

HEALTH-AWARE BATTERY FAST CHARGING STRATEGY USING ZONAL EQUIVALENT CIRCUIT MODEL

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TRIBOLOGY

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**HEALTH-AWARE BATTERY FAST
CHARGING STRATEGY USING ZONAL
EQUIVALENT CIRCUIT MODEL**

by

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Centre for Automotive Research and Tribology

submitted

in fulfillment of the requirements of **Doctor of Philosophy**

to the



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Dedicated to my Parents and Sister

Certificate

This is to certify that the thesis entitled “**Health-aware battery fast charging strategy using zonal equivalent circuit model**”, submitted by **Mr. Bibaswan Bose** to the Indian Institute of Technology Delhi, India for the award of the degree of **Doctor of Philosophy** in Centre for Automotive Research and Tribology, is a record of the original, bonafide research work carried out by him under our supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

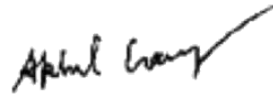
The results contained in this thesis have not been submitted in part or in full to any other university or institute for the award of any degree or diploma to the best of our knowledge.



09/05/2025

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A handwritten signature in black ink, written in a cursive style, that reads "Bibaswan Bose". The signature is enclosed within a thin, hand-drawn oval border.

Bibaswan Bose

Abstract

The long charging time of Li-ion batteries in comparison to ICEV (Internal Combustion Engine Vehicle) refuelling time is a barrier to the adoption of Li-ion-based EV. The electric vehicle industry believes that increasing the current rate (C-rate) will reduce charging time, but this increases the cell degradation rate. As a result, the need of the hour is to develop a health-aware battery fast charging strategy. Numerous research was conducted to develop an optimal charging algorithm, but the high complexity of the algorithms attracted fewer industries to adopt these strategies. The prevailing battery fast charging strategies employ open-loop charging, which leads to exponential degradation in battery health. EV battery chargers ought to generate tailored charging approaches to attain optimal efficiency, contingent upon the battery's condition. The aforementioned task is accomplished by utilizing a closed-loop battery charging mechanism. The health-aware battery fast charging (HABFC) methodology considers various degradation phenomena, such as temperature, lithium layer formation, and SEI layer formation, to accelerate the battery's charging process pack.

This work proposes the use of a zonal battery charging technique by providing a schematic layout for establishing a charging technique that increases the life of the battery pack. The closed-loop charging strategy has been realised by tracking the degradation using a robust cell model and dividing the charging phase into three zones, namely: pre-charging, boost charging and end charging. Thus, the project proposes the following contributions to achieve a robust HABFC. Firstly, the study introduces an innovative equivalent circuit model (ECM) for continuous battery condition monitoring during rapid charging cycles. By analysing anodic behaviour via diffusion coefficient and charge transfer resistance, it maps performance decline relative to the state of charge (SoC) to identify degradation causes. The proposed tri-zoned ECM (TZ-ECM) calculates solid phase diffusion dynamics and incorporates thermal, electrical, and aging characteristics into the thermo-electric ageing cell model (TEACM). Validated through cell cycling tests, the TEACM accurately predicts voltage (98.14%), current (97.95%), and aging (98.35%), demonstrating superior performance compared to benchmark methods. Secondly, the pre-charging strategies have been investigated. An electrochemical study demonstrates that

abruptly applying a high charging current to batteries induces an internal shock, resulting in suboptimal ion diffusion. The proposed method, pulse amplitude width modulation (PAWM), enhances ion excitation and diffusion during fast charging. Comparative analysis with established benchmark charging strategies shows that PAWM offers superior performance, improving ion diffusion efficiency.

Next, the boost charging strategies have been investigated, and the dual-step constant-current constant-temperature (DS-CC-CT) charging technique is proposed which addresses battery deterioration by managing thermal performance. It consists of two stages: charging at a constant current until a temperature threshold is reached, followed by charging at a controlled lower temperature. This process is repeated until a higher voltage threshold is met, effectively reducing degradation and extending battery lifespan. Compared to the 1C-CC-CV method, DS-CC-CT reduces cell charging time by 31% and increases cell cycle life by 66%. Finally, the study explores optimising the constant voltage (CV) phase by transitioning to CV mode at a low C-rate before reaching the voltage threshold limit. This method enhances ion passage, maximising charging capacity and extending cell longevity. Compared to the CC-CV method, it incurs a 4.22% increase in charging time but improves cell cycle life by 51.77%. Integrating this approach with pre-charging and boost charging makes the additional time negligible.

The results suggest that adopting the proposed method results in a decrease of 17.64% in charging duration and an improvement of 17.23% in the lifespan of the battery cycles compared to the conventional charging method. The proposed technique is validated by comparing results with benchmark charging strategies. The fast-charging rate, low battery degradation, and low complexity will facilitate faster industrial adaptation and encourage consumers to switch to EVs.

सार

आइसवी (आंतरिक दहन इंजन वाहन) की तुलना में ली-आयन बैटरी का लंबे समय तक चार्ज करने का समय, ली-ऑन-आधारित ईवी को अपनाने में एक बाधा है। इलेक्ट्रिक वाहन उद्योग का मानना है कि मौजूदा दर (सी-रेट) बढ़ाने से चार्जिंग में लगने वाले समय में कमी आएगी, लेकिन इससे सेल में गिरावट की दर बढ़ जाएगी। नतीजतन, समय की मांग है कि एक हेल्थ-वेयर बैटरी फास्ट चार्जिंग रणनीति विकसित की जाए। एक इष्टतम चार्जिंग एल्गोरिथ्म विकसित करने के लिए कई शोध किए गए, लेकिन एल्गोरिदम की उच्च जटिलता ने इन रणनीतियों को अपनाने के लिए कम उद्योगों को आकर्षित किया। मौजूदा बैटरी फास्ट चार्जिंग रणनीतियां ओपन-लूप चार्जिंग को नियोजित करती हैं, जिससे बैटरी के स्वास्थ्य में तेजी से गिरावट आती है। ईवी बैटरी चार्जर को बेहतर दक्षता प्राप्त करने के लिए टेल्ड चार्जिंग दृष्टिकोण तैयार करना चाहिए, बैटरी की स्थिति पर निर्भर रहना चाहिए। उपरोक्त कार्य एक बंद लूप बैटरी चार्जिंग तंत्र का उपयोग करके पूरा किया जाता है। हेल्थ-अवेयर बैटरी फास्ट चार्जिंग पद्धति बैटरी की चार्जिंग प्रक्रिया पैक को तेज करने के लिए तापमान, लिथियम लेयर फॉर्मेशन और एसईआई लेयर फॉर्मेशन जैसे विभिन्न क्षरण घटनाओं पर विचार करती है। इस कार्य में चार्जिंग तकनीक की स्थापना के लिए योजनाबद्ध लेआउट प्रदान करके एक जोनल बैटरी चार्जिंग तकनीक के उपयोग का प्रस्ताव है जो बैटरी पैक के जीवन को बढ़ाता है। क्लोज-लूप चार्जिंग रणनीति को एक मजबूत सेल मॉडल का उपयोग करके गिरावट को ट्रैक करके और चार्जिंग चरण को तीन क्षेत्रों में विभाजित करके महसूस किया गया है।

अध्ययन में त्वरित चार्जिंग चक्र के दौरान निरंतर बैटरी स्थिति निगरानी के लिए एक अभिनव समतुल्य सर्किट मॉडल (ईसीएम) पेश किया गया है। प्रसार गुणांक और चार्ज ट्रांसफर प्रतिरोध के माध्यम से एनोडिक व्यवहार का विश्लेषण करके, यह गिरावट के कारणों की पहचान करने के लिए प्रभारी राज्य (एसओसी) के सापेक्ष प्रदर्शन गिरावट का मानचित्र करता है। प्रस्तावित ट्राइ-जेडएन ईसीएम ठोस फेज डिफ्यूजन डायनामिक्स की गणना करता है और थर्मो-इलेक्ट्रिक एजिंग सेल मॉडल में थर्मल, इलेक्ट्रिकल और बुढ़ापे की विशेषताओं को शामिल करता है। सेल साइक्लिंग परीक्षणों के माध्यम से मान्य, टीईटीएम ने सटीक ढंग से वोल्टेज (98.14%), वर्तमान (97.95%), और वृद्धावस्था (98.35%) की भविष्यवाणी की है, जो बेंचमार्क विधियों की तुलना में बेहतर प्रदर्शन प्रदर्शित करता है। एक इलेक्ट्रोकेमिकल अध्ययन से पता चलता है कि बैटरी में हाई चार्जिंग करंट लगाने से एक आंतरिक झटका लगता है, जिसके परिणामस्वरूप सब ऑप्टिमल आयन प्रसार होता है। प्रस्तावित विधि, पल्स आयाम चौड़ाई मॉडुलन (पीएडब्ल्यूएम), तेज चार्जिंग के दौरान आयन उत्तेजना और प्रसार को बढ़ाता है। स्थापित बेंचमार्क चार्जिंग रणनीतियों के साथ तुलनात्मक विश्लेषण से पता चलता है कि पीएडब्ल्यूएम बेहतर प्रदर्शन प्रदान करता है, आयन प्रसार दक्षता में सुधार करता है।

डुअल-स्टेप निरंतर-तापमान (डीएस-सीसी-सीटी) चार्जिंग तकनीक थर्मल प्रदर्शन के प्रबंधन द्वारा बैटरी की गिरावट को दूर करती है। इसमें दो चरण होते हैं: तापमान सीमा तक पहुंचने तक एक स्थिर धारा पर चार्ज करना, उसके बाद नियंत्रित निम्न तापमान पर चार्ज करना। इस प्रक्रिया को तब तक दोहराया जाता है जब तक एक उच्च वोल्टेज सीमा पूरी नहीं हो जाती है, प्रभावी रूप से गिरावट को कम करते हुए और बैटरी जीवनकाल को विस्तारित करते हैं। 1 सीसी-सीसी-सीवी पद्धति की तुलना में, डीएस-सीसी-सीटी सेल चार्जिंग समय को 31% कम करता है और सेल चक्र जीवन को 66% तक बढ़ाता है। अध्ययन वोल्टेज सीमा तक पहुंचने से पहले कम सी-रेट पर सीवी मोड में संक्रमण करके निरंतर वोल्टेज (सीवी) चरण को अनुकूलित करने का प्रयास करता है। यह विधि आयन मार्ग को बढ़ाती है, चार्जिंग क्षमता को अधिकतम करती है और कोशिका लंबी आयु का विस्तार करती है। CC-CV पद्धति की तुलना में, यह चार्जिंग समय में 4.22% वृद्धि करता है, लेकिन सेल चक्र जीवन को 51.77% तक बढ़ाता है। प्री-चार्जिंग और बूस्ट चार्जिंग के साथ इस दृष्टिकोण को एकीकृत करने से अतिरिक्त समय नगण्य हो जाता है। परिणाम बताते हैं कि प्रस्तावित पद्धति को अपनाने से चार्जिंग अवधि में 17.64% की कमी आई है और पारंपरिक चार्जिंग पद्धति की तुलना में बैटरी चक्रों के जीवनकाल में 17.23% की सुधार हुआ है। प्रस्तावित तकनीक को बेंचमार्क चार्जिंग रणनीतियों के साथ परिणामों की तुलना करके मान्य किया गया है। फास्ट-चार्जिंग दर, कम बैटरी गिरावट और कम जटिलता से तेजी से औद्योगिक अनुकूलन में मदद मिलेगी और उपभोक्ताओं को इलेक्ट्रिक वाहन अपनाने के लिए प्रोत्साहित किया जाएगा।

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Abbreviations

Abbreviation	Abbreviation full form
EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicles
SEI	Solid Electrolyte Interphase
SoH	State of Health
BMS	Battery Management System
CEI	cathode electrolyte interphase
LAM	Loss of Active Material
IG	Impedance Growth
LLI	Loss of Lithium Inventory
C-rate	Charging rate
NMR	Nuclear Magnetic Resonance
XRD	X-Ray Diffraction
NFR	Non-linear frequency response
AC	alternating current
DC	direct current
DCFC	DC fast charging
CHAdEMO	CHArge de Move
CCS	Combined Charging System
SoC	State-of-Charge
SAE	Society of Automotive Engineers
PHEV	Plug-in hybrid electric vehicles
WPT	Wireless power transfer
SOA	safe operating area
ECM	equivalent circuit model
TZ-ECM	tri-zoned ECM

TEACM	Thermo-Electric Ageing Cell Model
CC	constant current
CV	constant voltage
CP	constant Power
MCC-CV	Multistep CC-CV
PSO	Particle Swarm Optimization
GA	Genetic Algorithm
CT	Constant Temperature
PID	Proportional-Integral-Derivative
PC	Pulsed charging
NP	Negative Pulse
CDC	Continuous Direct Current
PWM	Pulse Width Modulation
PAM	Pulse Amplitude Modulation
VCP	Variable Current Profile
PDE	partial differential equations
FOM	full order model
ROM	reduced order model
SP2D	simplified Pseudo-2-Dimension
HABFC	health-aware battery fast charging
BC	Boost Charging
DAq	Data Acquisition
GaN	gallium nitride
GITT	galvanostatic intermittent titration technique
GEIS	galvanostatic electrochemical impedance spectroscopy
EIS	electro-impedance spectroscopy
IR	Internal Resistance
R _{ct}	charge transfer resistance
R _{ser}	series resistance
C _{dl}	double-layer capacitance
1RC	First-order resistance Capacitance Model
2RC	Second-order resistance Capacitance Model
PAWM	Pulsed Amplitude Width Modulation
MSCCCTCV	multistep constant-current constant-temperature constant-voltage
SSCCCTCV	Single step constant-current constant-temperature constant-voltage

DSCCCTCV	Dual step constant-current constant-temperature constant-voltage
TSCCCTCV	Triple step constant-current constant-temperature constant-voltage
QOGA	Quad Objective GA
FLC	Fuzzy Logic Controller
MF	membership functions
SW	Switchover point