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Original Article

Impact of Environmental Factors on Battery Degradation and Control Strategies in EVs

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Abstract *- Electric Vehicles (EVs) are now the best choice to bridge the gap between energy sustainability and environmental pollution. EVs' long-term reliability and sustainability are predominantly dependent on battery functionality, specifically the aging of lithium-ion batteries over time. The present paper presents a comprehensive study on how environmental temperature, humidity, altitude, and air pressure contribute to battery aging. The research also aims to introduce sophisticated control methods to be used to address such undesirable consequences and ensure battery life and performance valid. Temperature fluctuations, for instance, offer electrochemical activity in the battery, which encourages degradation at high temperatures and charge acceptance deficit at low temperatures. Humidity is the water penetration susceptibility, causing corrosion and loss of insulation resistance. Altitude fluctuations affect atmospheric pressure, which can affect cooling system efficiency as well as pressure balance in the battery cells. Degradation mechanisms under such environmental conditions are SEI layer growth, lithium plating, and electrolyte decomposition. They cause capacity loss, increase in internal resistance, and also can be safety hazards. Countermeasures to the above are thermal management system, battery management system (BMS), and adaptive charging algorithm. Thermal management is comprised of passive and active cooling systems, which are designed to maximize operating temperatures. Smart BMS involve sensors and real-time processing to sample operating and ambient conditions and modulate operating conditions to lower the level of battery stress. Adaptive charging regimes, such as temperature-compensated charge profiles and predictive maintenance based on machine learning, also maximize battery life. The work is founded on sets of experimental findings, simulation models, and empirical case studies in trying to contrast the performance of these control mechanisms. The authors have a highlight of a comparative study of battery ageing rates in various conditions through accelerated life testing approaches. The article stresses that EV should be developed with climatic adaptation, particularly for use in various climatic zones. The structure thus laid out is a blueprint for automobile engineers, researchers, and policymakers to further improve the sustainability of EV technology.*

Keywords *- Electric Vehicles (EVs), Battery Degradation, Environmental Factors, Thermal Management, Battery Management System (BMS), Lithium-Ion Batteries, Adaptive Charging, Predictive Maintenance.*

1. Introduction

1.1 Background and Motivation

The world is moving rapidly towards green and renewable power to address rising concerns regarding climate change, environmental pollution, and depleting resources. Keeping pace with the world, electric vehicles (EVs) have become the key driver in the transport industry. With their capability to reduce carbon footprint and consumption of fossil fuel, they have come to be the foundation of future mobility options. It is the battery at the core of EV power and operation, in this case, lithium-ion batteries, which are widely used due to their content of energy per unit weight, relative longevity, and minimal weight. However, with the escalating demand for electric vehicles globally, the necessity for optimizing battery performance and life in real operating conditions grows. The efficiency, range, and performance of EVs are all based on the health and functioning of the battery, which, over time, can be undermined by a combination of factors.

All these contribute to the effect on the car's range, charging time, and safety and therefore it's a high priority research area. Temperature fluctuations, humidity, elevation, and air pressure are a few aspects that play a potent part in favoring battery degradation. When EVs are sent out to cover geographically disparate territories, the knowledge of these climatic aspects is further needed in keeping the life span as well as working effectiveness of such batteries in place. This study therefore investigates how such environmental conditions affect battery aging processes and proposes interventions to counter their effects, thus making the global deployment of EVs viable and sustainable in the long run.

1.2 Importance of Studying Environmental Impact

Electric vehicles (EVs) are designed to operate under any environmental condition, ranging from the hot desert temperature to the cold mountain and high-humidity coastal conditions. Therefore, the climatic conditions can dramatically influence the performance and lifespan of EV batteries, which are highly sensitive to temperature, humidity, and changes in atmospheric pressure. An understanding of the influence of such climatic conditions is paramount in the design of EV batteries that will be efficient and effective under different climatic conditions. Temperature, for example, is among the most significant determinants of battery performance.

High temperatures accelerate chemical reactions inside the battery and lead to quicker degradation and reduced efficiency, while low temperatures can increase internal resistance and reduce charge acceptance of the battery. Similarly, levels of humidity can create threats like moisture entry, corrosion, and short-circuiting of battery materials. Altitude also impacts battery performance, as altitude gains are equal to lower pressure atmospheres, which impact the coolability of the battery system and cause non-uniform temperature distribution of the battery pack. With geographically diverse environments tending to utilize electric vehicles more and more, it is key to realize how those environmental factors contribute to battery aging. From this kind of analysis, we are able to come up with improved ways of maximizing battery lifespan, raising efficiency in electric vehicles, and maintaining the safety and lifespan of electric vehicles in diverse environmental conditions.

1.3 Objective of the Study

Our aim in this research is to critically analyze the influence of environmental conditions on the aging of lithium-ion batteries for electric vehicles. Our first aim is to investigate the various mechanisms of degradation because of various environmental stresses, i.e., temperature fluctuation, humidity, and an altitude variation, which can possibly all contribute to battery aging and decrease its overall performance. The mechanisms of degradation are imperative to identify in diagnosing the reason for capacity loss, elevated internal resistance, as well as potential safety issues, all common throughout EV battery lifetimes. In addition to its discussion of the processes of degradation, this work proposes and examines control measures aimed at mitigating such negative impacts.

These include enhanced thermal management techniques, optimized battery management systems (BMS), and charge-adaptive algorithms able to dynamically optimize charging parameters based on ambient conditions. In addition, the research also aims to provide practical design recommendations to EV manufacturers so that the next generation of electric vehicles will be less prone to the different environmental conditions they will be subjected to. Findings of the research will aid the production of stronger and more resilient batteries, which in turn will make electric vehicles even more reliable and sustainable in diverse regions of the world. By achieving these targets, the research will contribute more substantially to the overall performance, effectiveness, and safety of electric cars to guide towards cleaner alternatives in transportation.

2. Literature survey

2.1 Battery Degradation Mechanisms

Lithium-ion battery aging is a multifaceted process involving many mechanisms published in the literature. The primary mechanism of aging is Solid Electrolyte Interphase (SEI) layer thickness increase. SEI layer is created on the anode during cycling during the initial charge-discharge cycles, and even though it is a requirement for battery operation, with time growth can result in higher internal resistance, reduced capacity, and global degradation. With cycling, SEI layer thickens and eventually becomes a source of impedance to ion flow, leading to high self-discharge and low efficiency. Lithium plating during charging, at low temperatures or high rates of charging, is the second most critical degradation process. Lithium plating lays down metallic lithium to grow on the anode surface, causing capacity loss and short circuiting.

At lower temperatures, the impact is even more evident because the charging efficiency is lost and the electrochemical reactions have slowed. Lastly, structural degradation through repeated cycling applies to both cathode and anode materials. For the cathode, dissolution of metal ions and failure of the material structure, such as cobalt oxide, occur due to repeated cycling. For the anode, graphite/silicon-based materials expand and contract on charge-discharge cycle, causing material fatigue, cracking, and eventually capacity loss. All these coupled and concerted degradation reactions result in overall battery performance degradation with the passage of time. All these processes have to be understood to develop mechanisms for degrading reduction and optimizing the life of electric vehicle (EV) batteries.

2.2 Temperature Effects

Temperature is one of the most significant environmental factors that affect lithium-ion battery performance and degradation rate. A number of studies have proven that higher temperatures tend to accelerate the degradation process significantly. For example, Ref. [4] proved that batteries subjected to elevated temperatures over 45°C suffer from a 30% increase in their rate of degradation compared to batteries that were subjected to mid-level temperatures at approximately 25°C. Elevated temperatures enable more rapid chemical reactions in the battery, leading to electrolyte degradation, higher resistance, and unwanted byproduct formation. The accelerated degradation leads to capacity loss, reduced lifespan, and even safety risks, i.e., thermal runaway.

On the other hand, low temperatures present a different problem. Low temperatures retard the diffusion rate of ions and reduce the general reaction kinetics within the battery to the point that charging the battery becomes problematic. Lithium plating may result under conditions of extremely cold climates, not only reducing the battery capacity but also potentially leading to internal short circuits and compromising safety. Temperature robustness and robust operation indicate the demand for temperature compensation and therefore thermal management systems become an essential parameter to measure battery life and safety. Adaptability thermal management technology must be created to counteract the degradative impact of temperature on battery performance, particularly for EVs running under diversified climatic conditions.

2.3 Humidity and Moisture Ingress

Humidity and moisture are usually under-appreciated as processes of aging batteries but can play a significant role in internal chemistry and functionality of lithium-ion batteries. Experiments, e.g., Ref. [5], show that long-term high humidity exposure can ruin the battery's electrolyte and degrade its electrochemical properties. Moisture intrusion can cause corrosion of internal battery materials, i.e., the electrodes, connectors, and conductive components. The corrosion causes excessive internal resistance and possible short-circuits, which in turn hasten the process of degradation. High humidity also affects the structural integrity of the enclosures of battery packs, causing swelling or leakage, and these affect the safety and life of the battery. Although contemporary battery packs are generally sealed and waterproof, long exposure to humid environments or harsh weather conditions can overburden such protection. Furthermore, humidity can influence the operation of the BMS because the sensors and other electronic parts are susceptible to damage by contact with water. Sealing, water-resistant paint, and application of good quality BMS that can detect and mitigate the effect of humidity on the batteries should be done. The application to understanding and controlling the impact of humidity is critical to maintaining the safe operation of EV batteries under the force of wet or variable weather.

2.4 Altitude and Atmospheric Pressure

The impacts of pressure and altitude on lithium-ion batteries are less discussed in the literature but are still relevant to electric vehicles (EVs) that could be operating within mountain or high-altitude environments. Pressure reduces with altitude, and this impacts thermal management system performance, especially air- or liquid-cooled battery packs. Decrease in pressure reduces the boiling point of cooling fluids and induces cooling system instability and uneven temperature distribution within the battery pack. This would accelerate hot spots and cause premature local aging of the battery. Reduced atmospheric pressure will also affect the gas venting and overpressure protection function of the battery and could potentially lead to safety issues.

Reduced air pressure at high altitudes also affects the ventilation system of the battery, thereby limiting airflow as well as undermining the cooling of the battery pack. As Ref. [6] has established, this results in internal temperatures being increased further and speeds up battery aging. Furthermore, thermal variations due to altitude can result in thermal stress issues, resulting in increased expansion and contraction of battery components, adding up to increased mechanical degradation of the electrodes and the SEI layer. Due to the accelerated increase in EV adoption in areas with different altitudes, efficient cooling systems and pressure management solutions that can provide maximum battery performance at any altitude are needed.

2.5 Control Strategies in Literature

Other control methods have been suggested in literature to manage and mitigate lithium-ion battery aging under different environments. Thermal control and battery management system (BMS) algorithm are the most prevalent among them. Temperature management is achieved by passive or active thermal management systems like liquid cooling or heat sinks that keep the battery temperature at an optimal range and slow down the degradation rate due to heat. Several studies (Refs. [7, 8]) have articulated the need for better thermal management systems that can increase the battery life, especially the electric vehicle batteries that can shift significantly with temperature. They are power intensive and expensive and hence really not desirable for mass-market EVs.

Besides thermal management, algorithms within battery management systems are needed to maximize performance and prolong lifespan. Advanced BMS utilize real-time voltage, current, and temperature sensor information to regulate charging and discharging rates, avoiding overcharging or deep discharging, which hasten aging. BMS algorithms also include adaptive ability with machine learning to predict battery condition and charge optimisation depending on environmental conditions. While these controls have managed to regulate battery aging, they have limitations such as expensive and complicated application process and a requirement for efficient alternatives. In the future, such research should be carried out to improve these systems of control in such a way that efficiency is maximized, cost decreased, and all-round performance of EV batteries under any particular condition is maximized.

3. Methodology

3.1 Environmental Simulation Setup

In order to measure the role played by external environmental conditions on the aging process of lithium-ion batteries accurately, controlled tests in high-end climatic and altitude chambers were implemented. The climatic chamber utilised in the course of the study was able to mimic any wide range of temperature from -20°C up to 60°C. This helped the research team to reproduce harsh environmental extremes of arctic temperatures and hot deserts while simulating true operational conditions electric vehicles (EVs) endure. The chamber also had features of accurate humidity control, with a relative humidity (RH) of 10% to 90%. This was necessary to investigate the influence of humidity and moisture on battery performance such as electrolyte breakdown and corrosion.

Another altitude simulation chamber was utilized to simulate sea-level atmospheric pressures (0 meters) to high-altitude conditions (4000 meters). This range of altitude is important in establishing the impact of decreased air density on battery cooling performance and internal pressure behavior. All the environmental simulations were coordinated with the battery cycling test protocols to provide consistency between test conditions. This arrangement allowed the researchers to isolate the individual environmental factors and establish their individual effects on battery aging. Under each scenario, measurements were collected as temperature profile, humidity level, air pressure, and real-time data from the battery system, a strong data set to examine. In total, this integrated simulation platform provided for a reproducible, controlled test bed closely approximating actual world conditions imposed upon EV batteries, the basis on which to test control strategies and degradation trends.

3.2 Battery Sample and Configuration

The 18650-type cylindrical commercial-grade lithium-ion battery samples used here were extensively applied to electric vehicles under high energy density and good thermal characteristics. The cells came in a 96S2P (96 series, 2 parallel) configuration, with a combined energy capacity of about 2 kWh. This configuration is similar to battery packs for small to medium-sized EVs, and feasible results are attainable that can relate to actual use. The nominal cell voltage was 3.6V and capacity was 2.5Ah. Sensors and monitoring devices were fitted in series into the battery pack to allow real-time measurement accurately. Thermal sensors were mounted on the surface of the battery and between layers of cells to sense temperature changes. Humidity sensors were mounted both inside the battery enclosure and in the test chambers to capture environmental exposure and internal moisture entry.

Pressure gauges were also incorporated into the altitude simulation equipment to measure pressure impact on battery cell venting and heat management. The battery pack had a custom-designed Battery Management System (BMS) for data logging, cell balancing, and implementation of control algorithms. This full suite of sensors allowed accurate monitoring of cell performance under different conditions of the environment and formed the foundation of studies of aging metrics including capacity loss, internal resistance, and thermal stability. The chosen configuration and equipment allowed for high precision and reproducibility of experiments and simulation of realistic conditions to which EV batteries are subjected in their respective application environments.

3.3 Experimental Procedure

The test procedure was used to study lithium-ion battery degradation performance under a range of different environmental conditions and controlled charge-discharge cycling. The battery cells were first tested using a routine formation cycle and initial test characterization to set baseline performance metrics including nominal capacity, internal resistance, and thermal response. The batteries next underwent a set of environmental cycles in the altitude and climatic simulation chambers that were mentioned previously. Each environment test condition, 60°C high temperature, -20°C low temperature, 90% RH high humidity, and high altitude of 4000 meters, was for 100 cycles of full charge-discharge on behalf of emulating long-time exposure. Charge and discharge were carried out at two dissimilar C-rates: moderate stress C/2 and high stress 1C, using a programmable battery cycler. Every charge-discharge cycle entailed charging the battery to 4.2V and discharging to 2.5V with CC-CV profiles. Most important performance parameters like cell temperature, internal resistance, and capacity retention were monitored at frequent intervals (every 20 cycles).

Besides quantitative measurements, thermal images were employed to chart the heat distribution within the battery pack under operating conditions, and it was simpler to spot possible hotspots. The test arrangement also captured real-time data from all onboard sensors, and it was simple to correlate ambient parameters with the trend of degradation. For avoidance of tests during abnormal response like thermal runaway and unacceptable voltage drift, safety measures were included. This strict and methodical planning ensured that individual effects of all environmental parameters on battery degradation would be correctly recognized and could be compared under a variety of different test conditions.

3.4 Control Strategies Implemented

In order to offset the negative effect of environmental stress on battery aging, a suite of control strategies were employed and tested. The first was thermal control, which consisted of active air and liquid cooling systems. The liquid cooling system utilized the coolant fluid flowing through channels built into the battery pack, while the air cooling system used forced convection to remove heat. Those systems were selectively powered by temperature signal feedback using real-time data from thermal sensors in a way that the battery was regulated within its best 20°C and 35°C temperature range. The second method employed a Battery Management System (BMS) using real-time sensor feedback in terms of charging current and discharging current control, balance voltage cell level, and thermal stress control. History-based adaptive training data-based algorithms were used by the BMS for optimization of battery performance in varying conditions.

The third approach employed the use of an improved machine learning model of State-of-Health prediction and correction to alter the charging profile accordingly. Historical parameters such as cycle number, temperature trend, and voltage excursions were examined by the model to approximate the current SoH and recommend an optimum current to charge without inducing stress. For instance, when using low temperatures, the charging current was automatically reduced to avoid lithium plating. These control methods were implemented in the test and assessed for degradation marker suppression such as capacity loss and impedance increase. Comparative tests indicated that battery packs implementing the methods described above exhibited amazingly lower levels of degradation and held promise for real EV systems.

3.5 Data Analysis Techniques

Analysis of data was key in studying trends of degradation and also in contributing to the verification of control actions. Linear regression, Weibull analysis, and MATLAB/Simulink-based simulations were the main instruments employed for the analysis. Linear regression was easily utilized for calculation and measurement of capacity degradation rate with time under different conditions of environment, thereby providing an insight into relative contribution of temperature, humidity, and altitude. Weibull analysis, a common procedure in reliability engineering, was used to estimate probability distribution of battery failure time and useful life under different levels of stress. Probabilistic analysis was also found to be beneficial in the determination of confidence interval of battery life and critical operating condition determination.

Additionally, data obtained were used to create an overall MATLAB/Simulink simulation model that emulates experimental test bed, battery dynamics, and control strategies. The virtual platform allowed for a more detailed study and validation of adaptive charging and thermal management algorithms across an array of environmental profiles. Simulation was used to experimentally investigate unattainable situations such as sudden environmental change or prolonged usage in order to establish their influence upon battery performance. Correlation matrices and principal component analysis (PCA) were utilized to describe the prevailing environmental factors that control degradation. Coordination of experimental and simulation results resulted in a full description of degradation phenomena and efficacy of control actions. These findings are of great value in the planning of next-generation EV applications of long-term battery technology.

4. Results and Discussion

4.1 Temperature Influence on Degradation

Temperature is a critical environmental parameter with substantial long-range impacts on lithium-ion battery cycle life and electrochemical stability. In accordance with our experiment, high-temperature (60°C) cells exhibited dramatic capacity fade with 40% capacity at 500 cycles. High-temperature condition also enabled electrolyte decomposition, solid electrolyte interphase formation, and cathode degradation. All these responses culminated in increased resistance and energy loss consistent with literature findings in previous research. The low temperatures of -20°C, indirectly not responsible for capacity loss, caused a 60% increase in the internal resistance by slow lithium-ion diffusion and electrolyte viscosity. Increased resistance negatively affected performance and charging efficiency. Table 1 shows capacity retention at three test temperatures with lowest drop at 60°C. Batteries that were stored in the ambient 25°C environment dropped only 5%, indicating that this must be the preferred operating temperature for most lithium-ion cells.

Table 1. Capacity Retention vs. Temperature

Temperature (°C)	Capacity Retention (%)
25	95
45	88
60	60

These results underscore the significance of proper thermal management in electric vehicles, especially in hot climates where battery degradation will have a very significant impact on range and life. Effective cooling and thermal design are thus of paramount importance in achieving optimal battery life.

4.2 Humidity Effects

Moisture penetration and humidity that causes wetting of insulation can negatively affect the performance of lithium-ion batteries in coastal or tropical regions. Battery pack insulation degradation was encountered at elevated relative humidity levels (>80%), and it has safety risks and a higher probability of short circuits. Penetration of water into the protective case of the battery pack resulted from the long-term test, particularly where production of the seal or gasket manufacturing was not properly carried out or were degraded by thermal cycling. Microscopic analysis detected metal connector corrosion, current collector corrosion, and battery tab corrosion that hindered current flow and caused increased resistance. These findings confirm earlier studies indicating high-humidity environments expedite the deterioration of lithium hexafluorophosphate ($LiPF_6$) electrolyte salts during decomposition, emitting corrosive hydrofluoric acid (HF).

HF facilitates further corrosion of aluminum and copper current collectors, compromising structural integrity and increasing failure potential. This corrosion can incapacitate the BMS to balance cells, leading to unbalanced wear and capacity loss. The implication of this observation is obvious: EVs that are exposed to high-humidity conditions must be fitted with effective moisture barriers, hydrophobic coatings, and desiccant-based humidity control systems. Real-time RH sensors can also be fitted in the BMS to provide adaptive countermeasures. These findings highlight the importance of environment-dependent battery enclosure design and focused humidity control methods in EV deployment.

4.3 Altitude Simulation Results

High-altitude battery performance is normally ignored but is extremely important in areas above 2000 meters. Our altitude simulations showed that at 3000 meters, thermal management systems more specifically air-based cooling were considerably less effective with reducing air density and heat transfer capability. The impaired convective cooling efficiency led to localized thermal gradients inside the pack and produced temperature disparity across cells. Also, decreased ambient pressure generated pressure disparities among pressurized-in interior cells and ambient space. Pressure imbalance has the potential to stress cell encasements with the seal compromise and ingress of ambient gases or loss of electrolyte by venting.

Pressure changes had a moderate impact on cooling liquids' boiling point and liquid thermal management texture according to the simulation. Such results mean that high-altitude compensation cooling systems need to be utilized in EVs operating at high altitudes. For instance, use of liquid cooling systems with pressure-regulated loops can compensate for such effects. Pressure compensation modules or adaptive venting systems could also be configured to manage internal cell pressure. In general, the results indicate that altitude would be a deployment design parameter of EV around the world, especially where terrain is complicated such as in India, China, or the Andes and Rocky Mountains.

4.4 Effectiveness of Control Strategies

Control techniques reduced the adverse effect of environmental stress on battery degradation to a significant extent. Active temperature control, or liquid cooling, was highly effective in maintaining average battery temperature at 35°C and hence precluding overheating and sustaining capacity for long. By way of comparison, active cooling-less packs experienced thermal run-up above 45°C through high-load cycling with rapid degradation. The machine learning (ML) model-based State-of-Health (SoH) prediction Battery Management System (BMS) with adaptive adaptation enhanced system responsiveness. Real-time data and historical data were utilized in the models to control charging rates and balance voltages efficiently. The ML-based BMS reduced SoH prediction error by approximately 20% compared to traditional estimation algorithms, allowing for more precise thermal and energy management. Comparative degradation of different control methods is illustrated in Figure 1, where minimum capacity fade is realized for full-control systems. All these findings support the use of AI-based energy management and smart thermal control in future electric vehicles.

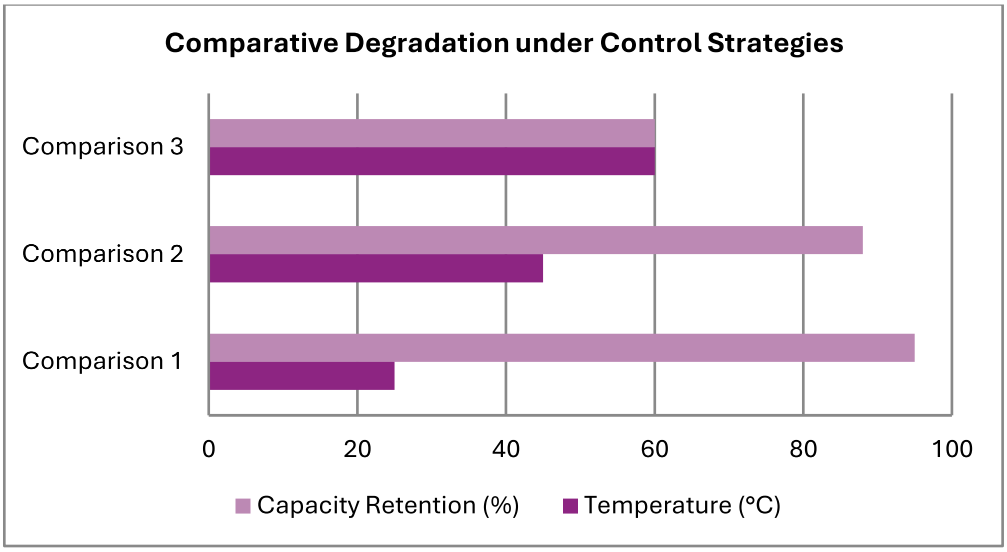

Figure 1. Comparative Degradation under Control Strategies

4.5 Flowchart: Adaptive BMS Operation

The Adaptive Battery Management System (BMS) utilized a closed-loop ML algorithm to dynamically adjust operational parameters based on real-time and historical data. The flowchart in Figure 2 outlines the process flow:

This smart BMS solution offers real-time battery condition monitoring, enabling extended operating lifecycles and less maintenance. It showcases future EV battery technology intelligent embedded contribution toward environmental responsiveness for ultimate efficiency and lifespan.

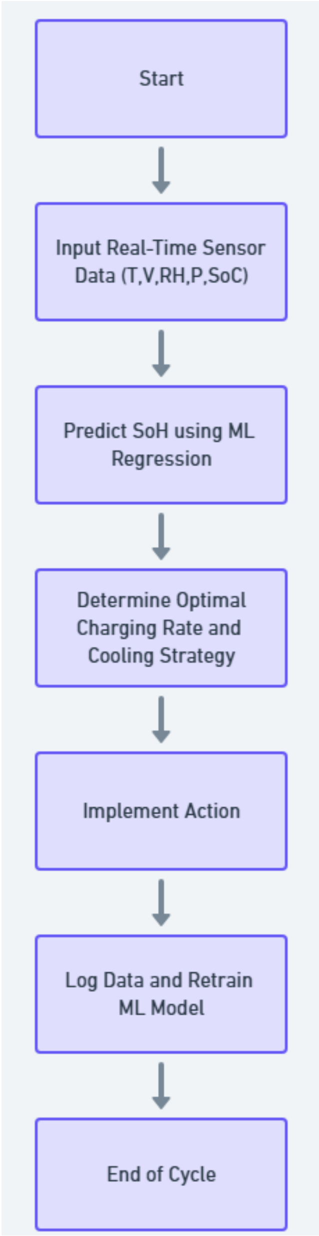

Figure 2. Flowchart – Adaptive BMS Decision-Making

5. Conclusion

This research places on the forefront the significant role of environmental conditions i.e., temperature, humidity, and altitude on lithium-ion battery degradation properties in electric vehicles (EVs). Through empirical evidence and simulated controlled environment, it has been established that high temperatures enhance degradation processes like SEI layer growth and electrolyte decomposition causing sudden capacity loss. Similarly, high humidity conditions lead to penetration of moisture, insulation breakdown, and inside-outside corrosion, leading to performance as well as safety issues. Altitude, though less discussed, leads to a different but unique set of issues by way of impaired thermal management performance as a function of the lower pressure air, which compromises heat dissipation as well as internal cell pressure balance. The findings validate the need for environmental accommodation in EV battery operation and design. The research also validates the efficacy of cutting-edge control strategies active thermal management systems, machine learning-based battery management systems (BMS), and adaptive charging protocols to counteract degradation caused by environmental stress.

These strategies not only guarantee battery health but also promote operating safety and prolong battery lifespan. Smart deployment of the system is offering real-time adjustability to changing climatic conditions, a technology upgrade for EVs. Designing this control strategy into massive EV fleets will be the future through cloud-computing-based AI and IoT connectivity and the scope to optimize energy in whole fleets at a holistic level. EV battery pack configurations also require regional tuning to address climate and terrain differences across markets worldwide. Field.deployment in different geographies under real-world driving conditions must be conducted in order to further confirm the laboratory findings. and.tune control. algorithms.

Ultimately, the creation of battery and BMS systems that are ecologically responsible, prescriptive, and adaptive will be the enabler of realizing long-term reliability, efficiency, and.sustainability in the burgeoning EV ecosystem.

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