**Lithium-Ion Battery Degradation: Mechanisms, Monitoring, and Applications**

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**Abstract.** Lithium-ion batteries are widely used in Electric vehicles & hybrid electric vehicles as they have high energy and power densities. However, battery degradation occurs by using it for a brief period remaining a major concern affecting battery’s performance & lifetime. This paper studies the various Lithium-Ion Battery degradation mechanisms, monitoring techniques etc. The paper combines 6 key research papers which primarily focuses on incremental capacity analysis, degradation costs in Vehicle to grid applications and the effects of degradation due to battery pack configurations. The findings denote the importance of combining advanced diagnostic tools and modelling techniques to predict, analyse & mitigate degradation effectively. The paper concludes by highlighting future research directions for improving battery longevity and efficiency

**Keywords:** Electric vehicles, Loss of Lithium Inventory, Loss of active material, Vehicle to grid, Battery Management Systems.

**INTRODUCTION**

Lithium-ion batteries play a crucial part in modern energy storing applications [1]. However, the degradation mechanisms of Lithium-Ion Batteries are influenced by various factors like operating temperature and placement of the batteries, which impact their longevity [2]. Understanding these mechanisms is important for improving battery lifespan and optimizing battery performance. Further, the adoption of Lithium-ion batteries in EVs and renewable energy storage indicates the need for effective battery degradation management strategies [3]. LIBs are degraded by numerous inter-connected factors such as temperature, charging/discharging cycles, Depth of Discharge of the battery, and battery chemistry [4]. Understanding these factors will help in optimizing the performance of the batteries and ensure long life in energy applications [5]. The paper aims to examine the existing research carried out and to provide insight as to the methodology on how degradation testing will be carried out as well as for techniques that are employed for degradation mitigation techniques. Understanding this degradation mechanism will allow the manufacturer & researchers to work in more efficient Battery Management Systems (BMS) that optimize parameters like battery performance and safety enhancement and extend the lifespan of the battery [6].

Some important factors involved in battery degradations are: Loss of Lithium Inventory (LLI) refers to the loss in the amount of lithium ions in the battery, that directly affects the ability of battery to charge [7]. These happens when lithium ions form irreversible bond within the battery and become no longer available for electrochemical reactions to charge and discharge [8]. Loss of active material (LAM) is another factor in battery degradation, which refers to the process in which active materials that participate in electrochemical like Lithium cobalt oxide, graphite degrades during charging and discharging cycles. These occur due to the structural breakdown of electrode materials in chemical reactions. The next factor is the Solid Electrolyte Interface (SEI), which is defined as a passive layer that is formed on the surface of anode when battery is charged [9]. This occurs due to the reaction between the anode material and the electrolyte in initial charging cycles. The last factor is the Internal resistance of the batter, which is defined as the opposite flow of charge in the battery’s internal components, which include electrodes, electrolytes and a separator. When these components degrade further, the internal resistance increases.

The main reasons for the battery degradation of Lithium-Ion batteries are Loss of Lithium inventory, loss of active material, solid electrolyte interphase growth, and increase in internal resistance [10]. These factors lead to capacity fade, power loss, and overall performance of the battery. The total available charge transfer within a cell is reduced by side reactions that irreversibly consume lithium ions [11]. The reactions that negatively impact the battery include electrolyte decomposition, lithium plating, and transition metal dissolution. Another significant degradation mechanism is Loss of active material, in which the electrode material's structural integrity deteriorates over repeated charging and discharging cycles, which can lead to mechanical stress, particle fracture, and phase transitions that reduce the electrode's ability to store and release lithium ions [10]. SEI layer formation is essential for stabilizing the anode from further reactions growing over time [12]. Battery power output is limited when the rate of movement of Lithium ions between electrodes is decreased, which happens when an excessive SEI layer is grown. The electrochemical performance of the cell is reduced when the SEI is thickened. Other factors that affect battery degradation are operating temperatures, charging and discharging cycles, cycling conditions [13]. Higher temperatures increase unwanted growth of SEI, electrolyte oxidation, and gas formation that further exacerbate capacity fade. Improper storage conditions are also a factor in accelerated degradation. Electrolyte decomposition and moisture-induced corrosion happen when exposed to high humidity, which results in overall battery instability. Storage at high states of charge increases the growth of Lithium dendrites, increasing the risk of short circuits. An overview of the battery degradation mechanism is given in Figure 1.

A diagram of a diagram

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**FIGURE 1.** Overview of battery degradation mechanism.

**MONITORING AND CHARACTERIZATION TECHNIQUE**

The Battery degradation assessment mainly relies on a combination of model-based and data-driven methodologies. Electrochemical and physical-based models are used in model-based approaches, while machine learning and statistical methods are used in data-driven techniques to analyse large datasets of battery performance in parallel. Fault diagnosis is done by asymptotic local approach as it finds parametric variations in electrochemical models, therefore ensuring early identification of battery degradation.

Degradation costs in Vehicle to grid(V2G) applications are also explored to get a deeper understanding of financial and economical implication of battery aging in V2G scenarios. Electrochemical impedance spectroscopy (EIS) is an advanced diagnostic tools that provide insights to internal resistance and variation in impedance, allowing the detection of degradation in advance. Another widely used technique is Incremental capacity (IC) analysis which identifies aging patterns and failure modes by analysing the variation of capacity as a function of voltage.

A computer screen shot of a computer program

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**FIGURE 2.** Battery protection circuit.

A Battery protection circuit is simulated in Figure 2. This battery protection monitoring system combines Arduino UNO, voltage sensor, relay module, LCD display, and LEDs to monitor voltage range, degradation prevention, or discharge by battery. For the protection of the battery, predefined voltage by the battery management device that has predefined voltage thresholds to determine the safe charging and discharging cycles limits. If the voltage exceeds the threshold, that is 12.5 in this case, the system triggers protective actions like displaying OVER VOLTAGE in the LCD display. Battery management systems are further developed to increase predictive maintenance by machine learning techniques like neural networks and support vector machines (SVMs). In addition to this, real-time sensor-based monitoring systems are developed to check variation in temperature for a more precise assessment of battery health. The infusion of these systems into battery systems increases the reliability and improves charging strategies that reduce degradation with increasing overall performance.

**IMPACT OF BATTERY PACK CONFIGURATION**

The battery pack configuration has a significant impact on battery degradation patterns, especially in large-scale applications like Electric vehicles [14]. Research indicates that inconsistency in the performance of cells leads to the acceleration of the overall degradation of the battery pack, leading to a loss in efficiency and a reduction in lifespan. Uneven distribution of the pack is due to differences in internal resistance, charge retention capabilities, and self-discharge rates among cells [15]. This uneven distribution causes localised heating and stress on weaker cells, increasing degradation. To reduce these effects, battery pack balancing techniques are deployed. Excess energy is dissipated as heat in Passive balancing while active balancing circuits redistribute the charge between weak cells to keep uniform voltage levels across the battery pack, therefore extending the lifespan of the battery [16].

Thermal management in the battery pack is another factor that leads to degradation. Poor thermal regulation leads to uneven temperature distribution, results in fast aging in specific cells, and increases the risk of thermal runaway [17]. Cooling solutions like liquid cooling systems, phase change materials, and development in ventilation designs are done to optimize heat dissipation and stable operating temperatures. By using effective thermal management techniques, the degradation impact can be reduced, therefore improving the life, efficiency and safety of Lithium-ion battery packs in relation to world application.

**SIMULATION RESULTS**

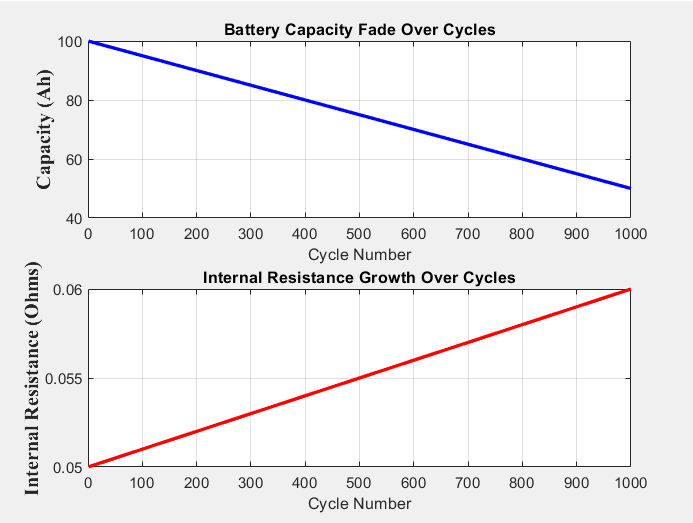
Lithium-ion battery degradation is characterized based on the combination of experimental analysis, statistical modelling and real-world validation. Experimental cycle life testing, data driven modelling approach and real-world testing are part of the methodology. In Experimental analysis, Figure 3, the simulation setup consists of controlled charging and discharging cycles that gives battery behaviour under different conditions. The test gives us idea of capacity fade, change in internal resistance, and formation of various degradation mechanisms like growth of Solid Electrolyte interphase (SEI) and lithium plating.

A screenshot of a computer

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**FIGURE 3.** Battery behaviour under different conditions consists of controlled charging and discharging cycles.

In the model-based analysis and Statistical Modelling, Incremental capacity (IC) analysis and electrochemical impedance spectroscopy are (EIS) the advanced statistical modelling techniques that are used to give early detection signs of battery degradation. IC analysis is done to track the changes in capacity as voltage, while EIS gives information about internal resistance growth and transfer of charge within the battery. In addition to that, fault diagnosis analysis like Asymptotic Local Approach is used to find the parametric differences in electrochemical models, therefore making sure of early identification of battery degradation



**FIGURE 4.** Battery capacity fade and internal resistance growth over cycles.

In Battery Pack Configuration and Thermal Management, the pack level degrading is understood by the configuration effects battery and managing thermal strategies. The impacts of cell imbalances are conducted by the experimental and simulation test as shown in Figure 5. Also, it examines the retention charge variation and self-discharge rates on packing overall. The technique of balancing active and passive to transfer the uneven degradation. Managing the thermal strategies which includes the liquid cooling and materials change tested to temperature regulation and minimal of thermal stress of cells battery.



**FIGURE 5.** Impact of cell temperatures in battery capacity and cell voltages.

The methodology multi-faceted that ensures a comprehensive of lithium-ion battery which provides and degrading the battery health span, V2G participation, improve battery strategies. In the case of capacity fade in battery, battery capacity decreased progressively with each cycle due to the loss of usable active material and other degradation factors like SEI growth and lithium plating. The capacity loss is relatively slow in the first few cycles but as cycles progress, the degradation becomes more that is after 500 cycles, the battery retains around 95% of initial capacity, needing mitigation strategies to improve battery health, as shown in Figure 4. In the case of internal resistance, the internal resistance gradually increases as shown in Figure 3 due to factors like SEI growth and lithium plating loss of active material. The increase in the internal resistance results in increase in energy losses during charging and discharging cycles. In the case of SEI growth, the layer grows gradually with each cycle, especially during charging, that makes less Lithium ions available for electrochemical reaction, that has direct impact on the battery performance as shown in Figure 3. The lithium plating is considered as a secondary degradation mechanism as it contributes to increase in internal resistance of the battery. As shown in Figure 4 shows the lithium plating grows overtime due to continuous charging and discharging cycles.

**CONCLUSION**

The experimental analysis of different factors that lead to Lithium-ion battery degradation highlights that, over 500 cycles, the battery shows a gradual increase in factors like internal resistance, capacity fade, SEI layer growth and lithium plating. The results show the need for advanced Battery management systems to monitor and solve these battery degradation factors to improve the lifespan and performance of Lithium-ion batteries. By monitoring the degradation factors simultaneously, it is possible to increase the battery lifespan and degradation prevention techniques like regulated charging and discharging cycles, thermal management to applications like Electric vehicles and Storage of Grid Energy.

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