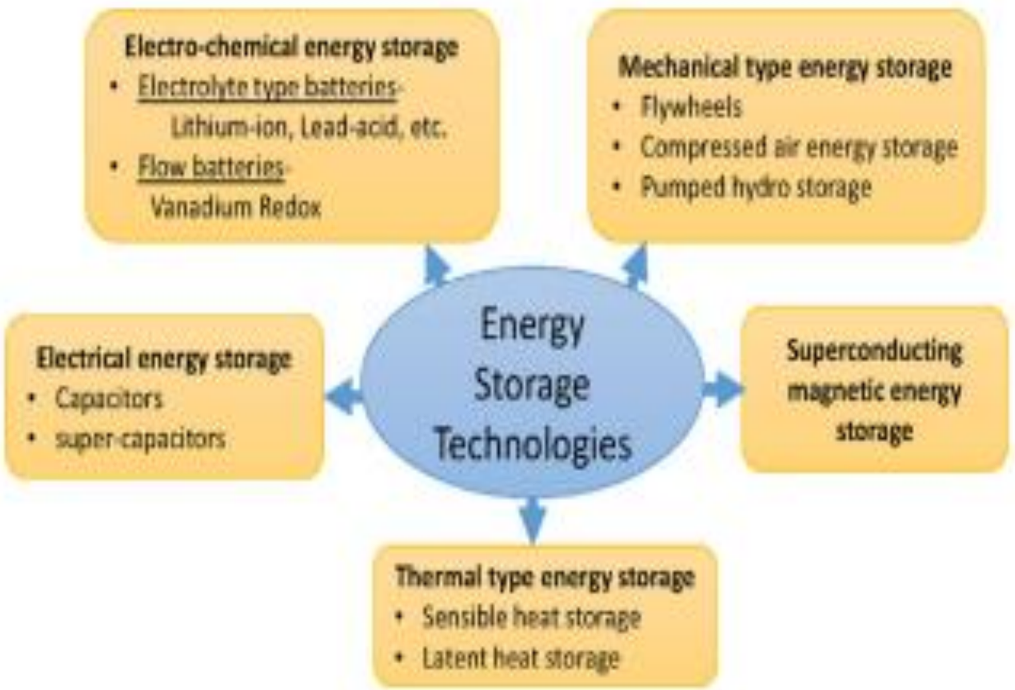

Figure 3 Types of energy storage technologies

Energy storage technologies encompass a diverse array of systems crucial for balancing supply and demand, enhancing grid stability, and integrating renewable energy sources. Mechanical storage options like pumped hydro and compressed air utilize gravitational potential and compressed gas, respectively, while electrochemical solutions such as batteries store energy through chemical reactions. Thermal storage methods, including sensible and latent heat technologies, capture and release energy through temperature differentials or phase changes. Electromagnetic systems like superconducting magnetic energy storage utilize magnetic fields, and hydrogen storage provides a versatile option for storing energy in chemical form. Each technology offers distinct advantages suited to various applications, ranging from grid-scale energy management to mobile applications like electric vehicles, collectively advancing sustainable energy solutions worldwide.

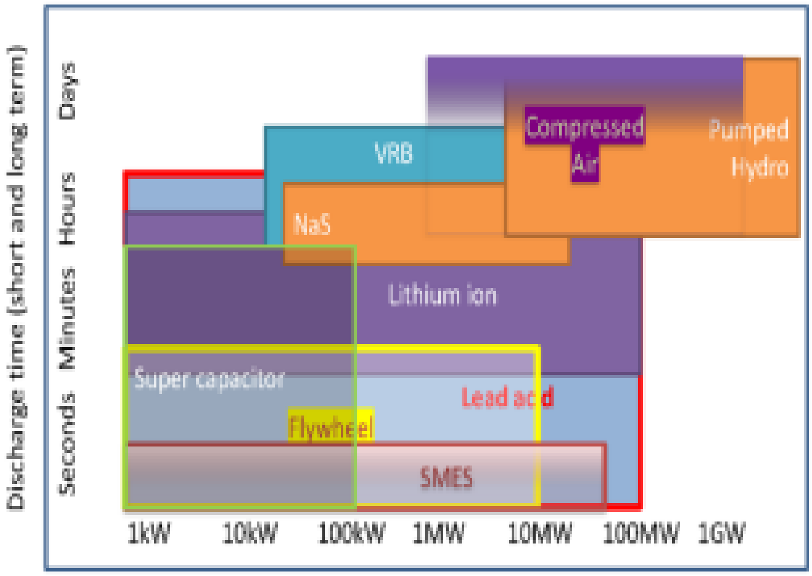

Figure 4 Energy storage technologies capability-operating time frame

Energy storage technologies vary widely in their capability and operating time frames, tailored to meet diverse energy management needs across different sectors. At one end of the spectrum, short-duration storage systems like flywheels and supercapacitors excel in rapid response times, delivering bursts of power almost instantaneously for applications requiring high-power output over short periods. These technologies are vital for grid stabilization, frequency regulation, and smoothing out fluctuations in renewable energy generation. Moving to medium-duration storage solutions such as lithium-ion batteries and flow batteries, these systems offer flexibility with capacities ranging from minutes to several hours. They are utilized extensively in grid-scale applications to optimize energy dispatch, manage peak demand, and provide backup power during grid outages. At the longer end of the spectrum, pumped hydroelectric storage (PHS) and thermal storage systems store energy for hours to days, even weeks, leveraging large-scale infrastructure and natural resources. These technologies are pivotal for managing seasonal variations in renewable energy generation, ensuring grid reliability, and providing continuous power supply to communities and industries. The choice of storage technology depends on factors such as response time requirements, energy capacity, cost-effectiveness, and environmental impact, collectively shaping their role in modern energy systems striving for efficiency, resilience, and sustainability.

V. CONCLUSION

Battery Energy Storage Systems (BESS) represent a cornerstone technology in modern power systems, facilitating the seamless integration of renewable energy sources and bolstering grid stability and reliability. In LV power grids, BESS ensure consistent power supply for residential and commercial sectors, safeguarding sensitive electronic equipment and supporting renewable energy adoption. Meanwhile, in HV power grids, BESS optimize transmission efficiency, mitigate voltage fluctuations, and uphold grid stability crucial for industrial operations. Despite challenges like voltage compatibility, ongoing advancements in BESS technology, especially in lithium-ion batteries, continue to drive their widespread adoption worldwide. Future research endeavors should focus on overcoming these challenges to further enhance BESS capabilities and effectiveness in meeting evolving energy demands sustainably.

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