Performance Evaluation and Commissioning of a 110V, 440AH VRLA Battery Bank at Dagachhu Hydropower Plant

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Abstract

Valve-Regulated Lead Acid (VRLA) batteries are important components in hydropower plants, as they provide the critical DC supply for auxiliary, protection, and emergency systems. Despite their widespread use, the reliability of these battery banks is often compromised by a lack of systematic testing after installation, leaving operators without precise data on actual capacity, internal resistance, or real-world degradation rates. Furthermore, improper commissioning, such as placing new batteries on float charge without pre-commissioning inspections, can significantly shorten a battery's operational lifespan. This study establishes a baseline performance evaluation for a newly installed 110 V, 440 Ah VRLA battery bank at the Dagachhu Hydropower Plant (DHP) to ensure operational readiness. Adhering to IEEE Std. 450-2010 and IEEE Std. 1188-2005, the methodology involved three regulated charging and discharging cycles combined with precise impedance measurements using diagnostic tools such as the TORKEL 860 and Megger BITE3. The obtained results demonstrated a progressive improvement in the battery bank's health by the second cycle, and the measured capacity achieved the full rated capacity by the third cycle. Complementing this capacity growth or improvement, the cell impedance measurements were taken, as the impedance values are usually correlated to the capacity. The quantitative impedance analysis revealed an average reduction in internal impedance of 11.27% before discharge and 13.98% post-discharge between the first and third cycles. This study validates the successful initiation of the battery bank and provides the necessary baseline data, ultimately enhancing the reliability and safety of the plant's auxiliary power systems.

Keywords: *VRLA Battery, Commissioning Test, Capacity Test, Impedance Measurement*

1. INTRODUCTION

Druk Green Power Corporation Ltd. (DGPC) is one of the major contributors to Bhutan's revenue, mainly through the export of hydroelectric power to India. DGPC contributed Nu. 3,841 million in 2024-2025 as Corporate Income Tax (National Revenue Report FY 2024-25, 2025). DGPC has numerous hydropower plants, which are wisely operated and maintained. DHP is one of the hydropower plants, where 59% of the share is held by DGPC and the remaining 26% and 15% by Tata Power, India and National Pension and Provident Fund, Bhutan, respectively. DHP is a run-of-the-river hydro power plant built on the Dagachhu river of Bhutan and has two numbers of 63 MW generators.

Reliable DC systems in hydropower facilities guarantee the uninterrupted functioning of essential protection and control operations, whereas any failure may jeopardise safety and lead to expensive breakdowns. Consistent testing and appropriate commissioning guarantee that DC components in a hydropower plant function properly, thereby preventing failures and improving the reliability and lifespan of the system. The battery system serves as a vital component for a hydropower plant.

2. PROBLEM DESCRIPTION

In a hydropower plant, once the final bolt has been secured on a new battery installation and its assembly is considered complete, the subsequent step is the appropriate commissioning of the system. Often, the battery system is merely placed on float charge at a random voltage. Pre-commissioning measurements and inspections are not consistently conducted. When they are carried out, certain steps may be omitted, or the commissioning may be executed improperly. This can lead to numerous issues affecting the battery's lifespan. (Tressler, n.d.) explains that the universal commissioning standard is unavailable; thus, it is crucial to thoroughly examine, understand, and adhere to all guidelines provided by the battery manufacturer.

Proper commissioning becomes even more critical if an acceptance test is to follow. In case of any doubts or operational challenges, it is advisable to seek technical support and guidance from the manufacturer. Therefore, a proper commissioning of the battery banks of hydropower plants becomes an inevitable test for maintaining the battery bank's health.

3. LITERATURE REVIEW

Vishnupriyan et al. (2014) reported that battery degradation primarily results from temperature fluctuations, thermal aggregation, and sulfation, which increase internal resistance and diminish discharge performance. Accurate measurement of electrical parameters is essential for assessing the condition of the battery. (Lakhdari & Midoun, 2018), given the constraints of full-capacity testing, non-intrusive techniques such as electrochemical impedance spectroscopy have become increasingly important for assessing the health of VRLA batteries. While impedance is a useful measure of battery degradation, it is not as reliable for directly indicating the state of charge. (Badeda et al., 2018) investigated impedance-based techniques, including EIS, Hioki BT3554, and LEM Sentinel 2, that facilitate non-invasive monitoring of VRLA battery health. Nevertheless, high-frequency impedance measurements might not effectively identify ageing processes like sulfation and water loss, resulting in erroneous state of health (SoH) assessments. Furthermore, the precision of impedance-based diagnostics is influenced by factors such as state of charge, temperature, and measurement conditions. (Waters, Bullock, & Bose, 1997), Ohmic measurement techniques, including impedance, resistance, and conductance, offer a rapid and non-invasive approach for evaluating the state of health (SoH) of VRLA batteries, typically correlating with their capacity. These methods are primarily utilised as screening tools and techniques. (Megger 2019), the Megger BITE 3 is a non-invasive tool designed for testing batteries, specifically for the commissioning and monitoring of VRLA batteries. It employs ohmic impedance measurements to evaluate battery condition by analysing cell impedance and associated parameters. The baseline impedance values are instrumental in identifying ageing and degradation, offering a quicker, safer, and more economical option compared to conventional discharge testing.

4. METHODOLOGY

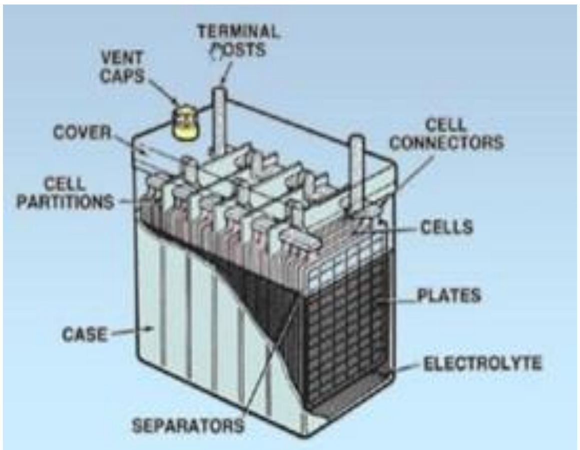

Fig. 1: *Battery Construction*

A VRLA (valve-regulated lead-acid) battery is made up of lead electrodes that are submerged in a diluted sulfuric acid solution. Commonly known as "dry" batteries, VRLA batteries can be positioned in any orientation and necessitate less frequent maintenance than conventional flooded (wet) batteries. Fig. 1 shows the basic battery construction of a lead-acid battery. The experimental study was carried out on a VRLA battery bank comprising 55 cells linked in series.

Fig. 2 shows the flowchart illustrating the approach employed to conduct the battery discharge test and ascertain the battery capacity through a structured series of testing and monitoring procedures.

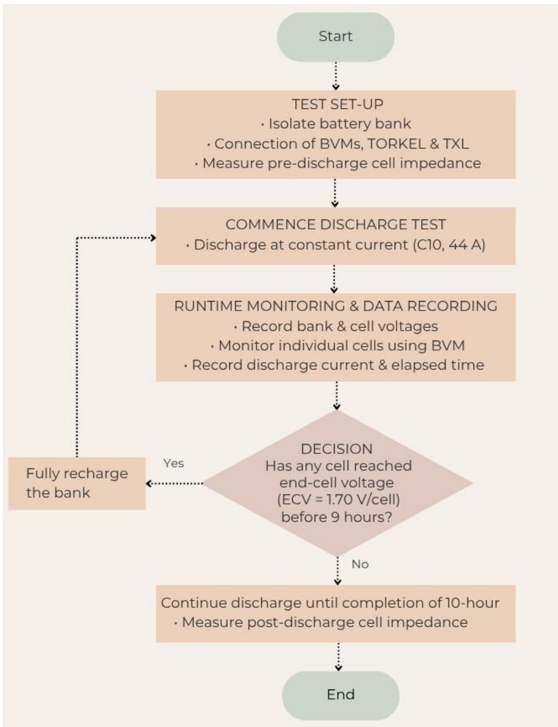

Fig. 2: *Methodology flowchart*

4.1. Failure Mechanisms Unique to VRLA Batteries

VRLA batteries employ two primary techniques to immobilize the electrolyte: gel-based (VRLA-GEL) and absorbed glass mat (VRLA-AGM), with some newer hybrid models utilizing both methods. The various designs encounter failure mechanisms in distinct ways due to their specific electrolyte immobilization techniques. This (EPRI, 2009) emphasizes the failure mechanisms themselves, rather than contrasting the susceptibility of the designs.

4.1.1. Negative lug and strap Failures

Failures of negative plate lugs and straps in early VRLA batteries primarily resulted from corrosion when these components were exposed rather than submerged in electrolyte. This corrosion led to high-resistance connections or broken straps, frequently resulting in open-circuit cell failures. Factors contributing to this issue included the use of dissimilar alloys, insufficient cathodic protection, and inadequate alloy or casting practices.

4.1.2. Negative plate Discharge (Hydrogen Balance) and water loss

Negative plates in VRLA batteries undergo self-discharge and emit hydrogen, which needs to be replenished during the charging process. However, the oxygen recombination cycle utilizes the majority of the required ions and electrons, resulting in the negative plates remaining undercharged.

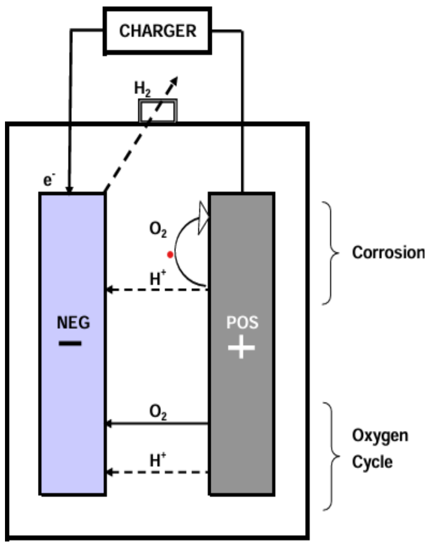

Fig 3: *Simplified gas and ion flow inside the VRLA cell*

Additionally, the corrosion of the positive grid offers only a minimal amount of replacement hydrogen, allowing the discharge of the negative plates to persist to extremely low and unacceptable capacity levels. Fig 3 shows the gas and ion flows inside the VRLA battery cell.

4.1.3. Water Loss Versus Loss of Compression (AGM)

The failure mechanism known as water loss includes the impact of diminished compression in AGM cells. Variations in fiber saturation within the AGM may result in a reduction of compression, which is directly linked to the depletion of water in the cell. Therefore, for the objectives of this study, the mechanism is characterized in relation to water loss.

5. BATTERY TESTING AND DIAGNOSTIC METHODOLOGY

This battery is completely sealed and does not provide access to the electrolyte. Therefore, this type of battery requires no maintenance.

5.1. System Description

Table 1 summarizes the battery system parameters. The particular battery bank consists of 55 VRLA cells, rated 2V and 440 Ah, all connected in series, making for a 440 Ah total capacity.

Table 1: *System Description*

Parameter	Specification/Details
Battery Type & Capacity	110V, 440Ah VRLA, Exide Industries Ltd.
Cell Configuration	55 Cells, 2.0 V (nominal), C10 & connected in series
Application	DC supply system for DHP

5.2. Battery Diagnostic Instruments

Fig. 4 shows that the TORKEL 860 is used to discharge the battery; it is a device primarily intended for capacity testing. It is applicable for systems operating between 12 V and 480 V, and it can discharge at currents of up to 110 A. Subsequently, the BVM (Battery Voltage Monitor) is a device shown in Fig. 5, designed to measure battery voltage, capable of assessing the voltage of individual battery cells, with each unit able to manage up to 20 V. The Megger BITE3 battery impedance tester shown in Fig. 6, assesses the condition of lead-acid cells with a capacity of up to 2000 Ah by measuring key battery parameters. The BITE3 evaluates cell impedance, conducts an internal ohmic test, measures cell voltage, checks intercell connection resistance, and analyses ripple current.

Fig. 4: TORKEL 860

Fig. 5: BVM unit

Fig. 6: The Megger BITE3 battery impedance tester

5.3. Battery Discharging

The VRLA battery bank utilized in this research has a specified capacity of 440 Ah. During the capacity verification test, the battery was discharged at the 10-hour rate using a constant-current method. The discharge current was sustained at 44 A, which aligns with C10 discharge conditions. To avoid excessive discharge and the risk of irreversible damage to the battery cells, the end-of-discharge voltage was established at 1.70 V/cell. The battery discharge test was performed over three successive cycles. Following each discharge cycle, the battery bank was completely recharged until the charging current achieved a minimum steady-state value, which remained stable for three consecutive hourly observations prior to commencing the next discharge cycle. Throughout each discharge cycle, the terminal voltage of the battery, the voltage of individual cells, the discharge current, and the duration of discharge were consistently monitored. The capacity measured was derived from the discharge current and the time of discharge.

5.4. Battery Impedance

Zhendong et al., (2012) investigated the impact of different physical and chemical factors on a battery's internal resistance, impedance and capacity. His research suggests that internal resistance typically increases as the battery degrades, except in cases of internal short circuits or high temperatures.

The (Institute of Electrical and Electronics Engineer, 2006) standard indeed suggests utilizing internal resistance as a supplementary inspection technique for VRLA batteries, mandating that it be measured and documented every quarter. The standard emphasizes that internal ohmic measurements are significant for monitoring performance trends over time.

6. TEST RESULT AND ANALYSIS

Table 2: *Capacity Performance During Discharge Cycles*

Cycle	Duration	Terminal End-Voltage	Capacity
First	09:30:55	97.00 V	95.15 %
Second	08:36:30	96.80 V	85.10%
Third	10:00:00	107.80 V	100.0%

Table 2 shows the three cycles of discharging and charging of the bank to achieve 100% capacity. The initial discharge cycle attained 95.15% of the rated capacity, suggesting that the battery bank was nearing its anticipated performance. The diminished capacity observed in the second cycle (85.1%) could be attributed to incomplete charge recovery or stabilization phenomena typically seen during the early cycles of VRLA batteries. Following a full recharge, the third discharge cycle reached 100% capacity, thereby verifying that the battery bank achieved its rated performance. It is important to note that the battery is deemed fully recharged only when the charging current has reduced to a stable minimum value and has remained constant for three consecutive hourly observations, as per the manufacturer's recommended charging procedure.

Table 3*: Individual Cell Voltage Behavior*

Cycle	Cell Number	Time reaching 1.75 V
First	# 42	07:08
	# 1	09:03
	# 13	09:22
Second	# 42	07:49
	# 14	08:16
	# 4	08:30
	# 3	08:31
Third	-	-

Table 3 shows the cells reaching ECV before achieving at least 90% of their rated capacity. Cell #42 exceeded the voltage threshold sooner than the other cells in both discharge cycles, suggesting a relatively lower discharge performance. This discrepancy may be linked to variations in internal resistance, state of charge, or the utilization of active materials. Nevertheless, the complete recovery of capacity during the third cycle suggests that the noted deviation was not a result of irreversible degradation. The discharge characteristics of the 55-cell, 110 V, 440 Ah VRLA battery bank are illustrated in Fig. 7, Fig 8 and Fig 9, specifically during the first, second, and third discharge cycles.

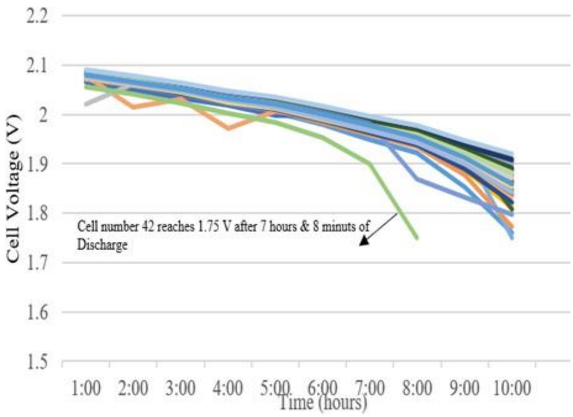

Fig. 7: *First Discharge characteristics of 55 cells, 110V, and 440Ah*

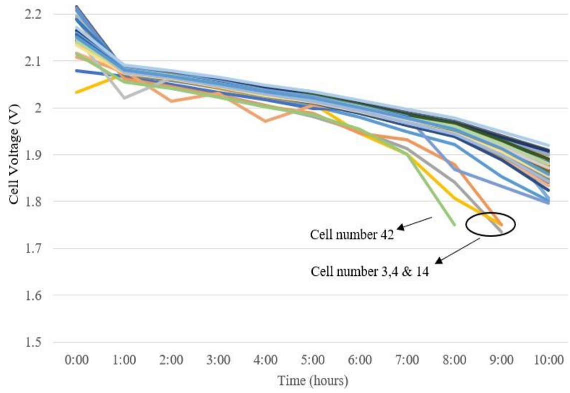

Fig 8: *Second Discharge characteristics of 55 cells, 110V, and 440Ah*

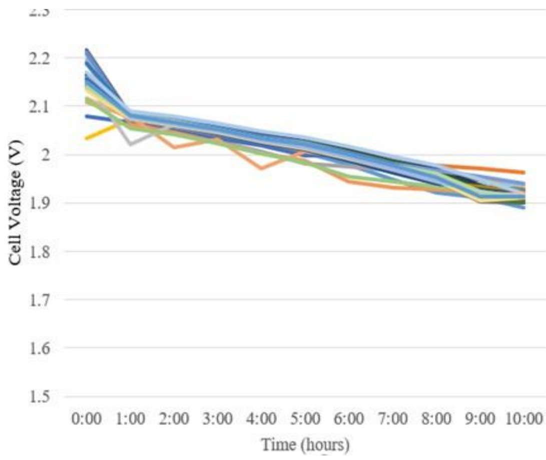

Fig 9: *Third Discharge characteristics of 55 Cells, 110V, and 440 Ah*

Table 4: *Summary of Impedance Measurements*

Cycle	Cell Imp. Before (mΩ)	Cell Imp. After (mΩ	Strap Imp. Before (mΩ)	Strap Imp. After (mΩ)
First	0.692	1.001	0.352	0.357
Second	0.700	1.006	0.600	0.345
Third	0.614	0.861	0.322	0.319

Table 4 shows the summary of cell and strap impedance measurements during three discharging cycles. The rise in cell and strap impedance following discharge primarily results from the electrochemical and physical transformations that take place during battery usage. As the battery discharges, the state of charge diminishes, active materials convert to lead sulfate, and electrolyte conductivity declines, all of which contribute to an increase in internal resistance and polarization effects, leading to elevated cell impedance. The minor increase in strap impedance could be attributed to temperature fluctuations, the effects of current flow, and alterations in contact resistance during discharge. The Fig. 10, Fig. 11, Fig. 12, Fig 13, Fig. 14 and Fig. 15 show the cell impedance before and after discharge, and the strap resistance before and after discharge during the first, second, and third discharging cycles, respectively.

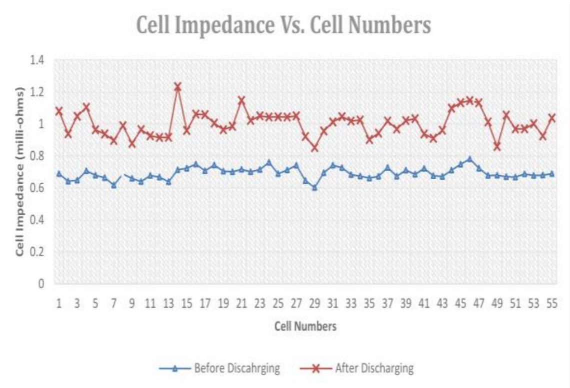

Fig. 10: *Cell Impedance Vs Cell Number during the first discharging cycle*

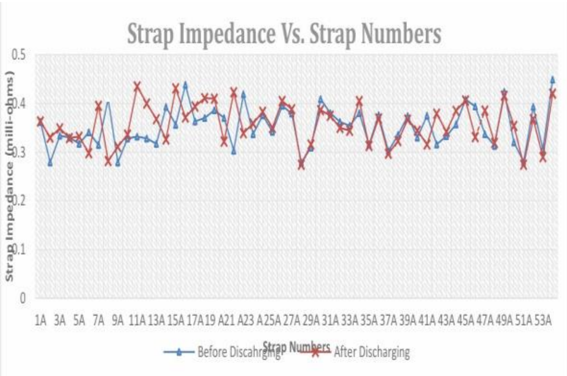

Fig. 11: *Strap Impedance Vs Strap Number during the first discharging cycle*

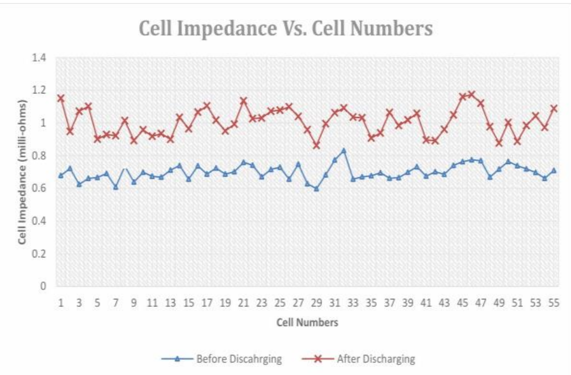

Fig. 12: *Cell Impedance Vs Cell Number during the Second Discharging Cycle*

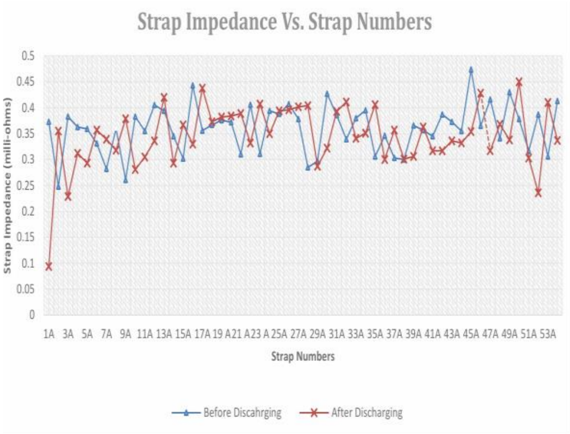

Fig 13: *Strap Impedance Vs Strap Number during the Second Discharging Cycle*

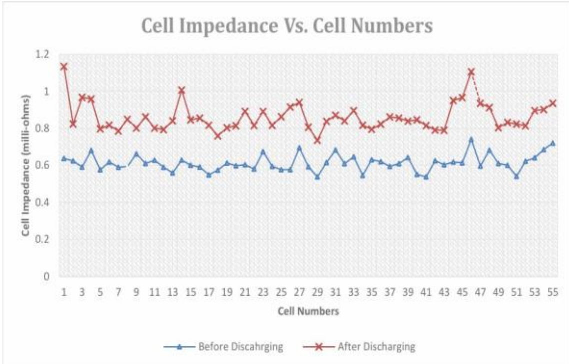

Fig. 14*: Cell Impedance Vs Cell Number during the third discharging cycle*

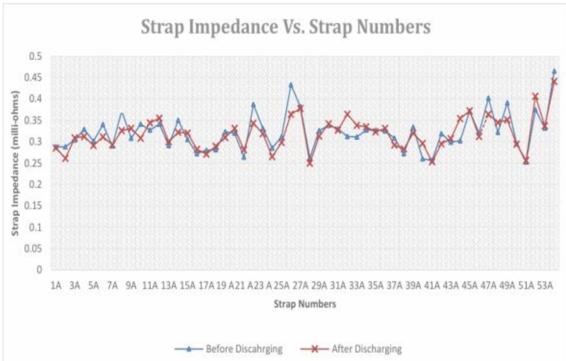

Fig. 15: *Strap Impedance Vs Strap Number during the third discharging Cycle*

Institute of Electrical and Electronics Engineer, (2006) states that "Batteries may have less than rated capacity when delivered. Unless 100% capacity upon delivery is specified, the initial capacity of every cell should be at least 90% of rated capacity". In the first discharge cycle, while the overall battery bank exceeded 90% of its rated capacity, Cell 42 did not fulfil the minimum requirement of 90% capacity. In the second discharge cycle, cells 42, 14, 4, and 3 similarly failed to achieve 90% of their rated capacities. Nevertheless, by the third discharge cycle, all cells successfully reached at least 90% of their respective rated capacities, demonstrating the effective activation of the battery bank.

Moreover, the IOM Manual indicates that a battery system might need as many as five consecutive charge–discharge cycles to attain its full rated capacity. The repeated cycling of charge and discharge in a newly installed battery bank promotes the activation and stabilization of its internal electrochemical components. As cycling continues, enhanced oxygen transport and recombination efficiency lead to a reduction in internal resistance, allowing for the complete utilization of active material, which ultimately results in greater capacity and overall battery performance. The cell impedance was observed continuously during the monitoring phase. Following the first and third discharging cycles, the average impedance reduction before discharge and post-discharge is recorded at 11.27% and 13.98%, respectively.

7. CONCLUSION

The newly commissioned 110V, 440Ah VRLA battery bank at DHP demonstrated satisfactory performance, achieving 100% rated capacity after three charge-discharge cycles. The tests validated the health of all cells, ensuring readiness for operational service. The impedance data and voltage profiles will serve as baseline references for future maintenance and trend analysis

8. REFERENCES

Badeda, J., Kwiecien, M., Schulte, D., & Sauer, D. U. (2018). Battery state estimation for lead-acid batteries under float charge conditions by impedance: Benchmark of common detection methods. *Applied Sciences*, 8(8), 1308. https://doi.org/10.3390/app8081308

EPRI. (2009). *Valve-Regulated Lead Acid (VRLA) Battery Qualification Assessment.* Palo Alto, CA: 1019216.

Installation & Operation Manual for sealed Maintenance-free UPST VRLA batteries.

Institute of Electrical and Electronics Engineer. (2006). *IEEE recommended practice for maintenance, testing, and replacement of valve-regulated lead-acid (VRLA) batteries for stationary applications (IEEE Std 1188-2005).* New York.

Institute of Electrical and Electronics Engineers. (2011). *IEEE standard for maintenance, testing, and replacement of vented lead-acid batteries for stationary applications (IEEE Std 450-2010).* New York, NY 10016-5997.

Lakhdari, F., & Midoun, A. (2018). Monitoring state-of-charge and state of health of VRLA batteries using the impedance spectroscopy: Experimental analysis. *International Journal on Energy Conversion (IRECON)*, 6(1), 1–7. https://doi.org/10.15866/irecon.v6i1.15547

National Revenue Report FY 2024-25 (2025). https://mof.gov.bt/pages/nationa-revenue-reports/.

Simanjuntak, V. I., Heryanto, Rahmawaty, Y. &., & Manurung, T. (2021). Performance Analysis of VRLA Battery for DC. *ELKHA: Jurnal Teknik Elektro, 13(2)*, 148–154.

Tressler, R. (n.d.). Proper Commissioning Procedures for Lead-Acid Batteries. Pompano Beach.

Vishnupriyan, J., Manoharan, P. S., & Seetharaman, V. (2014). Performance analysis of VRLA batteries under continuous operation. *International Journal of Research in Engineering and Technology, 3*(Special Issue 7), 275–281. https://doi.org/10.15623/ijret.2014.0319050

Waters, A. R., Bullock, K. R., & Bose, C. S. C. (1997). Monitoring the state of health of VRLA batteries through ohmic measurements. *In Proceedings of the IEEE International Telecommunications Energy Conference (INTELEC)* (pp. 1–7). IEEE

Zhendong, Z., Zihan, L., & Nan, H. (2012). The VRLA battery internal resistance on-line measuring device. *International Conference on Information Management, Innovation Management and Industrial Engineering* (pp. 404-406). 978-1-4673-1931-7/12/$31.00 ©2012 IEEE.