A COMPREHENSIVE REVIEW ON BATTERY ENERGY STORAGE SYSTEMS AND HEALTH INDICATORS

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Abstract - *The global society is rapidly embracing renewable energy sources and integrating them into the current system to mitigate the escalating environmental issues, including the surge in carbon dioxide emissions over the past century. Renewable energy sources provide significant capacity to mitigate carbon dioxide emissions as they virtually generate no carbon dioxide or other pollutants. However, these energy sources are typically affected by weather, geographical location, and other stochastic factors. The battery energy storage system used to store the energy generated by renewable energy sources (RESs) and then used as needed to mitigate the intermittent nature of these sources. The primary objective of the review article is to provide an overview of Battery Energy Storage System (BESS). The study provides precise estimation of the health indicators (HIs) of the battery, which is particularly significant in the context of Managing the Battery System. This research offers a thorough examination and analysis of several health indicators for BESSs, utilizing a suitable categorization system based on major distinguishing features.*

Key Words: (Energy storage, Battery, Health indicators, Temperature, Current, Voltage]

1.INTRODUCTION

Battery energy storage systems (BESS) ensure a reliable energy supply and are essential for reducing expenses and addressing the increasing need for sustainable energy solutions. In addition to its function in driving cost reduction and its contribution to satisfying the growing need for clean and reliable energy on a global scale, a BESS is becoming increasingly relevant as a result of its significance in the integration of renewable energy sources. Electricity storage systems, also known as battery energy storage systems (BESS), are often studied and used for a range of purposes in power generation, transmission, and distribution, and they also offer end-user benefits that make the investment worthwhile. Among the many electric grid services provided by these installations are voltage support, frequency control, smoothing and levelling of renewable energy, demand reduction, arbitration of renewable energy time-shift, and assistance with power dependability, power quality, and islanding operations. The BESS has also been used to increase reliability in distribution and transmission networks, saving money compared to line upgrading projects.

Energy storage devices with the ability to recharge are widely utilised in various applications, including high-capacity electrical grids and portable low-energy gadgets. These devices effectively address the issue of renewable energy intermittency and allow for long-term reuse. The electricity output of wind and solar farms is determined by fluctuations in the weather, season, and time of day [1]. Recent developments in battery technology have also resulted in better energy storage densities, increased cycle capabilities, increased reliability, and decreased costs.

Battery energy storage systems (BESSs) experience numerous charge and discharge cycles throughout their lifespan. The battery's lifespan is the most critical factor in the cost of BESS operation. The charging and discharging schedule of a battery determines the number of lifecycles it can sustain throughout its lifespan. The battery longevity is adversely affected by the high current during charging and discharging operations. As they age, their performance deteriorates and their reliability becomes uncertain. Battery ageing can be quantified by assessing battery health indicators, which in turn are utilised to calculate battery degeneration.

Within the scope of this article, the concept of battery energy storage systems (BESS) and its applications in the power sector are discussed. The research investigates Health Indicators (HIs) and their Classification, which are indispensable instruments that are employed for the purpose of measuring and evaluating the overall health condition of an individual battery or group of batteries in a Battery Energy Storage System (BESS).

2. BATTERY ENERGY STORAGE SYSTEMS (BESS)

Batteries are frequently employed as an energy storage technology when incorporating renewable resources into the power grid. The compact size, high power and energy densities, and high round-trip efficiency of these batteries make them ideal for both distributed energy storage applications and large-scale storage systems. These systems can be installed at various locations to effectively meet the power grid's requirements. Battery energy storage systems

(BESS) have the potential to enhance system responsiveness, reliability, and flexibility, while also reducing capital and operating costs for suppliers and customers [2].

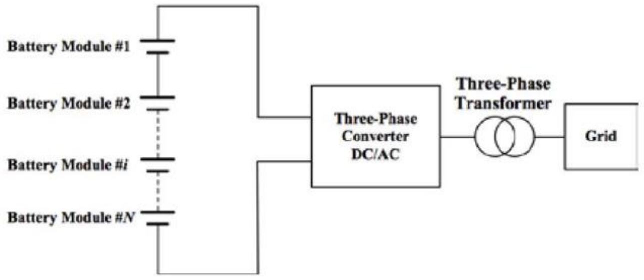

Figure 1. Circuit Diagram of Battery Energy Storage System

A comprehensive battery storage system primarily comprises battery modules, power electronic converters, and a battery management system. A battery module is composed of numerous cells that are interconnected either in series, in parallel, or in both configurations, depending on the desired output voltage and capacity. Figure 1 [3] displays the system configuration of a traditional Battery Energy Storage System (BESS).

In this design, the battery modules are interconnected in a series configuration to create a string. Multiple strings can be connected in parallel for a Battery Energy Storage System (BESS). The battery modules are interconnected with a DC/AC converter and subsequently linked to the electrical grid via a three-phase transformer. The DC/AC converter might comprise many powers electronic converters that are interconnected in parallel to minimize the dimensions of each converter. However, when evaluating reliability, all the components are considered to be connected in series because they all need to function for the entire system to operate correctly. In the event of a failure in any of the components, the entire system will fail.

3. BESS IN INDIA

Battery energy storage systems (BESS) in India have a combined capacity of 219.1 MWh, or around 111.7 MW, as of March 2024. Adding 40 MW in the first quarter of 2024 alone brings the total up to 120 MWh. Significant growth is anticipated in the energy storage capacity of the nation in the next years, which is already growing at a quick pace. A total of 9.7 GW of renewable energy projects in India will be operational by 2027, with an additional 1.6 GWh of standalone battery storage expected by the same year.

4. BESS's APPLICATION

BESS can be used in many different ways in power grids to help with problems like integrating green energy, keeping the grid stable, and making the whole system more resilient. As technology improves, BESS is likely to become an even more important part of updating and improving power lines.

Following are the List of BESS Application

Grid Stabilization:

- Frequency Regulation
- Ancillary Services
- Power Quality Improvement

Load Management

- Peak Shaving and Load Leveling:
- Peak Demand Management
- Demand Response

Renewable Energy Integration:

- Intermittency Smoothing
- Renewable Firming

Transmission and Distribution Support:

- Congestion Management
- Voltage Support

Grid Resilience:

- Black Start Capability
- Emergency Power Backup

Grid Planning and Deferral:

- Capacity Deferral

5. BESS's HEALTH INDICATORS:

Health indicators are essential tools used to measure and assess the overall health status of individual battery or group of batteries in Battery Energy Storage System (BESS). These indicators provide valuable information about various aspects of that can impact the performance and lifespan of the battery. By quantifying the degradation, valuable insights can be gained into the health and condition of the battery, further usage and maintenance.

One way to measure battery degradation is with the use of Health Indicators (HIs) [4]. Batteries state of health (SOH) is estimated using below parameters,

- ➢ The battery's capacity to hold energy
- ➢ Its ability to deliver current
- ➢ Battery mechanical integrity and self-discharge stress data

The efficacy of the electrochemical process can be evaluated by measuring HIs using a standardized set of parameters, including voltage, current, and temperature [5,6]. These markers are then employed to measure the state of health (SOH).

6. CLASSIFICATION OF HEATH INDICATORS

A comprehensive categorization of HIs is explained below, distinguishing between primarily measured and calculated HIs as the main types. This classification provides a framework for understanding the different ways in which HIs can be determined and evaluated.

6.1 MEASURED HEALTH INDICATORS

- The Voltage Current based measured HIs
- The Temperature based measured HIs

6.2 CALCULATED HEALTH INDICATORS

- The Voltage and Current based the Calculated HIs
- The Temperature based calculated HIs
- The Voltage and Current Integral based Calculated HIs
- The Temperature Integral based calculated HIs

6.1.1 The Voltage and Current based Measured HIs

The following HIs are based on voltage and current and are part of the measured HIS [7]

- The Time interval for Charging at a Constant Current from a discharged condition is depicted and it is abbreviated as CCCT.

- The Constant Voltage Charge Time (CVCT) - The duration of charging at a constant voltage following constant-current charging.

- Time of Equal Current Drop, or TECD, is the amount of time it takes for the charging current to decrease by the same amount during several charging cycles while the voltage remains constant.

- The time it takes for the voltage to increase by the same amount across numerous charging cycles when using a constant current charge is known as TEVR, or Time of Equal Voltage Rise.

- VRET, Voltage Rise of Equal Time: with constant-current charging, the voltage increases at a consistent rate across several charging cycles.

- Current Drop of Equal Time (CDET) - constant voltage electrostatic transfer current decline during several charging cycles of the same duration.

- The time it takes to discharge from a full charge to a discharge state at a constant current is known as the Constant Current Discharge Time (CCDT).

- Voltage Drop over Equal Time (VDET): The voltage drops over several discharge cycles with a constant current.

- Time of Equal Voltage Drop, or TEVD, is the duration of a constant-current discharge in which the voltage drops by the same amount throughout each discharge cycle.

6.1.2 The Temperature Based measured HIs

In the measured HIs segment, the temperature-based HIs are listed below [7,8]:

- HCCCT and LCCCT stand for Highest & Lowest Constant Current Charge Temperatures, respectively: Over the charging interval with a steady current, the maximum and minimum temperatures found.

- The two variables that make up the HCT and LCT are the Highest & Lowest temperatures that were recorded throughout the Charging period, respectively.

- HT, LT: Highest & Lowest temperature: Maximum and minimum temperatures during the charging and discharging cycle.

- TETR, or Time of Equal Temperature Rise, is the duration of repeated cycles of constant-current discharge where the temperature rises by the same amount.

- TRET, Temperature Rise of Equal Time: the rate of temperature increases during several cycles of constant-current discharge, measured in intervals of the same length of time.

- The two variables that represent the Highest & Lowest values of Temperature throughout the Constant Voltage Charging interval are HCVCT and LCVCT, respectively.

- Extremely High and Low Discharge Temperatures (HDT and LDT, respectively): Extremely high and low temperatures recorded during the discharge interval

6.2.1 The Voltage and Current based Calculated HIs

The following are the computed HIs depending on voltage and current [9.10]:

- RCCCV, or the Ratio of Constant Current to Constant Voltage, refers to the proportion of time that is dedicated to maintaining a constant current compared to maintaining a constant voltage.

- At the constant voltage charging interval, the Slope of the Charge Current (SCC) is defined as dI/dt.
- At the constant current charging interval, the slope of the charge voltage (SCC) is dV/dt.
- SCC = dV/dt during the constant current discharging interval; SDV is the Slope of the Discharge Voltage.

6.2.2 The Temperature Integral based calculated HIs

In the segment of computed HIs, the temperature-based HIs are listed below [11,12,13]:

- In the constant current discharging interval, the Slope of the Discharge Temperature (SDT) is defined as dT/dt

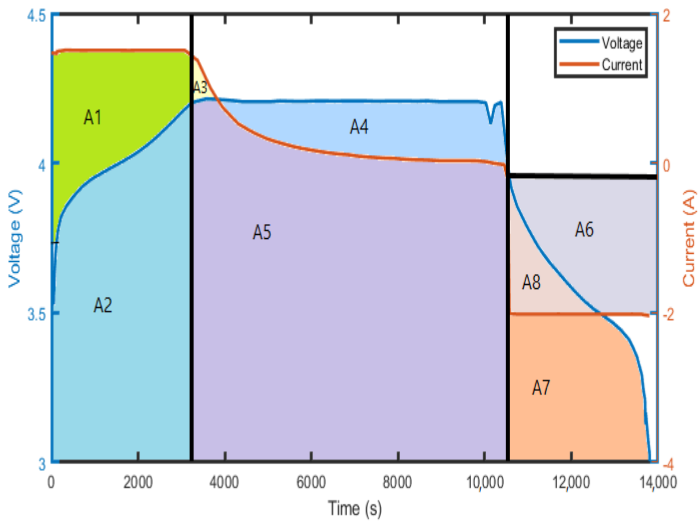

Figure 2. Voltage and current integral based HIs [16].

- Mean Discharge Temperature (MDT): The Mean temperature during the timeframe of continuous current discharge.
- MCT, or Mean Charging Temperature, is the average temperature reading for the whole charging cycle.
- The Mean Constant Current Charge Temperature (MCCCT) is the average temperature during the charging time that is constant-current.
- MT, mean temperature: An MCVCT's Mean Constant Voltage Charge Temperature is the average value the thermal parameters measured throughout the whole charging process.

6.2.3 The Voltage and Current Integral based Calculated HIs

The integration of the voltage and current graphs yields the area components, as depicted in Figure 4.

Following is the Integral HIs that are dependent on Current and Voltage [14,15]:

- The area under the voltage in the interval of constant-current charging is represented as A2 in Figure 2, which stands for Area under Constant Current Charge Voltage (ACCCV).
- A1 + A2 in Figure 2 represents the Area under The Current During the Interval of Constant Current Charging, which is abbreviated as ACCCC.
- The Area under the Voltage over the full Charging interval is represented in Figure 2 as A2 + A4 + A5, which is abbreviated as ACV.
- ACC stands for Area under Charge Current and is shown in Figure 2 as A1 + A2 + A3 + A5. It encompasses the full charging interval.
- The Area under Voltage during the Constant Current Discharging interval is shown as A7 + A8 in Figure 2, which stands for ADV and ACCDV. Since we are just interested in constant-current discharge, these are identical.
- ADC and ACCDC, also known as Area under Discharge Current and Area under Constant Current Discharge Current, are depicted in Figure 2 as A6 + A8
- The area under the voltage during the interval of constant voltage charging is shown as A4 + A5 in Figure 2, which stands for Area under Constant Voltage Charging Voltage, or ACVCV.

Area under Constant Voltage Charge Current (ACVCC): A3 + A5 in Figure 2 illustrate the area under the current during the interval of constant-voltage charging.

6.2.4 The Temperature Integral based calculated HIs

The determined heat indices (HIs), which are obtained by integrating the temperature over time to determine the area under the temperature curve, are displayed in Figure 2 and are as follows [17-20]:

- The Area under the temperature during the Time of Constant Current Charging, or ACCCT, as seen in figure 3.

- A1 + A2 in Figure 3 represents the Area under the Temperature for the full Charging interval, which is abbreviated as ACT. discharging
- ADT- Area under Discharge Temperature and ACCDT - Area under Constant Current Discharge Temperature: Area under temperature in the interval of constant current discharging, shown as A3 in Figure 3. These are the same, as constant current is considered in this case.
- ACVCT - Area under Constant Voltage Charge Temperature: Area under temperature in the interval of constant voltage charging, shown as A2 in Figure 3.

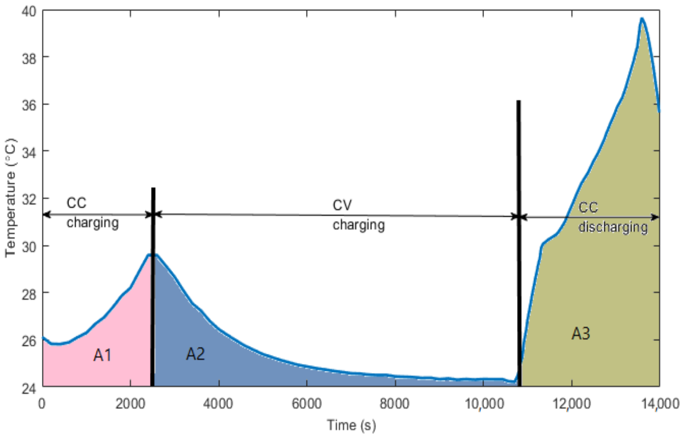

Figure 3. Temperature integral based HIs [16].

Advance bits of knowledge into the application and ease of use of HIs in real-world applications are variations as the battery ages. The operation unwavering quality and life expectancy of a BESS improve when controlling the charging and releasing designs based on the weakening of the battery wellbeing as computed utilizing HIs. The variety in the HIs with battery cycles shows that the HIs that alter more amid the afterward life of the battery are especially more useful in following a battery's wellbeing.

7. CONCLUSIONS

Finally, Health Indicators (HIs) play a crucial role in integrating Battery Energy Storage Systems (BESS) to support the growing need for energy storage and to counteract the intermittent nature of renewable energy sources. an important part in keeping an eye on the batteries' SOH and predicting their RUL, which is critical for making sure BESS is reliable and efficient.

Continuous Current Charge Time (CCCT), Constant Voltage Charge Time (CVCT), Time of Equal Current Drop (TECD), and temperature-based indicators like Highest Continuous Current Charge Temperature (HCCCT) and Mean Discharge Temperature (MDT) are few of the HIs highlighted in the study. These indicators are great for monitoring battery health since they follow certain patterns as the battery ages, and several of them alter significantly towards the end of the battery's life.

The operational dependability and lifespan of BESS can be greatly enhanced by managing the charging and discharging patterns depending on the degradation of battery health as computed by HIs. As a result, managing and deploying battery energy storage systems effectively requires precise assessment of battery health indicators and regular monitoring of the systems.

REFERENCES

1. Tian, J.; Xiong, R.; Shen, W. A review on state of health estimation for lithium-ion batteries in photovoltaic systems. E Transportation 2019, 2, 100028.

2. N. Garimella and N.-K. C. Nair, "Assessment of battery energy storage systems for small-scale renewable energy integration," in Proc. IEEE Region Conf., Singapore, 2009, pp. 1–6.

3.J. Schmutz, "Primary frequency control provided by battery," Semester thesis, EEH Power Syst. Lab., ETH Zürich, Swiss Fed. Inst. Technol., Zürich, Switzerland, Jun. 2013.

4. Merrouche, W.; Trari, M.; Djellal, L.; Mammeri, M.; Tebibel, H.; Blaifi, S.; Chong, L.W.; Ould-amrouche, S.; Boussaha, B. Improved model and simulation tool for dynamic SOH estimation and life prediction of batteries used in PV systems. Simul. Model. Pract. Theory 2022, 119, 102590.

5.Hu, X.; Che, Y.; Lin, X.; Onori, S. Battery health prediction using fusion-based feature selection and machine learning. IEEE Trans. Transp. Electrif. 2020, 7, 382–398.

6.Ma, Y.; Shan, C.; Gao, J.; Chen, H. A novel method for state of health estimation of lithium-ion batteries based on improved LSTM and health indicators extraction. Energy 2022, 251, 123973.

7.Saha, B.; Goebel, K. "Battery Data Set", NASA Prognostics Data Repository; NASA Ames Research Center: Mountain View, CA, USA, 2007.

8.Li, Y.; Stroe, D.I.; Cheng, Y.; Sheng, H.; Sui, X.; Teodorescu, R. On the feature selection for battery state of health estimation based on charging–discharging profiles. J. Energy Storage 2021, 33, 102122.

9.Jiang, N.; Zhang, J.; Jiang, W.; Ren, Y.; Lin, J.; Khoo, E.; Song, Z. Driving behavior-guided battery health monitoring for electric vehicles using machine learning. arXiv 2023, arXiv:2309.14125.

10.Liu, Z.; Zhao, J.; Wang, H.; Yang, C. A New Lithium-Ion Battery SOH Estimation Method Based on an Indirect Enhanced Health Indicator and Support Vector Regression in PHMs. Energies 2020, 13, 830.

11.Gou, B.; Xu, Y.; Feng, X. State-of-Health Estimation and Remaining-Useful-Life Prediction for Lithium-Ion Battery Using a Hybrid Data-Driven Method. IEEE Trans. Veh. Technol. 2020, 69, 10854–10867.

12.Liu, D.; Zhou, J.; Liao, H.; Peng, Y.; Peng, X. A Health Indicator Extraction and Optimization Framework for Lithium-Ion Battery Degradation Modeling and Prognostics. IEEE Trans. Syst. Man, Cybern. Syst. 2015, 45, 915–928.

13.Krupp, A.; Ferg, E.; Schuldt, F.; Derendorf, K.; Agert, C. Incremental Capacity Analysis as a State of Health Estimation Method for Lithium-Ion Battery Modules with Series-Connected Cells. Batteries 2021, 7, 2.

14.Pan, W.; Luo, X.; Zhu, M.; Ye, J.; Gong, L.; Qu, H. A health indicator extraction and optimization for capacity estimation of Li-ion battery using incremental capacity curves. J. Energy Storage 2021, 42, 103072.

15.Yun, Z.; Qin, W. Remaining Useful Life Estimation of Lithium-Ion Batteries Based on Optimal Time Series Health Indicator. IEEE Access 2020, 8, 55447–55461.

16.Sun, Y.; Hao, X.; Pecht, M.; Zhou, Y. Remaining useful life prediction for lithium-ion batteries based on an integrated health indicator. Microelectron. Reliab. 2018, 88–90, 1189–1194.

17.Wang, R.; Feng, H. Remaining useful life prediction of lithium-ion battery using a novel health indicator. Qual. Reliab. Eng. Int. 2021, 37, 1232–1243.

18.Huang, Z.; Xu, F.; Yang, F. State of health prediction of lithium-ion batteries based on autoregression with exogenous variables model. Energy 2023, 262, 125497.

19.Jia, J.; Liang, J.; Shi, Y.; Wen, J.; Pang, X.; Zeng, J. SOH and RUL Prediction of Lithium-Ion Batteries Based on Gaussian Process Regression with Indirect Health Indicators. Energies 2020, 13, 375.

20.Nazaralizadeh, S.; Banerjee, P.; Srivastava, A.K.; Famouri, P. Battery Energy Storage Systems: A Review of Energy Management Systems and Health Metrics. Energies 2024, 17, 1250. https://doi.org/10.3390/en17051250.

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