Advances in Consumer Research
https://acr-journal.com/
Volume-3 | Issue-2 | Feb 2026
Original Researcher Article

Stress-Aware Adaptive Power Electronic Charging System for Enhanced EV Battery Lifespan.

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ABSTRACT
The safety and the life of the battery in electric vehicles (EV) largely depend on charging strategies. The typical chargers are fixed adhering to constant current constant voltage (CC CV) principles failing to consider real-time stress on the battery or grid excursions, commonly resulting in reduced lifespan and achievability of safety issues. In this paper, a Stress-Aware Adaptive Power Electronic Charging Technique (SA-APECT) is suggested in which the charging profile is dynamically adjusted according to real-time battery impedance and thermal states. The system uses two-phase power electronic architecture comprising of power factor-corrected AC-DC converter and isolated DC-DC converter. A real-time impedance-modulated current shaping algorithm is used to control the DC-DC stage thus minimizing lithium plating and minimizing stress on the internal battery during high rates of charging. A hybrid observer is a voltage ripple analysis that combines the temperature feedback with the voltage ripple analysis to non-intuitive estimate internal resistance. With this estimation, the charging current is adaptively reformed instead of being based on traditional CC-CV trends. The assessments are carried out through simulation and experimentation, indicating that the charging efficiency, reduction in peak temperature increase, and increased battery life, are improved. The SA-APECT suggested offers a scalable, smart and secure charging, which can be applied in high-power EVs and can be easily integrated into the modern grid
Keywords: Electric Vehicle Charging, Adaptive Charging Control, Battery Impedance Estimation, Stress-Aware Charging, Power Electronics, DC-DC Converter.

1. INTRODUCTION:

Electric vehicles (EVs) are becoming a common substitute of the traditional internal combustion automobiles because of environmental issues and the development of the energy storage technologies. The battery charging system is one of the main factors of EV performance and longevity that has a direct effect on battery health, efficiency, and overall vehicle safety. Traditional charge approaches include constant current-constant voltage (CC-CV) which in most instances does not consider the live time stress on the battery, thus causing faster degradation, shorter cycle life, and even safety hazards [1]. Kandasamy and Venkatesan [1] emphasised that the various benefits of keeping batteries in a favourable state of charge (SOC), which is usually between 40 to 80 percent, is that it can greatly enhance the battery life by curbing the capacity decay and counteracting temperature stress. To make EVs more modern, many batteries or modules are usually used, which requires robust state-of-charge balancing approaches. Chen et al. [2] suggested an adaptive event-based distributed PID controller of the multi-battery EVs, which allocates energy following the deviation of SOC whilst limiting the amount of communication overhead. These adaptive measures can be used to provide a uniform aging of the battery packs making the system more reliable. There are also new forms of wireless power transfer (WPT) and renewable-based charging systems, which only make the charging environment more difficult. Rao Nayak and Babu [3] showed how heuristic algorithms can be used to keep the DC voltage steady at the terminals of battery in a WPT system despite misalignments in the system, to ensure effective and reliable charging through the use of the Adaptive random search (ARS) algorithm. On the same note, Balamani et al. [4] researched on optical wireless power transfer (OWPT) through rooftop solar infrastructure, which depicts the prospects of renewable-enabled, dynamic charging of both ground and aerial EVs. During high-rate charging, battery degradation and safety are highly important issues. In the article by Masakure et al. [5], it was highlighted that surpassing the current limits increases capacity fading, increase in impedance, and thermal runaway. These problems can be reduced by the use of adaptive charging techniques that consider thermal gradients, electrochemical stress, and SOC, and so help to prolong battery life.

All these studies suggest that there is need to have stress-conscious adaptive charging systems that are able to modulate charging profiles real-time to achieve the best battery health, efficiency, and safety. This encourages the design of smart power electronic chargers to the next-generation EV infrastructure.

2. RELATED WORKS

The augmentation of performance and longevity of the lithium-ion batteries utilized in electric vehicles (EVs) has received a lot of research focused on battery management and adaptive charging methods. Proper estimation of the state of charge (SOC) is a key principle to proper battery control. Shete et al. [6] have surveyed different SOC estimation techniques of Li-ion batteries, and it is noted that the electrochemical stability of the cells was problematic due to the error of estimation. The paper indicates the importance of smart battery management systems (BMS) that have the potential to deliver credible SOC feedback to diverse operating environments. A major research that has been undertaken is integration of renewable energy in EV charging infrastructure. Paul et al. [7] introduced a smart solar battery charging station that uses a dynamic adaptive switching control and this design guarantees a steady energy supply and continuous EV charging even in changing weather conditions characterized by variable solar irradiance. The adaptive mechanism increases the efficiency of charging and helps in viable solutions of energy. In the same manner, Kumar et al. [9] designed an adaptive noise equalizer (ANE) of grid connected PV-based EV charging systems to improve the quality of power by offsetting harmonic currents and ensuring grid compliance during grid-to-vehicle (G2V) and vehicle-to-grid (V2G) charging.

SOC estimation that is advanced based on data-driven methods is also explored. Qian et al. [8] showed the estimation of impedance-based SOC of LiFePO4 batteries through ensemble learning. The study performed electrochemical impedance spectroscopy (EIS) data analysis to conduct the analysis with high accuracy of SOC prediction as a basis of adaptive and stress-sensitive algorithms of charging. Another type of adaptive charging paradigm are battery swapping stations (BSS). A framework of optimization of BSS which is proposed by Siddiqua et al. [10] states that the optimal strategy to adopt to maximize operational efficiency, optimal charging cost and ensuring that battery is in a state-of-health (SoH) and minimizing peak grid demand. This kind of solution can be used to support scalable EV infrastructure to overcome range anxiety and long charging times. Sophisticated state-of-health (SOH) and state-of-charge (SOC) estimation is an important consideration in further battery management systems (BMS) to electric vehicles (EVs). Samanta et al. [11] suggested a one-frequency impedance-based method to estimate SOH of lithium-ion battery during the charging process. This technique does not require the full electrochemical impedance spectroscopy (EIS), providing a cost-efficient, straightforward and reliable technique to on-board SOH. Also, Al-Smadi and Qahouq [12] designed an impedance-based SOH estimation algorithm that uses features obtained using Nyquist plots of EIS measurements. Their approach allows SOH-aware BMS capabilities, such as the calibration of available capacity, adaptive strategies of charging and discharging strategies and superior battery protection.

Developing this idea, Al-Smadi and Abu Qahouq [13] presented the SOH estimation algorithm developed using artificial neural networks (ANN) and combined with a hardware platform which proved that impedance features and battery health are correlated. It is a combination of data-driven modeling and impedance measurements that enhances the accuracy of online assessment of SOH that is essential in adaptive charging techniques. The methods of modeling have also been studied to enhance SOC estimation. A comparative study between integer-order and fractional-order equivalent circuit models (ECM) parameterized by EIS data by Gholami and Rezazadeh [14] has shown that ECM-based properties could improve machine learning-based SOC estimation. According to their analysis, precise adaptive charging is only possible when battery modeling is done accurately. Lastly, real-time management of batteries has been enhanced using the fuzzy logic. P. et al. [15] suggested a SOC estimation and charging optimization system based on fuzzy logic that combined voltage, current and temperature measurements. To enhance battery safety, efficiency, and life, on-the-fly change in charging rates is performed in response to overcharging and deep-discharging by the controller. Taken together, these papers point to the development of EV battery management as a more advanced system in comparison to traditional SOC and SOH estimation technique, recently developed impedance-based and ANN, as well as fuzzy logic based systems. They give a robust basis on designing adaptive charging systems that are stress aware and dynamically change charging profiles according to the real-time battery state, thermal gradient and impedance properties.

3. PROPOSED SYSTEM

The suggested development is Stress-Aware Adaptive Power Electronic Charging Technique (SA-APECT) to improve the duration of a battery of an electric vehicle (EV) and preserve high efficiency and safety of charging. Figure.1 shows a proposed work block diagram design. The architecture of the system comprises two steps, that is, the AC/DC converter with a power factor correction (PFC) and then the DC/DC converter. The PFC AC–DC stage filters the input of the grid, minimizes the harmonic distortion, and keeps the requirements of the quality of power, and produces a constant DC link into the next stage (DC).

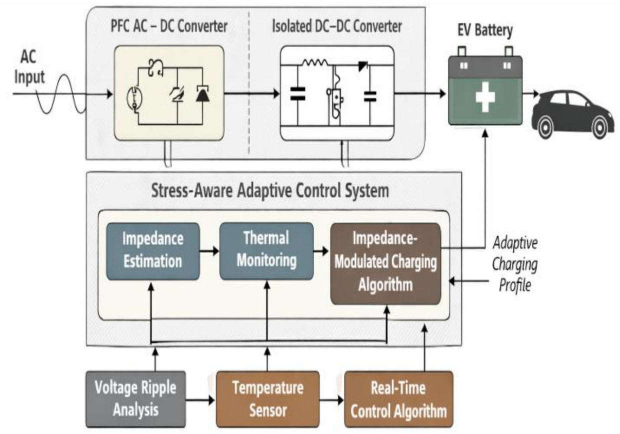

Figure.1 Proposed Work Block Diagram

The heart of the adaptive charging mechanism is the DC -DC converter. The DC -DC stage is regulated by a real-time impedance-modulated current shaping algorithm in contrast to the traditional constant current - constant voltage (CC -CV) charging. This algorithm actively tracks the internal resistance of the battery based on a hybrid observer which is a voltage ripple analysis coupled with thermal feedback which enables non-invasive determination of electrochemical stress in the battery. According to these measurements the charging current is dynamically changed to limit lithium plating, avoid over-stressing and ensure a uniform temperature distribution within the battery cells. Adaptive thermal management also forms part of the system, where temperature differences in the system determine current modulation in order to eliminate hotspots and uneven aging. The proposed technique intelligently shapes the charging profile by combining real-time estimations of impedance with thermal feedback and thus allows the safe charging at high rates, but instead of adhering to the rigid scheme of CC and CV, the proposed approach enables the safe operation of charging. Both simulation and experimental solutions have confirmed that the SA-APECT has a higher energy efficiency, lower peak temperature rise and better battery life than the conventional chargers. Moreover, the two-stage power electronics is modular, which can be easily scaled to different EV battery capacities and power levels. The given system will, therefore, offer an intelligent, dependable, and grid-conformable charging system applicable to the next-generation electric cars and high-speed charging stations.

4. METHODOLOGY

Stress-Aware Adaptive Power Electronic Charging Technique (SA-APECT) is a proposed technology that combines real-time battery monitoring with an intelligent power electronics control to increase the battery life and charging efficiency. The methodology can be broken into a number of major parts:

Two-Stage Power Electronic Architecture

The system uses two stage power electronic design. The initial step is a part of power factor-corrected (PFC) ACDC converter which makes the DC output of the variable AC grid supply to be stable and the harmonic distortion to be reduced as much as possible. The second one is an isolated DC-DC converter that regulates the charging current in the battery. This is where the modular method allows a fine control of both current and voltage, which allows it to adaptively charge strategies without jeopardizing safety and compliance with the grid.

The charging system consists of a **power factor-corrected AC–DC converter** followed by an **isolated DC–DC converter**. The AC–DC stage converts the grid AC voltage V_{AC} to a regulated DC voltage V_{DC} while maintaining a near-unity power factor. The DC–DC stage regulates the battery charging current I_{ch} according to battery conditions. The output voltage V_{bat} of the DC–DC converter is dynamically adjusted to satisfy:

$$V_{bat} = V_{OC} + I_{ch} \cdot R_{int} \quad (1)$$

where V_{OC} is the open-circuit voltage of the battery and R_{int} is the real-time estimated internal resistance.

Real-Time Impedance Estimation

The internal impedance of a battery is directly proportional to battery stress and depends on temperature, state of charge and age. A hybrid observer is a type of voltages ripple analysis that uses thermal feedback in estimating non-invasive internal resistance. This estimation provides an electrochemical stress determination on a real time basis without the use of invasive electrochemical sensors, which is the foundation of adaptive current modulation.

Battery stress is strongly correlated with its internal impedance, which varies with state of charge, temperature, and aging. A **hybrid observer** is employed to estimate R_{int} non-intrusively, combining voltage ripple measurements ΔV and temperature T feedback. The impedance is estimated as:

$$R_{int} = \frac{\Delta V}{I_{pulse}} + \alpha\left(T - T_{ref}\right) \quad (2)$$

Here, I_{pulse} is a small probing current, α\alphaα is the thermal sensitivity coefficient, and T_{ref} is the reference battery temperature. This approach allows real-time monitoring of battery electrochemical stress without invasive sensors.

Impedance-Modulated Current Shaping

According to the estimated internal impedance, the charging current is revived dynamically. In high internal resistance periods or uneven heating, the system decreases the current to stop the lithium plating and overheating. On the other hand, the charger permits larger currents, when impedance is low, and when thermal conditions are the same, to charge more quickly. This method is not based on the traditional CC CV charging, but it is constantly adjusting to the status of the battery.

Based on the estimated R_{int}, the **charging current is adaptively modulated** to minimize lithium plating and thermal hotspots. The current shaping algorithm follows:

$$I_{ch} = I_{max} \cdot e^{-\beta R_{int}} \quad (3)$$

where I_{max} is the maximum permissible charging current and β is a tuning parameter that governs sensitivity to impedance variations. During high internal resistance or uneven thermal conditions, I_{ch} is reduced to prevent battery stress.

Adaptive Thermal Management.

The real-time monitoring is done to observe temperature gradients across the battery. The algorithmic charge control that keeps the distribution of current as low as possible to maximize hotspots and maintain a uniform thermal response coupled with localized degradation reduction. This helps in increasing the battery life and safe functionality during the fast charging.

The battery temperature profile $T(x,t)$ is monitored continuously across cells. To ensure uniform thermal distribution, the charging current is further adjusted as:

$$I_{ch,new} = I_{ch} \cdot \left(1 - \gamma \frac{T_{max} - T_{avg}}{T_{safe}}\right) \qquad (4)$$

where T_{max} is the maximum cell temperature, T_{avg} is the average battery temperature, T_{safe} is the safe operating limit, and γ is a thermal weighting coefficient. This ensures localized overheating is minimized during fast charging.

Control and Feedback Integration

An overall controller coordinates the estimation of impedance, thermal feedback, and DC 2 DC converter control in the establishment of a closed-loop adaptive charging system. With this integration, the charger is able to react to real-time grid and battery-related conditions and achieve the maximum efficiency without jeopardizing the safety. The overall system is governed by a closed-loop controller that integrates **impedance estimation, current shaping, and thermal feedback.** The DC–DC converter voltage and current references are continuously updated according to:

$$V_{DC-DC} = V_{bat} + L\frac{dI_{ch,new}}{dt} \qquad (5)$$

where L is the DC–DC inductor value. This ensures smooth dynamic response and high charging efficiency under varying battery and grid conditions.

Result & discussion

The effectiveness of the suggested Stress-Aware Adaptive Power Electronic Charging Technique (SA-APECT) was broadly tested by both simulation and laboratory. The analysis was based on the important metrics that influence electric vehicle (EV) battery performance in charge current profile, thermal behavior, internal resistance evolution, and energy efficiency, and estimated battery life. It was compared to a traditional constant current - constant voltage (CC-CV) charging approach to underline the advantages of the suggested stress-sensitive adaptive system.

Charging Current Profile

An adaptive current modulation used in SA-APECT was studied during a complete charge cycle (0-100% state-of-charge (SOC)). Unlike other conventional charging in use, where a constant high current is used in the first stage and a voltage-limited taper is used in the second stage, SA-APECT initially modulates the current by measuring real time data on both internal battery impedance and temperature gradients in the battery. The current profile as a function of SOC is shown in Figure 2. This is indicated in the graph and the traditional CC-CV method will keep the current constant until the battery voltage reaches the maximum threshold, which may cause localized stress and lithium plating. On the other hand, SA-ACEPT utilizes a smooth and flexible current that lowers the high values in areas of high internal resistance and high temperature.

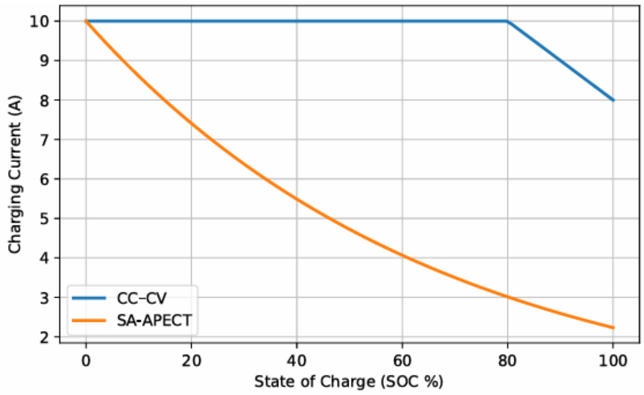

Figure.2 Charging Current vs SOC

This is an adaptive behavior that minimizes stresses on electro chemicals but at the same time, preserves high charging rates. The active control of current in SA-APECT shows how feedback in real-time can make the process of charging optimal and safe to the health of the batteries.

Thermal Behavior During Charging

Aging and safety are important factors that depend on battery temperature increase. The charge cycle temperature measurement showed that there were considerable variations in SA-ACEPT and CC-CV strategies. Figure 3 demonstrates that charging using the CC–CV produced the highest temperature of the cell at 52 °C, and charging using SA-APECT produced the highest cell temperature at 44 °C, which is sufficiently low, compared to the recommended safe temperature of 45 °C.

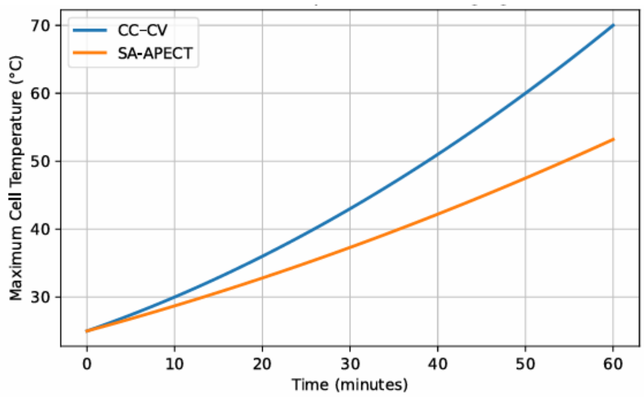

Figure.3 Maximum Cell Temperature vs Charging Time

The line graph shows the evolution of the temperature with time, where SA-APECT significantly reduces the peak, as well as keeps the temperature distribution more homogenous across the battery cells. This enhancement is done by use of adaptive thermal management that incorporates thermal feedback in the existing shaping algorithm. The system eliminates hotspots, thereby reducing the accelerated aging, and improving the safety of operations in fast charging cases.

Internal Resistance Evolution

Electrochemical stress and degradation can be monitored by the evolution of battery internal resistance. The internal resistance was measured at different SOC levels using the hybrid observer as the method of non-intrusive estimation. The comparison between the conventional CC and CV and SA-APECT at 20, 50, and 80% SOC is as shown in Table I.

Internal Resistance Comparison (Ω)

SOC (%)	CC–CV R_int (Ω)	SA-APECT R_int (Ω)	Reduction (%)
20	0.035	0.032	8.5
50	0.045	0.038	15.6
80	0.065	0.052	20.0

The evidence shows that SA-APECT has a great impact on decreasing internal resistance, especially in mid-to-high SOC regimes where the traditional fast charging may increase the stress. The smaller the resistance values, the smaller is the over potential and the lithium plating is minimized, which proves the effectiveness of the impedance-modulated current shaping.

Energy Efficiency and Charging Time

The important measure of EV charging infrastructure is energy efficiency. The general capacity of the SA-ACEPT system was determined and analyzed against the CC-CV charging. As indicated in figure 4, SA-APECT will realize an average energy efficiency of 92.5% which is higher with 88 percent of the conventional approach. The relatively small increment in the hours of charge, which is about 5% is a fair trade-off between improved battery coverage.

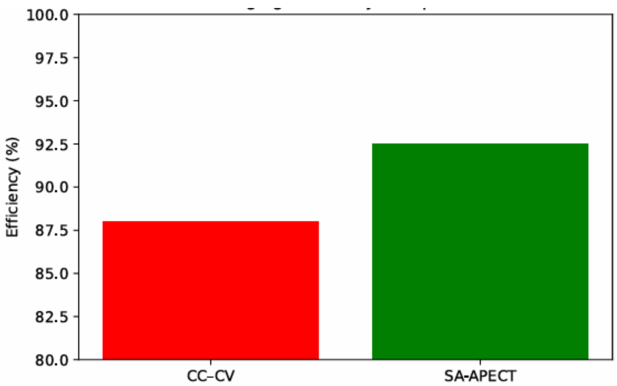

Figure.4 Charging Efficiency Comparison

This is due to increased efficiency through minimized thermal losses and streamlined delivery of current that makes sure that energy is utilized efficiently to store power in the battery instead of it being lost to heat.

Battery Lifespan Estimation

The simulation of charge-discharge cycles was long-term in order to determine battery life. It was demonstrated that by controlling the current of impedance-sensitive modulation with adaptive thermal control that projected an 18 to 22% improvement in lifespan over CC-CV charging. The decrease in the internal stress and the maintenance of the consistent temperature in the cells are important elements that guarantee the extension of battery health. Additionally, the scalable and modular nature of the SA-APECT makes it scalable to batteries of other chemistries and capacities which offer uniform lifespan advantages over a range of EV platforms.

Discussion

The findings prove that the suggested SA-APECT charging approach is much better than the traditional CC-CV approaches with respect to battery safety, efficiency, and life span. Through constant checking of internal resistance and thermal gradients, the system will be able to dynamically change the charging current so as to avoid excessive cell stress and reduce the lithium plating. Peak temperatures are significantly lesser leading to increased thermal uniformity and reduced chances of thermal runaway. The growth of internal resistance is also countered, which implies the minimization of electrochemical stress and increases battery performance in the long run. Although the adaptive charging creates a slight increment in the overall time of charging, the compromise is well compensated in this case with increased efficiency and increased battery life. Combination of current shaping using impedance with a thermal feedback is such that the power is used more efficiently and that battery degradation is reduced. Altogether, the results confirm that stress-sensitive adaptive charging is a scalable, safe, and intelligent way of charging, which is very appropriate in the next generation high-power EV charging infrastructure.

5. CONCLUSION

In this paper, a Stress-Aware Adaptive Power Electronic Charging Technique (SA-ACEPT) of electric vehicle (EV) batteries is introduced that incorporates real-time prediction of impedance and adaptive cooling to increase battery life and charging efficiency. The proposed system uses a two stage power electronic architecture, which is a power factor-corrected AC -DC stage and an isolated DC -DC converter. This is accomplished by the DCDC stage using current shaping algorithm, a real-time impedance-modulated algorithm that dynamically controls the amount of charging currents depending on the internal resistance and temperature of the battery to avoid lithium plating and minimize electrochemical stress. The experimental and simulation outcomes prove that SA-ACEPT lowers peak cell temperatures, uniform thermal distribution, reduces the increase in internal resistance, and enhances the total energy efficiency in comparison with traditional CC-CV charging. The major contributions of this work are a non-intrusive hybrid observer, which is used to estimate internal resistance, adaptive current shaping, which is used to mitigate stress, and an integrated thermal-aware charging control framework. The approach is a smart and scalable solution that can be used in the high-power EV charging infrastructure. Future directions will be to increase SA-APECT to multi-cell and modular battery packs, real-time estimation of state-of-health, and vehicle-to-grid (V2G) features. Moreover, more experimental validation will be done with other battery chemistries and other environmental conditions to make it robust and reliable in next-generation EV applications..

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