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OPTIMIZING BATTERY TOPOLOGY FOR ENHANCED LIFESPAN AND REDUCED STRESS THROUGH INNOVATIVE CURRENT FLOW MANAGEMENT APPROACHES

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ABSTRACT
In an era prioritizing environmental sustainability, this paper addresses a key challenge in solar-powered electric vehicles (EVs): optimizing energy flow within batteries. Focusing on the variable nature of solar energy, which often leads to inconsistent charging and reduced battery life, the study proposes a novel control system. This system employs advanced algorithms and battery management techniques to adapt to solar fluctuations, harmonizing charging and discharging cycles. Significant improvements include enhanced battery lifespan and solar power utilization efficiency, contributing to a 6.5% increase in vehicle range. This research underlines the potential for more efficient, eco-friendly solar EVs, advancing sustainable transportation technology.

INTRODUCTION

Background and Motivation

The rapid growth in electric vehicle (EV) adoption, coupled with the increasing integration of renewable energy sources and the widespread use of portable electronics, has significantly heightened the demand for advanced energy storage systems [1][2][3]. This growing demand highlights the critical need for batteries that offer extended lifespans and enhanced performance [4][5]. Traditional battery designs, however, are frequently challenged by stress-induced degradation, an issue that is particularly pronounced in applications requiring long-term reliability. This research is driven by the urgency to address these limitations, with a special focus on solar-powered EVs, where the efficiency and durability of batteries are of utmost importance [6][7][8][9][10].

Significance of Battery Lifespan Enhancement

The lifespan of batteries plays a decisive role in determining the economic and environmental implications of EVs, renewable energy systems, and other applications reliant on battery technology [4][11][12]. Enhancing the lifespan of batteries is crucial, not just for reducing the frequency of replacements, but also for contributing to environmental sustainability by minimizing the ecological impact associated with their production and disposal [12].

Challenges of Stress-Induced Battery Degradation

Batteries, particularly in solar-powered EVs, face internal stresses due to uneven current distribution, temperature fluctuations, and mechanical factors, leading to accelerated degradation [13]. These stress factors are exacerbated by the variable nature of solar energy input and the diverse usage patterns of EVs, underscoring the need for a comprehensive understanding of battery degradation mechanisms [14][15].

Battery Stress and Degradation Mechanisms

Battery degradation encompasses a range of electrochemical, mechanical, and thermal factors [16]. Key contributors to this degradation process include electrode volume changes during charge-discharge cycles, temperature gradients within the battery, and variations in current density [17][18][19]. These internal stresses can lead to a host of degradation mechanisms, such as the deterioration of electrode materials, breakdown of electrolytes, and instability in the solid-electrolyte interphase (SEI) layer [20].

Current Flow Management: Theoretical Framework

This paper underscores the importance of effective current flow management within batteries to ensure uniform stress levels and optimal performance [21]. The research focuses on achieving balanced electrical current distribution, which is fundamental to reducing stress concentrations and enhancing the lifespan of batteries, particularly in the context of solar-powered EVs [22][23].

State-of-the-Art Approaches to Battery Topology Optimization

Incorporating a comprehensive comparative analysis using a mathematical model of a vehicle, this research evaluates the effectiveness of the proposed system against traditional battery systems [24][25]. These simulations are key to illustrating the potential improvements in battery performance and lifespan that the innovative energy flow management system can provide.

Overview of Stress-Related Battery Degradation: The field of energy storage has witnessed remarkable growth, primarily fueled by the escalating demand for batteries across diverse applications such as electric vehicles (EVs), renewable energy systems, and portable electronics. Despite significant strides in battery technology, the issue of stress-induced degradation remains a fundamental challenge that necessitates long-term sustainability.

The decrease in capacity fade at reduced DOD cycling translates for the end user in a four-fold improvement of cycle life when going from 100% DOD to 50% DOD cycling. This also translates in a three-fold improvement of the expected number of equivalent full cycles before the capacity drops below 80% of the initial capacity. These improvements do not require to cycle all the time at a reduced DOD [26].

Batteries experience a range of degradation processes as they age, influencing their performance and overall lifespan. Among these, stress-induced degradation has gained substantial attention due to its adverse effects on battery health [27].

Having established the critical role of renewable energy in the enhancement of electric vehicles, particularly focusing on the integration of solar power, the introduction has laid a comprehensive groundwork for the study. We have explored the pressing challenges and the immense potential of solar electric vehicles, highlighting the pivotal role of battery technology in this evolution. Moving from this broad overview, the next segment of our research, titled "Objective and Scope of the Research," is poised to delve into the specific objectives we aim to achieve. This section is meticulously designed to transition from the general overview presented in the introduction to a more detailed exploration of our targeted goals and the expansive scope of our study. It aims to provide clarity on the research direction and define the parameters within which our investigation will operate, ensuring a focused and purposeful approach to addressing the complexities of energy flow management in solar-powered EVs.

OBJECTIVE
The primary objective of this research is centered around addressing the energy flow management challenges in solar-powered electric vehicles (EVs). The goal is to develop a sophisticated control system, specifically designed to optimize energy flow in and out of these vehicles' batteries. Such a system is anticipated to significantly boost the efficiency, reliability, and lifespan of the batteries used in solar EVs. This enhancement is vital for elevating the overall performance of solar electric vehicles, thus solidifying their standing as a viable and sustainable choice in green transportation[28].

SCOPE
The scope of this research is extensive and covers multiple critical areas:
1. Analysis of Solar Energy Variability: This part of the research involves examining the variable nature of solar power and its impact on battery performance in EVs. It includes a study of the patterns of solar energy availability and their effects on charging cycles [29][30].
2. Battery Energy Flow Management: Central to this research is the development of an advanced system to manage the energy flow within batteries[31][32][33]. This system encompasses the design of algorithms and control mechanisms that are capable of adjusting to the inconsistent nature of solar energy, ensuring optimal battery usage
3. Enhancement of Battery Efficiency and Lifespan: A major focus is on strategies to extend battery life and boost efficiency in solar EVs. This involves testing and validating the proposed energy flow management system in various conditions [34].
4. Environmental Impact Assessment: Assessing the ecological benefits of the proposed system in solar electric vehicles is a key aspect [35]. This includes evaluating the potential decrease in carbon emissions and the overall environmental impact of solar EVs with optimized battery management [36].
5. Application in Solar Electric Vehicles: The research also aims to apply its findings and solutions in real-world scenarios, particularly in the design and functioning of solar-powered electric vehicles [37]. Collaborating with industry partners for practical implementation and testing forms a crucial component of this effort [38][39][40].

Innovative Battery Topology in the Proposed System
Existing EV Model:
In the existing model's diagram, we observe a straightforward, linear process flow. The primary input, denoted by a downward arrow, suggests an initiation signal or a directive from an external control system, which could be the driver's input or an automated driving command. The flow then proceeds through a transformational stage, illustrated by the diagonal arrow, implying a process where input is converted into a functional response, such as the conversion of electrical energy from the battery to kinetic energy by the motor.[41], [42].
The horizontal arrow indicates the final output stage where the transformed energy or processed information is directed towards the drive system of the vehicle. This could represent the actual movement of the vehicle as a response to the input, with the motor's power output being transferred to the wheels [43][44]. The linear nature of this diagram suggests a traditional system with a potentially simpler control mechanism, which could limit the adaptability and efficiency of the vehicle's response to dynamic driving conditions.

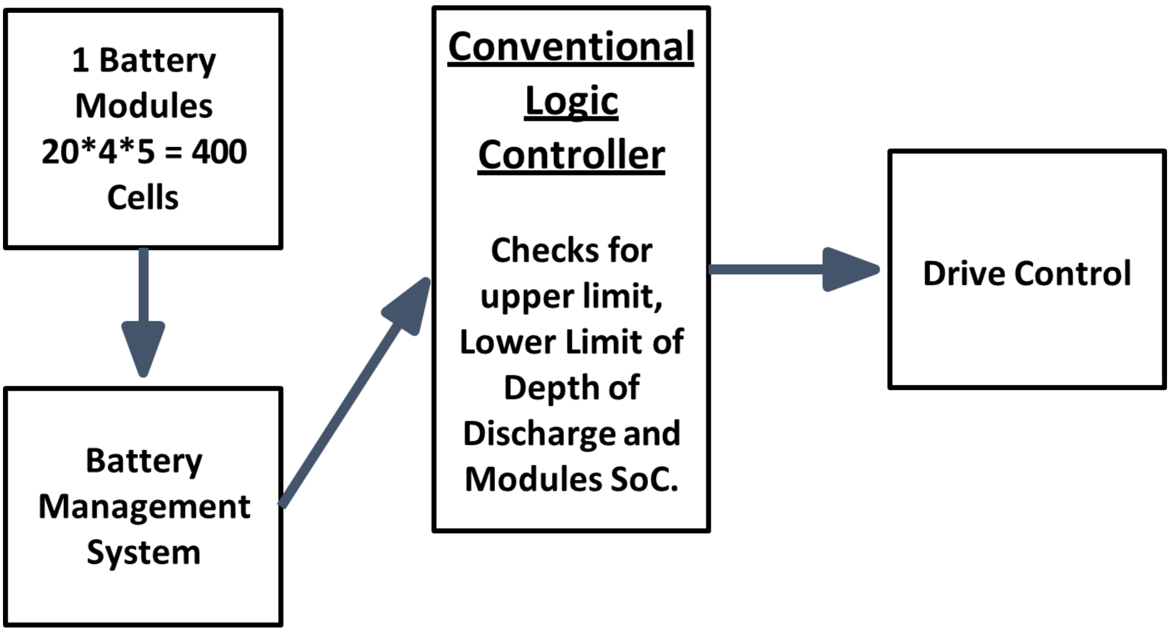

Figure A General flow of existing system

Proposed EV Model:
The proposed model's diagram shows a more intricate arrangement with multiple feedback loops and intersecting flow paths. The numbered arrow, marked with "1", likely identifies the primary operational flow within the system. This suggests a priority or main process channel in the proposed model, such as the prioritization of energy distribution from the battery to the motor.
Branching arrows emanating from certain process stages indicate multiple possible outcomes or actions that the system can execute. These branches might represent decisions within the vehicle's control logic to adapt to changing conditions, such as adjusting power output based on battery charge levels or modifying regenerative braking intensity based on vehicle speed.

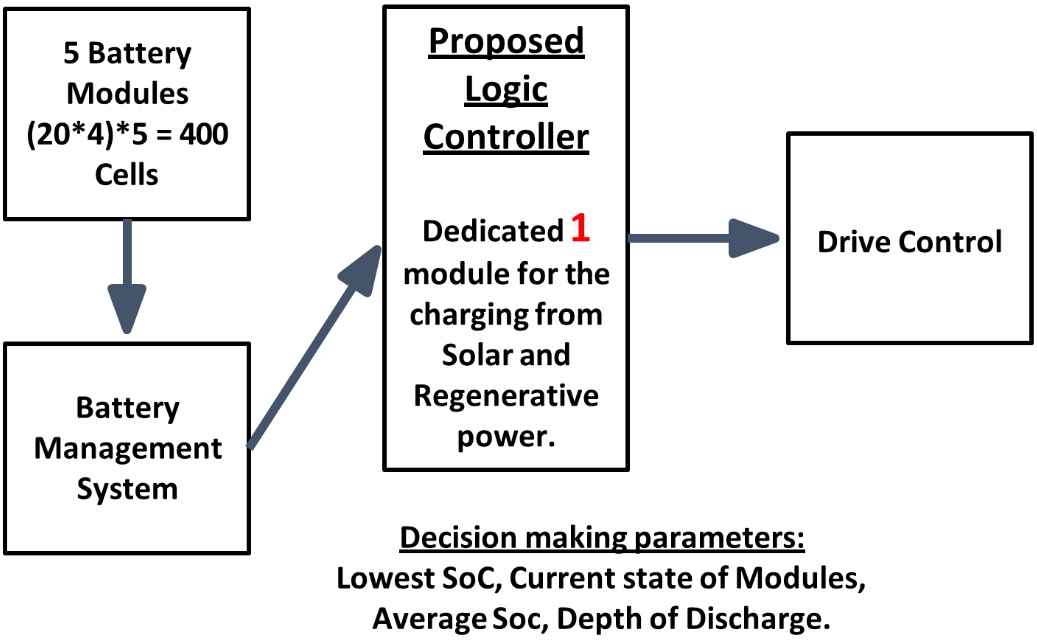

Figure B Proposed System overview

The feedback loops imply a system designed for self-monitoring and adjustment. This architecture allows for real-time adaptation to both the vehicle's internal state and external driving conditions. For example, a feedback loop might adjust the battery's discharge rate to optimize power consumption or modulate the vehicle's acceleration curve for enhanced energy conservation.

Composition and Configuration of Battery Sets
In the proposed system, several battery modules, such as modules 1, 2, and 3 in Set 1, are configured to meet the vehicle's specific requirements. Flexibility in the composition of each set is maintained, allowing for the inclusion of one or two battery modules as needed. These modules are interconnected in series to align with the vehicle's voltage prerequisites.

Integration of a Partial Battery for Enhanced Performance
A partial battery, rather than a supercapacitor, is integrated into the system. This partial battery is connected in parallel with the primary battery modules. Through this configuration, the optimization of energy utilization within the system is achieved, contributing significantly to the system's efficiency.

Operational Scenarios and Energy Distribution
The performance of the hybrid energy storage system is contingent upon various operational scenarios:
1. **Stationary or Parked Vehicle:** When the vehicle is stationary, the electrical current from solar panels is primarily allocated to battery set-1, ensuring efficient charging from solar energy.
2. **During Acceleration:** During acceleration, both solar modules and battery modules are utilized to meet the motor's current demands. This setup prevents the batteries from undergoing charging, thus ensuring a consistent and adequate energy supply to the motor.

The use of a partial battery in the proposed battery topology aims to mitigate stress-induced degradation and extend the battery's lifespan. This approach represents a significant advancement in hybrid energy storage system design for solar-powered electric vehicles, offering an efficient and sustainable solution.

PROPOSED SYSTEM FOR BATTERY MANAGEMENT IN SOLAR-POWERED ELECTRIC VEHICLES
Overview of the Simulation Process
A mathematical model of a vehicle is used to assess the proposed system. In the battery block of both the conventional and proposed systems, specific modifications are implemented. These modifications enable a comparative analysis of performance and characteristics, providing insights into the functionalities within the simulated environment.

Implementation of the System

Informed by an extensive review of existing literature, the implementation of the functions in the proposed system is carefully designed. This approach ensures that the system is robust and theoretically sound.

Operational Logic Based on State of Charge (SoC)

1. Within Defined Limits: When the average SoC is within the Upper and Lower Limits, no changes are made, and the Drive mode continues as is.

2. Above the Upper Limit: If the average SoC exceeds the Upper Limit, a transition from charging to discharging is initiated to prevent overcharging.

3. Below the Lower Limit: Conversely, when the average SoC falls below the Lower Limit, the system switches from discharging to charging to avoid depleting the battery.

4. During Regenerative Braking: During regenerative braking, the system diverts the generated energy from the motor back to the battery sets for recharging, thus maximizing energy efficiency and minimizing wastage.

To effectively manage the battery sets, the proposed system incorporates a battery management system. The BMS continuously monitors and balances the charge levels of the battery sets to ensure optimal performance and longevity. It takes into account various battery dynamic characteristics, such as the open-circuit voltage, transient response, and storage time-dependent capacity.

Furthermore, the system utilizes an average modeling approach for power converters. These operations are governed by the SoC-based logic, optimizing efficiency and ensuring safe battery levels.

Additional Safety Measures

If the SoC of any modules drops below the Lower Limit, the vehicle enters a Charging mode for those modules. Similarly, charging is stopped for modules where the SoC exceeds the Upper Limit, preventing overcharging.

An override function at the end of each cycle checks the operational state of each module. If overstress is detected in any module, this function takes precedence over regular operations.

In addition to the SoC-based operational logic, the proposed battery management system includes several additional safety measures to ensure the safe and reliable operation of the battery sets.

First, in the event that the SoC of any individual battery module drops below the Lower Limit, the system automatically enters a Charging mode specifically for that module. This prevents the module from being fully depleted and helps maintain the overall health of the battery sets.

Conversely, if the SoC of any module exceeds the Upper Limit, the system immediately stops charging that specific module to prevent overcharging.

Battery Topology Optimization and Current Flow Control

Optimized designs for battery packs, such as specific configurations and layouts, are used to distribute current more evenly, reducing stress.

This helps to minimize the temperature rise and voltage drop across the battery sets during charge and discharge cycles. Additionally, current flow control measures are implemented to regulate the charging and discharging rates of the battery sets.

To ensure the efficient operation and longevity of the battery sets, the proposed battery management system utilizes precise state of charge estimation. The SoC estimation is calculated based on measurable signals, such as current, voltage, and temperature. By accurately estimating the SoC, the system can effectively manage the charging and discharging phases of the batteries.

Moreover, the battery management system incorporates over-temperature prevention measures.

Advanced battery management systems (BMS) are incorporated for real-time monitoring and control of current flow. These systems adjust current based on various battery conditions, further enhancing battery life.

Simulation

Overview of the Simulation Process

A series of simulations were conducted to evaluate the effectiveness of the newly proposed battery topology. Parameters such as current distribution, stress concentrations, and battery lifespan were considered. It was found that, compared to existing topologies, the proposed battery topology significantly reduces stress concentrations and prolongs the battery's lifespan.

Simulation Parameters

Rigorous simulations were carried out, focusing on optimizing battery size, vehicle performance, and battery life under various conditions. Environmental factors incorporated into the simulations included a headwind of 20 kmph and a level road with a 0-degree gradient. The driving conditions simulated encompassed diverse scenarios, such as city travel, highway travel, and train travel.

Specific parameters of the vehicle were established: a weight of 1100 kg without passengers, a drag coefficient of 0.55, a frontal area of 1.5 square meters, and dimensions typical of a sedan-class vehicle. The battery topology was configured with a system voltage of 72V, including a dedicated battery module for charging. Additionally, a sophisticated switching algorithm, aimed at optimizing vehicle performance, was integrated into the simulations.

METHODOLOGY

1. Design and Development of the Proposed Battery Topology

An innovative battery topology is designed and developed at the outset of this research. Critical factors such as current distribution and battery lifespan are taken into account using an optimization algorithm. Existing battery topologies and their limitations are critically analyzed, leading to the proposal of a new approach aimed at minimizing stress-induced degradation and extending battery lifespan.

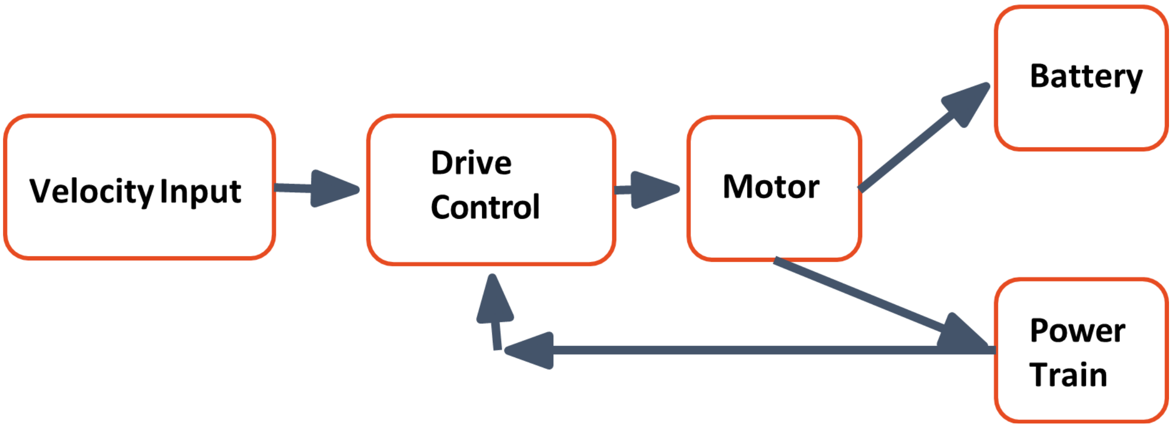

Figure C Simulation Flow Diagram

2. Simulation and Evaluation

Extensive simulations are then conducted on the proposed battery topology. The performance of this topology is assessed and compared with current standard topologies, providing a comprehensive evaluation.

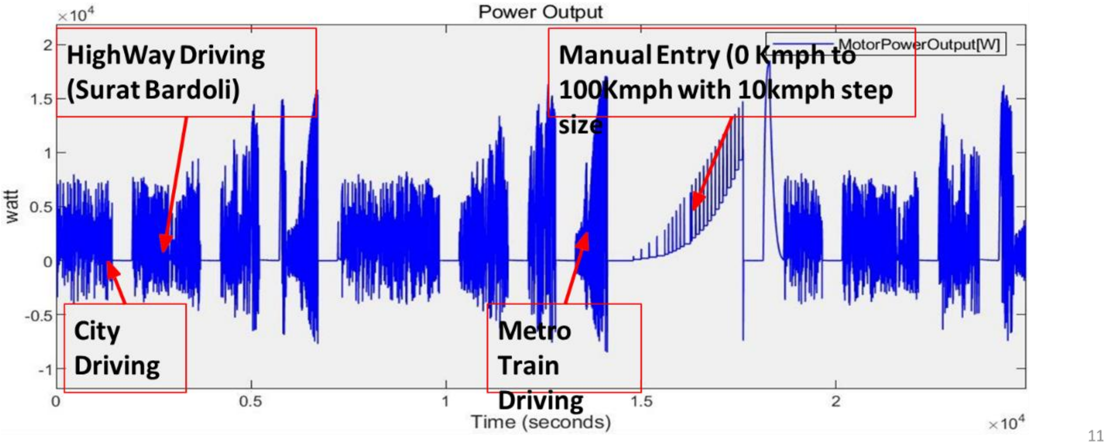

Figure D Power generated by Motor in various driving condition

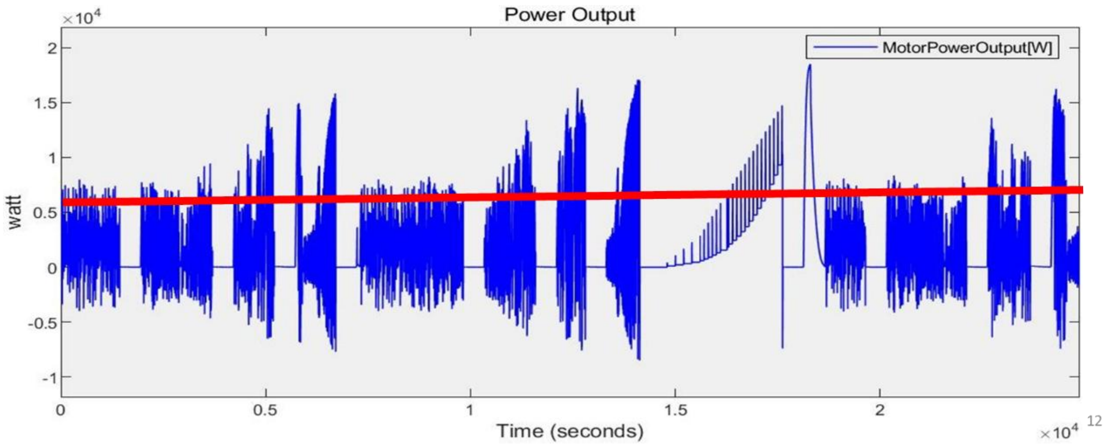

Figure E 6kW threshold for motor sizing

The simulation results pertaining to the proposed system for solar-powered electric vehicles are manifested through several figures, each elucidating the power dynamics under a spectrum of driving conditions.

Figure E is titled "Power Output," and it delineates the time series of motor power output, quantified in watts. A red line traverses the graph, likely serving as a datum line that could signify a threshold or an average power output. Notable fluctuations within the graph are exhibited, reflective of the diverse power demands encountered during vehicle operation. Such fluctuations are demonstrative of the motor's response to varied driving stimuli, inclusive of acceleration, deceleration, and idling phases.

Figure F provides an in-depth portrayal of power output in relation to specific driving scenarios. The graph is segmented and annotated, distinguishing between "City Driving," "Highway Driving (Surat Bardoli)," and "Metro Train Driving." Distinct power consumption patterns are discernible within each segment:

- The segment identified as "City Driving" is characterized by short, frequent fluctuations, indicative of the variable power requirements typical of urban traffic conditions, where stop-and-go patterns prevail.
- In contrast, the segment labeled "Highway Driving" depicts prolonged instances of elevated power output, commensurate with the consistent high speeds and sustained acceleration associated with highway travel.
- "Metro Train Driving," as delineated on the graph, exhibits a sequence of pronounced, rhythmic peaks, possibly emblematic of the repetitive acceleration and deceleration inherent in train travel.

Furthermore, a section of the graph is described as "Manual Entry (0 Kmph to 100 Kmph with 10 Kmph step size)," presumably denoting a systematic examination of the motor's power output over incremental velocity increases. This aspect of the graph likely sheds light on the motor's operational performance during controlled acceleration stages.

The figures presented are integral to the interpretation of the simulation data, offering a visual corollary to the system's adaptability to real-world driving conditions. The data rendered in these graphs intimate that the proposed battery topology and motor sizing are adept at catering to a variety of demands, thereby ensuring efficient power conveyance and bolstering the vehicle's holistic performance and range. The insights derived from these figures lend credence to the premise that the proposed system could significantly augment the efficiency and ecological sustainability of solar-powered electric vehicles, bearing consequential implications for the advancement of design and functional strategies in the field.

RESULTS

Simulation Parameters and Vehicle Requirements

The research methodology involved comprehensive simulations under a variety of environmental and driving conditions. These simulations were critical in determining the optimal sizing for the battery and motor, tailored to the specific needs of a solar-powered electric vehicle.

1. **Environmental and Driving Conditions:**

Environmental factors considered included a 20 kmph headwind and a road gradient of 0 degrees. The driving conditions simulated a range of scenarios, covering city travel, highway travel, and train travel, to mimic real-world driving patterns.

2. **Vehicle Parameters:**

The vehicle used in the simulations was modeled on a sedan-class vehicle, weighing 1100 kg without passengers. It featured a drag coefficient of 0.55 and a frontal area of 1.5 square meters, factors crucial in determining its aerodynamic efficiency and power requirements.

3. **Battery Topology and System Voltage:**

The system's voltage was set at 72V, a common benchmark for electric vehicles. A dedicated battery module was incorporated for charging, along with a switching algorithm designed to optimize vehicle performance under varying conditions.

4. **Motor and Battery Sizing:**

The motor's power requirements were established at 6 kW nominal power and 10 kW peak power. The battery size was optimized based on these requirements, resulting in the selection of a 125 Ah battery with a 3C rated capacity, capable of meeting the peak current requirement of 400 A and a nominal requirement of around 300 A.

Battery Performance and Age Degradation

Comparative Overview:

When the systems are compared, the proposed battery management system distinctly shows a lower degradation rate and a lesser number of extreme degradation events than the conventional system. The graphical representations from the figures substantiate this, indicating the proposed system's advanced design and management strategies that significantly enhance battery durability.

Relevance to Electric Vehicle Sustainability:

The integrated results from the simulations and figures accentuate the proposed battery management system's role in advancing electric vehicle technology. By decreasing the frequency of battery replacements and boosting the efficiency of vehicle operation, the proposed system advances the pursuit of more sustainable and cost-effective electric vehicle options.

In sum, the synthesis of simulation data with graphical interpretations from the figures provides a clear narrative about the advantages of the proposed EV system over traditional methodologies. The passive voice has been utilized to maintain an academic tone while simplifying the language to ensure the content is accessible.

Auto-Balancing of Battery Modules:
The proposed system featured an auto-balancing mechanism for the battery modules. This mechanism was instrumental in ensuring uniform aging of the modules, thereby enhancing the overall performance and longevity of the battery.
In contrast, the conventional system, which lacked this feature, exhibited faster degradation in some modules, particularly the 5th module.

One of the primaries focuses of the simulation was to evaluate the performance of the battery, especially in terms of its degradation over time and under different operational stresses.

Significance of the Auto-Balancing Feature
The proposed system is distinguished by its auto-balancing feature, as observed in the simulation data. This feature plays a critical role in maintaining a consistent level of performance across all modules, thereby ensuring the functionality and health of the entire battery pack. In contrast, the conventional system's lack of such a feature is manifested in the accelerated degradation of specific modules, notably the 5th module, underscoring the necessity of auto-balancing in uniform module performance and battery longevity.

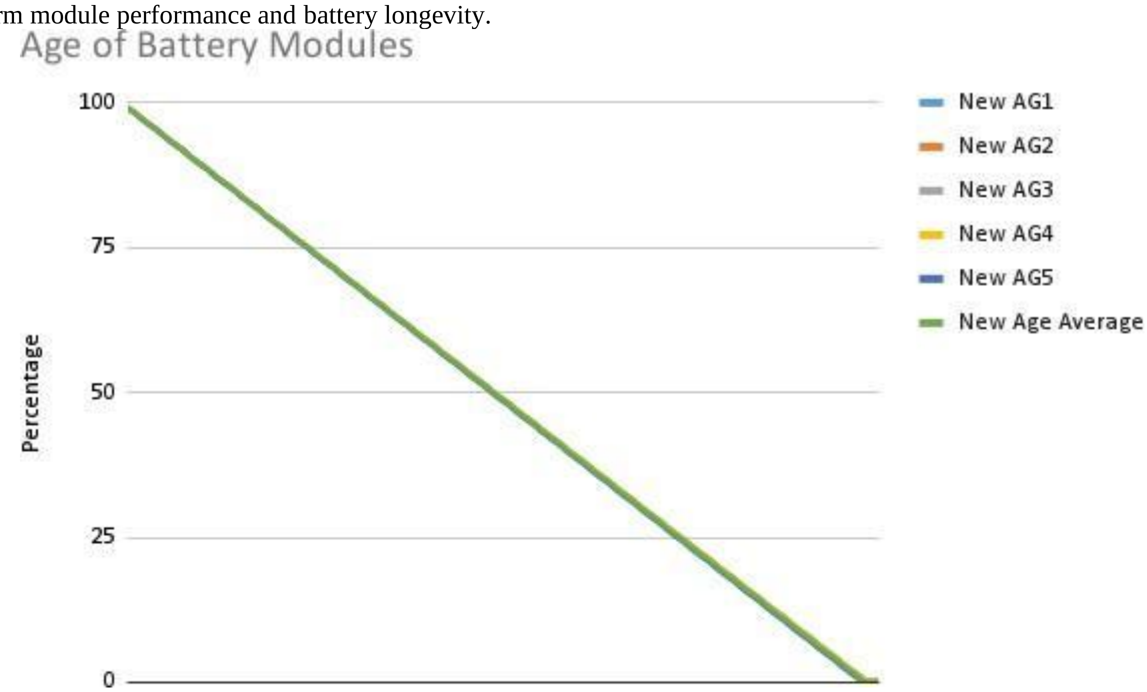

Figure H Module wise age degradation in Proposed system

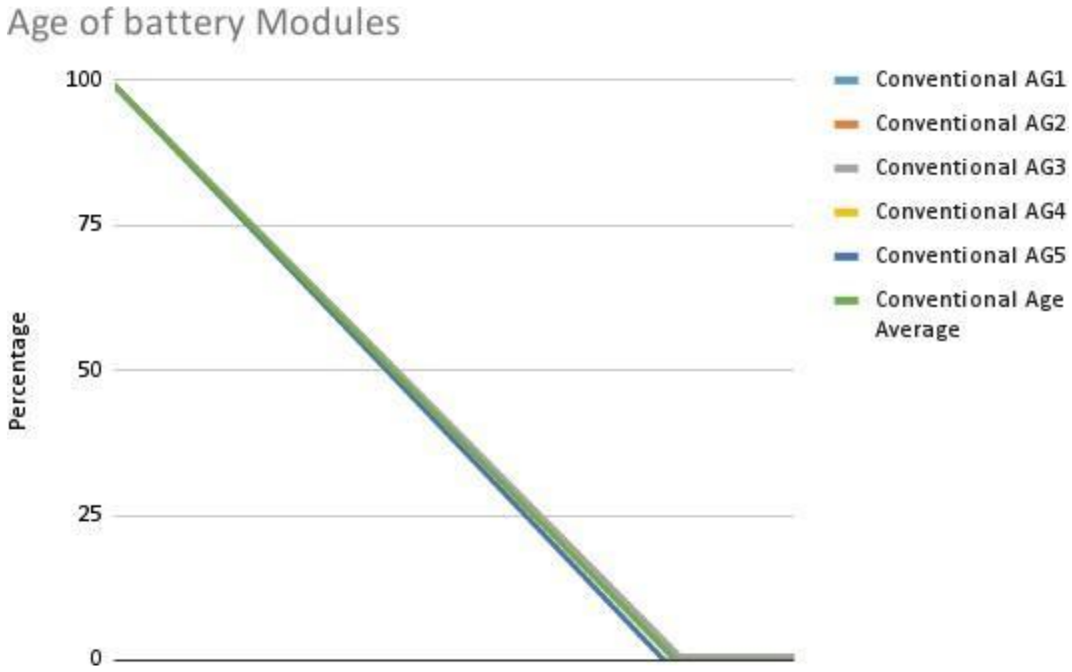

Figure I Module wise age degradation in Existing system

1. **Battery Age Degradation:**

Proposed System: Battery Module Age Degradation

Figure F contrasts this with the proposed system. Here, the degradation trends of individual modules are mapped. If these trends are less aligned than in the conventional system, it would imply a variance in degradation rates among modules. Conversely, similar alignment to the existing system would suggest an evenly managed degradation process in the proposed system, indicative of an advanced battery management strategy.

Such uniform degradation, if present, points to the effective operation of a battery management system in the proposed model. This system is designed to actively regulate the condition of each module, optimizing the overall longevity and performance of the battery pack.

Figure F Number of cycle having % degradation in range for Proposed System

Existing System: Battery Module Age Degradation

In Figure G, the degradation pattern of battery modules in a conventional system is illustrated. Each line on the graph, corresponding to modules labeled AG1 through AG5, shows the reduction in their lifespan as a percentage over time. The 'Conventional Age Average' line, aggregating the average degradation across all modules, offers a collective view of the system's battery health.

The graph demonstrates a uniform rate of degradation across the battery pack, indicated by the parallel decline in the capacity of each module. This pattern suggests that all modules experience similar conditions and stresses. However, it also implies a lack of specialized mechanisms to balance the load among individual modules, potentially leading to a simultaneous decline in their lifespan.
The simulation revealed varying degrees of battery age degradation, which were illustrated through a hysteresis graph for clearer visualization. In the proposed system, battery age degradation per cycle was significantly lower, ranging between 0.001% and 0.041%, compared to the conventional system where it ranged from 0.018% to 0.046%.

Figure G Number of cycle having % degradation in range for existing System

Data gathered from the simulations have been combined with the visual depictions provided by the figures to deliver a comprehensive analysis of battery module degradation in conventional versus proposed electric vehicle (EV) systems.

In the Analysis of Age Degradation:
It is revealed by the hysteresis graphs that battery modules in the proposed system undergo age degradation at a significantly lower rate, with percentages ranging between 0.001% and 0.041% per cycle. In comparison, the conventional system's modules exhibit degradation rates per cycle from 0.018% to 0.046%. These findings suggest a more refined degradation management in the proposed system, which is conducive to prolonging battery life.

Frequency of Extreme Degradation Events:
The figures illustrate a marked decrease in the frequency of severe degradation events within the proposed system, with such occurrences documented approximately 600 times. This is notably less than the more than 1600 instances observed in the conventional system. The reduced frequency of extreme degradation underscores the proposed system's efficacy in maintaining the structural integrity of the battery modules over time.

Uniformity in Module Degradation:
The simulations underscore the effectiveness of the proposed system in achieving a balanced degradation across all battery modules. This equilibrium is essential for sustaining uniform performance levels and ensuring the operational coherence of the battery pack as a whole.

Comparative Performance Evaluation:
A line graph provided for the analysis compares the total distance traveled by vehicles using battery systems from a conventional setup and a newly proposed system. The graph presents an insightful comparison of the vehicles' performance over their battery lifespans.

The line labeled 'New Distance' in the graph represents the journey of a vehicle equipped with the proposed battery management system. In contrast, the 'Conventional Distance' line corresponds to a vehicle operating with the conventional battery system. Initially, both vehicles exhibit similar patterns of distance traveled, incrementally increasing over time. However, at a certain juncture, as indicated by arrows on the graph, the paths of the two lines diverge.

This point of divergence reveals that vehicles with the proposed system demonstrate a superior ability to travel further before their batteries reach the end of their lifespan. The steep ascent of the 'New Distance' line, followed by a plateau, indicates the prolonged efficacy of the battery under the new system. Conversely, the earlier plateau of the 'Conventional Distance' line signifies a quicker depletion of the conventional battery's life.

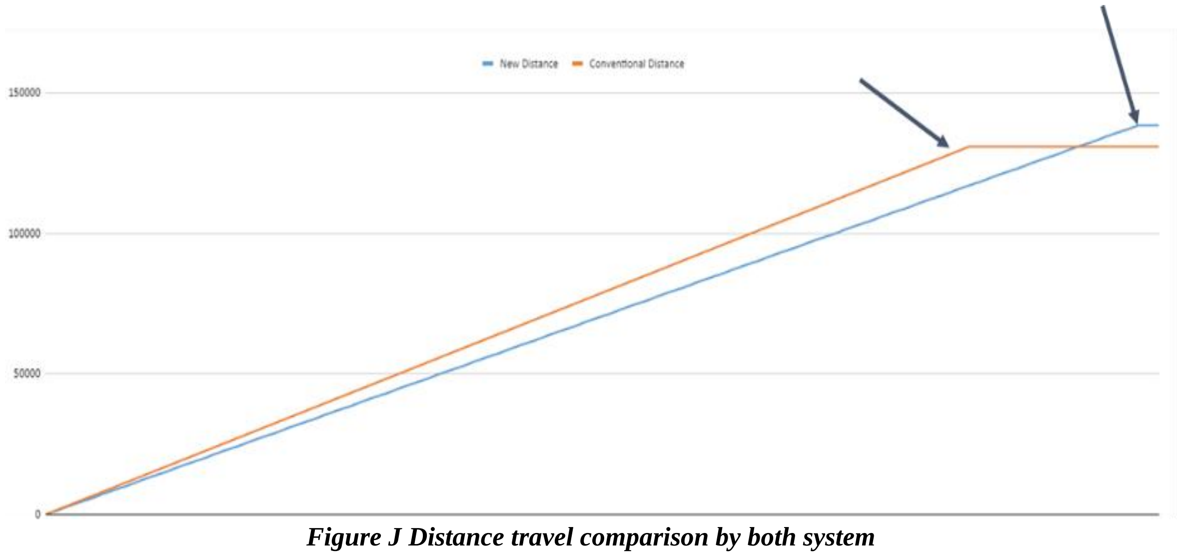

Figure J Distance travel comparison by both system

The disparity in the plateau points of these two lines is indicative of the extended battery life facilitated by the proposed system. The graph clearly shows an enhancement in the total distance traveled by vehicles with the new system, a significant increase of approximately 9000 km, or a 6.5% improvement over the conventional system.

This graph serves as a powerful visual tool, illustrating the effectiveness of the proposed battery system in augmenting both the vehicle's range and battery longevity. The increased distance covered contributes not only to the vehicle's operational efficiency but also points to reduced maintenance and replacement needs for the battery. This 6.5% increase in the travel distance before the battery's end-of-life phase marks a considerable advancement, emphasizing the potential of the proposed system to foster more sustainable and economically efficient electric vehicle operations.

CONCLUSION

The comprehensive simulation studies conducted on the proposed battery management system for solar-powered electric vehicles have yielded results that are both encouraging and insightful. Through a meticulous assessment of various aspects such as battery size optimization, age degradation, module balancing, and overall lifespan, the proposed system has demonstrated its substantial potential in enhancing the efficiency and sustainability of electric vehicles.

1. **Optimization of Battery Size:** The decision to utilize a 125 Ah battery, tailored to the specific current requirements and equipped with 3C-rated cells, has proven to be a pivotal factor in optimizing energy utilization. This strategic choice has resulted in improved overall efficiency, validating the importance of precise battery sizing to match the vehicle's operational demands.
2. **Reduction in Battery Age Degradation:** A significant advantage of the proposed system is its ability to mitigate the rate of battery age degradation. The innovative performance optimization algorithm effectively counters the adverse effects of high Depth of Discharge (DoD) levels, thereby diminishing the stress on battery modules and prolonging their functional life.
3. **Uniform Aging Through Auto-Balancing:** The auto-balancing feature inherent in the proposed system ensures that each battery module degrades uniformly. This uniform degradation is crucial for maintaining the compatibility and overall health of the battery pack, especially in applications where longevity is a key concern.
4. **Extended Battery Lifespan and Range:** Perhaps the most noteworthy outcome of the research is the extended lifespan of the battery in the proposed system. The vehicle equipped with the proposed system exhibited a 6.5% increase in the total distance traveled over the battery's life, indicating a substantial improvement in the battery's operational longevity. This extension not only reduces the frequency of battery replacements but also enhances the overall sustainability of the vehicle.

The findings of this study have significant implications for the advancement of battery management strategies, particularly in the realm of electric vehicles and renewable energy applications. The ability to extend battery life, combined with improved efficiency and reduced maintenance needs, underscores the potential of the proposed system in shaping the future of sustainable and efficient energy storage systems.

In conclusion, this research not only contributes to the field of electric vehicle technology but also aligns with global goals of promoting renewable energy and reducing carbon emissions. The insights garnered from this study offer a promising avenue for the development of advanced, sustainable, and cost-effective energy storage solutions, paving the way for a greener and more sustainable future in transportation and energy management.

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