Effect of the Depth of Discharge and C-Rate on Battery Degradation and Cycle Life

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Abstract

The performance and durability of rechargeable batteries are paramount in a wide range of contemporary applications. Depth of Discharge and C-Rate are pivotal factors in battery degradation. Deeper discharges and rapid charge/discharge rates subject batteries to increased stress, accelerating their wear and capacity loss. Understanding and carefully managing these factors are vital for extending battery lifespan and improving the performance of electric vehicles and renewable energy systems. This research delves into the complex interaction between Depth of Discharge and C-Rate, providing insights into their individual and combined effects on battery performance and aging mechanisms. By examining Depth of Discharge and C-Rate, this study offers valuable perspectives on the compromised energy storage capacity and long-term robustness. The simulation results demonstrate that elevated Depth of Discharge and C-Rate can expedite battery degradation while presenting prospects for customized applications through the careful equilibrium of energy demands and longevity.

1. Introduction

Batteries have become ubiquitous daily, powering an ever-expanding range of devices and applications. From portable electronics to electric vehicles and renewable energy storage, they are integral to the functioning of modern society [1]. However, batteries' performance and lifespan remain critical, and longer-lasting, more sustainable energy solutions are strived for [2]. Among the multitude of factors that influence battery degradation and lifetime, two critical parameters rise to prominence: Depth of Discharge (DoD) and C-Rate. These factors hold paramount importance in the batteries because of direct impact to the chemistry of the battery [3].

DoD is a fundamental metric to quantify how much a battery's stored energy is utilized during a single charge-discharge cycle. It is typically expressed as a percentage of the battery's total capacity [4]. DoD holds a critical position in the realm of battery technology due to its direct influence on the stress experienced by the battery during its operation. When a battery is discharged to higher DoD levels, it undergoes more pronounced chemical and physical changes. This heightened stress can expedite the degradation processes, making DoD a pivotal factor in assessing and managing battery lifespan [5]–[7].

To ensure the longevity and reliability of batteries in various applications, it is essential to choose DoD levels carefully. By avoiding deep discharges and operating within recommended DoD limits, it is possible to mitigate the detrimental effects of high DoD and extend the useful life of batteries [8]. This emphasizes the significance of DoD as a critical parameter in the design and utilization of energy storage systems [9].

The C-Rate defines the rate at which a battery undergoes charging or discharging relative to its capacity [10]. The C-Rate is a crucial factor in battery technology, significantly influencing battery performance and durability as it governs the pace of internal chemical reactions. When the C-Rate is elevated, signifying a rapid charging or discharging process, it can potentially introduce challenges to the battery's long-term health. The increased rate of energy transfer within the battery can lead to heightened heat generation and mechanical strain, factors that can, in turn, accelerate the battery's degradation [11], [12].

The management of the C-Rate is of paramount importance in applications where battery lifespan and reliability are essential. In fields such as electric vehicles and portable electronics, where rapid charging and discharging are prevalent, advanced thermal management and control systems are often employed to counteract the adverse effects of elevated C-Rates [13]. By maintaining control over the C-Rate, these systems help safeguard the battery, optimize its performance, and extend its operational life, making it a pivotal consideration in developing and using battery-powered technologies across diverse sectors [14].

This paper intends to investigate the complex interplay between DoD and C-Rate, along with their collective impact on battery degradation and lifespan. Obtaining insights into this interrelationship is essential for improving battery utilization. The simulation results reveal the fundamental mechanisms behind battery degradation and elucidate the specific roles played by DoD and C-Rate in these processes. In conclusion, this comprehensive examination of the impact of DoD and C-Rate on battery degradation and lifetime promises to provide valuable insights towards optimizing battery utilization in various applications.

2. Material and Methods

Battery aging is a complex process influenced by a multitude of parameters. These include factors such as DoD, C-Rate, temperature, cycle count, and the specific chemistry of the battery. Understanding and managing these parameters is essential for prolonging battery life and maintaining optimal application performance.

2.1. Depth of Discharge

DoD measures how much of a battery's stored energy is utilized during a single charge-discharge cycle, expressed as a percentage of the battery's total capacity. In simpler terms, it quantifies how much a battery's potential is harnessed within a single cycle. High DoD levels, where a battery is deeply discharged before recharging, can significantly accelerate degradation processes. One of the critical factors impacted by DoD is the complex electrochemical reactions occurring within a battery's cells. High DoD can lead to more extensive and intense chemical reactions, causing changes in the internal structure and chemistry of the battery materials. These changes, over time, contribute to the gradual loss of capacity and a reduction in the battery's cycle life [8]. Another critical aspect affected by high DoD is heat generation. When a battery is discharged to a high DoD level, there is an elevated current flow, resulting in increased heat production. This excess heat can lead to thermal stress within the battery and may even cause irreversible damage to its components, including the electrolyte and electrodes. Mechanical stress is also a concern with high DoD levels. As a battery is discharged to deeper levels, the volume of active materials within the electrodes expands and contracts more dramatically. This mechanical stress can lead to physical degradation, such as electrode cracking or damage to the separator, over repeated charge-discharge cycles [15]. Capacity fade is a notable consequence of high DoD, particularly in lithium-ion batteries. It signifies that the battery's overall capacity gradually decreases with each cycle, diminishing its ability to hold and deliver energy efficiently over time. Consequently, high DoD can substantially reduce the battery's cycle life, meaning it may need replacement sooner, incurring additional costs [16].

2.2. C-rate

C-Rate quantifies the rate at which a battery charges or discharges concerning its capacity, typically expressed as a multiple of its nominal capacity. At its core, the C-Rate significantly influences the electrochemical reactions transpiring within the battery. When subjected to higher C-Rates, the battery undergoes faster charge and discharge cycles, producing heightened chemical reactions within its cells [17]. These accelerated reactions are contributing to an expedited degradation process.

Moreover, elevated C-Rates lead to increased current flow, generating excess heat within the battery. This excessive heat can prove detrimental, causing thermal stress that hastens the battery's deterioration. Not only does it compromise the battery's components, but it also escalates safety concerns, including the risk of thermal runaway, a catastrophic event. Internally, batteries inherently resist the flow of electric current. At higher C-Rates, this internal resistance becomes more pronounced, giving rise to voltage drops and reduced energy efficiency [14].

Consequently, the battery's usable capacity diminishes, impeding its overall performance. High C-Rates can also contribute to gradual capacity loss [18]. Furthermore, elevated C-Rates also possess the capability to shorten the battery's cycle life. Repeated exposure to high C-Rates accelerates the degradation process, resulting in a reduced lifespan for the battery. This situation often necessitates frequent battery replacements, particularly in applications demanding high power output and rapid energy transfer. Therefore, managing C-Rates is critical to preserving battery longevity and reducing the operational costs associated with frequent battery replacements. It is a crucial consideration for industries reliant on power-hungry applications [19].

2.3. Effects of Depth of Discharge and C-Rate on Battery Degradation

The battery's state of health (SoH) is the percentage description of the degradation and is defined as the ratio of the instantaneous capacity of the battery [20]. Q_n to the initial capacity Q_{init}. Equation 1 presents the expression of the SoH parameter in percentage terms.

$$\mathrm{SoH}(\%) = \left(\frac{\mathrm{Q}_n}{\mathrm{Q}_{init}}\right)\mathrm{x}100 \tag{1}$$

As expressed in [21], the effect of aging on the battery capacity and internal resistance is given as follows;

$$Q(n) = \begin{cases} Q_{init} - \varepsilon(n) \cdot (Q_{init} - Q_{ep}) \ if\ k/2 \neq 0 \\ Q(n-1) \qquad otherwise \end{cases} \tag{2}$$

$$R(n) = \begin{cases} R_{init} + \varepsilon(n) \cdot (R_{ep} - R_{ep}) \ if\ k/2 \neq 0 \\ R(n-1) \qquad otherwise \end{cases} \tag{3}$$

$$n = kT_h \quad (k = 1, 2, 3 \dots \infty \tag{4}$$

where, Q_{init} represents the battery's initial capacity, T_h represents the time duration of half a cycle, measured in seconds, and under standard temperature conditions, Q_{ep} represents the battery's capacity at the end phase, R_{init} stands for the internal resistance of the battery, measured in ohms after production and R_{ep} is the internal battery resistance, measured in ohms, at the end phase and under the rated ambient temperature conditions, ε represents the battery's degradation variable.

DoD is a fundamental metric in comprehending a battery's operational performance and energy utilization. It quantifies how much of a battery's stored energy has been depleted or utilized during a discharge cycle. DoD offers a straightforward measure of the energy extraction process, expressed as a percentage of the battery's total storage capacity. In simpler terms, it delineates how much energy has been harnessed concerning the battery's maximum energy-holding capacity. This information is paramount in managing and optimizing battery usage, as it directly influences critical factors such as battery lifespan, efficiency, and the system's overall performance.

DoD maintains a close association with the State of Charge (SoC), a relationship that can be expressed mathematically using equation 6. SoC represents the present charge status of the battery as a percentage of its highest capacity. A profound understanding of DoD and SoC is indispensable for developing effective battery management strategies, ensuring batteries are employed optimally while safeguarding their health and prolonging their operational life. These metrics assume pivotal roles in a spectrum of applications, ranging from electric vehicles to renewable energy systems, where maximizing energy utilization and extending battery longevity are of utmost importance.

$$\Delta SoC(k) = SoC(k) - SoC(k-1) \tag{5}$$

$$DoD(n) = 1 - SoC(k) \ \ if\ \Delta SoC(k) \neq sign \Delta SoC(k-1) \tag{6}$$

The effect of DoD on the aging factor is as follows.

$$DoD_{ef} = \left(2 - \frac{DoD(n-2) + DoD(n)}{DoD(n-1)}\right) \tag{7}$$

and also, ε can be shown as;

$$\varepsilon\,(n) = \begin{cases} \varepsilon\,(n-1) + \dfrac{0.5}{N(n-1)} DoD_{ef} \; if\; k/2 \neq 0 \\ \varepsilon(n-1) \qquad\qquad otherwise \end{cases} \tag{8}$$

If we express the average charge and discharge currents during the half cycle, factoring in the exponential component that depends on these currents, as,

$$I_{ch-dis} = \left(I_{dis\_ave}(n)\right)^{-\gamma_1}\left(I_{ch\_ave}(n)\right)^{-\gamma_2} \tag{9}$$

In that case, N represents the maximum number of cycles, and the following equation can describe it.

$$N(n) = H\left(\frac{DoD(n)}{100}\right)^{\varepsilon} \exp\left(-\psi\left(\left(\frac{1}{T_{ref}}\right) - \left(\frac{1}{T_a(n)}\right)\right) I_{ch-dis}\right) \tag{10}$$

where H represents the cycle constant, ξ is the DoD's variable, ψ is the Arrhenius rate constant, I_{dis_ave} represents the average discharge current, I_{ch_ave} signifies the average charge current, γ_1 represents the exponential discharge current variable, while γ_2 represents the exponential charge current factor. As can be seen from the mathematical expression of the number of cycles given in Equation 10, C-Rate, which is related to charge and discharge currents, significantly affects battery aging.

3. Simulation Results

Simulink diagram is established using Matlab/Simulink for simulation studies. The data of the LiFEPO4 battery operated are given in Table 1.

Table 1 LiFEPO4 Battery Specifications

Parameter	Value
Nominal Voltage	12.6 V
Q_{init}	40 Ah
Cut-Off Voltage	10.5
Nominal Current	20 A (0.5C)
Q_{ep}	40*0.8 Ah
Nominal Charge Current	20 A (0.5C)
R_{init}	0.015 Ohm
R_{ep}	0.01512 Ohm
DoD	Variable

The DoD and C-rate effects were analyzed separately in two scenarios.

3.1. Case 1: DoD effect on battery degradation

In the first scenario, battery aging simulation studies were performed for different DoD values under constant 0.5C and 25°C ambient temperature. For DoD=[60 65 70 75 80 90 90 100] values, the entire battery cycle life was consumed, and the total operating time, total energy drawn, and total number of cycles given in Table 2 were determined with the data obtained.

Figure 1 compares the total energy extracted from the battery in simulation studies performed with different DoDs. As can be seen, as the DoD is increased, the battery gets closer to the deep discharge state, and the total amount of energy obtained from the battery decreases.

Table 2 Effect of different DoD values on battery degradation

DoD	C-rate	Time (Hour)	Cycle	Energy (kWh)
60	0.5	6561.22	3084	1729.6
70	0.5	6135.57	2476	1612.74
80	0.5	5802.53	2050	1519.81
90	0.5	5520.73	1734	1438.97
100	0.5	5305.64	1484	1372.18

In the scenario with DoD=60, the total amount of energy extracted is %20.66 more than in the scenario with DoD=100.

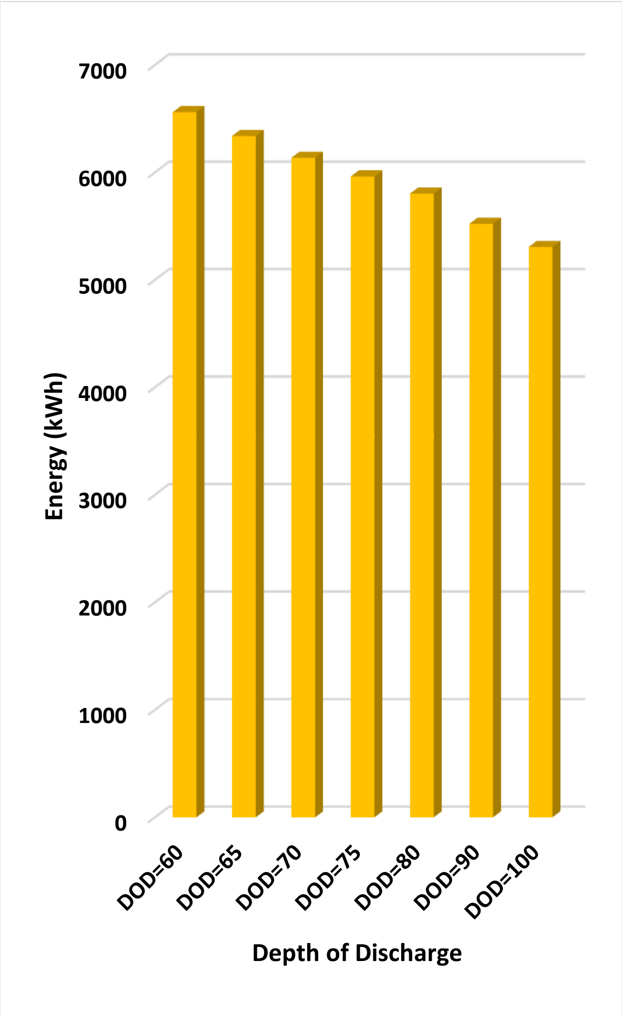

Fig. 1 Comparison of the total amount of energy provided by the battery under different DoD scenarios

Figure 2(a) shows the time variation of battery life for different DoD scenarios. As can be seen, DoD is a parameter that directly affects the battery life. The difference between DoD=60 and DoD=100 scenarios regarding usage time is %19.13. Figure 2(b) shows the number of cycles. The number of cycles is higher with low DoD utilization. Longer time and higher number of cycles explain why the total energy drawn from the battery is higher.

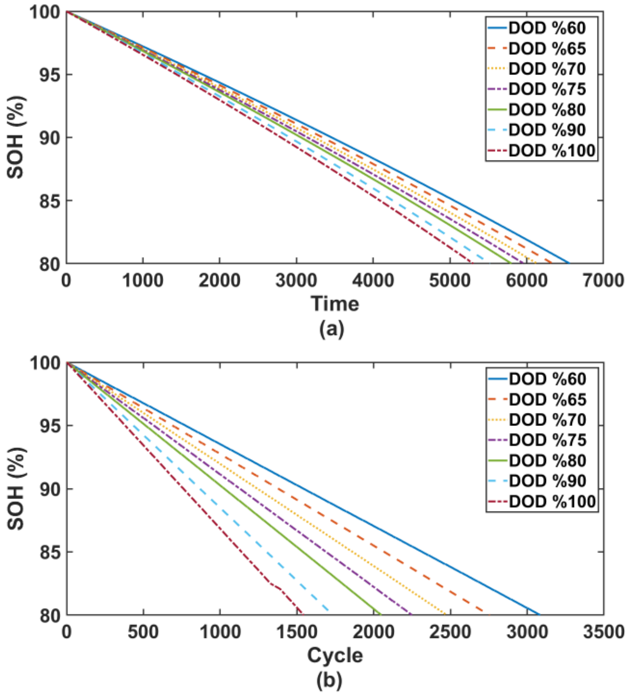

Fig. 2 a. Effect of DoD on battery usage time, b. Effect of DoD on battery cycle

3.2. Case 2: C-Rate effect on battery degradation

In the second scenario, battery aging simulation studies were performed for different C-Rate values regarding charging current under DoD=80 and 25°C ambient temperature. For C-Rate=[0.25 0.5 1 1.5] values, the entire cycle life of the battery was consumed, and the total operating time, total energy drawn, and total number of cycles given in Table 3 were determined with the data obtained.

Table 3 Effect of different C-Rate values on battery degradation

DoD	C-rate	Time (Hour)	Cycle	Energy (kWh)
80	0.25	9608.09	2271	2502.24
80	0.5	5802.53	2050	1519.81
80	1	4205.25	1987	1114.85
80	1.5	3612.40	1916	994.75

Figure 3 shows the comparison of the total amount of energy extracted from the battery in simulation studies performed with different C-Rate. As can be seen, as the C-Rate is increased, the battery gets closer to the deep discharge state, and the total amount of energy obtained from the battery decreases. In the scenario performed under 0.25C, the total amount of energy withdrawn is %60.2 more than the scenario with 1.5C.

Figure 4(a) shows the time variation of battery life for different C-Rate scenarios. The difference between 0.25C and 1.5C scenarios regarding usage time is %62.39. Figure 4(b) shows the number of cycles. The number of cycles is higher with low C-Rate utilization. Longer time and higher number of cycles explain why the total energy drawn from the battery is higher.

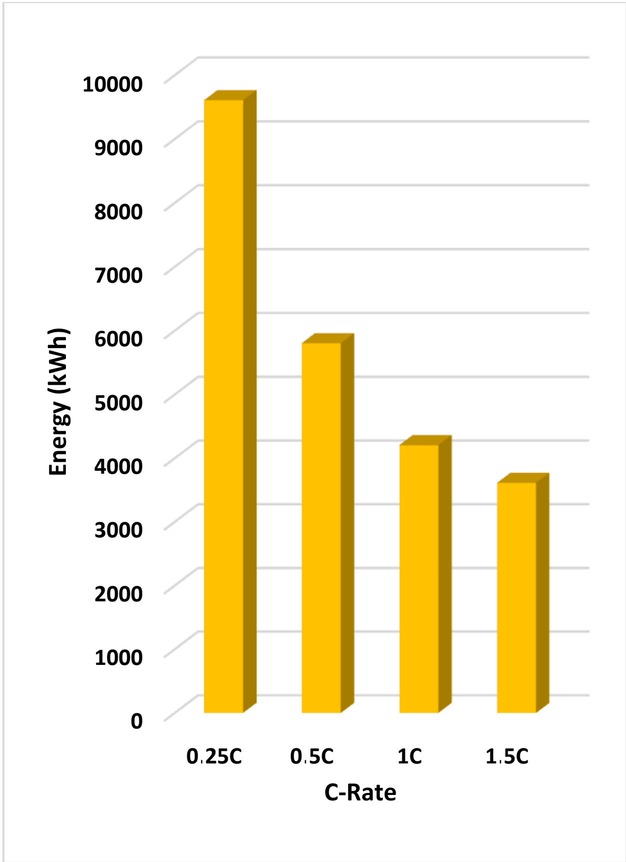

Fig. 3 Comparison of the total amount of energy withdrawn from the battery under different C-Rate scenarios

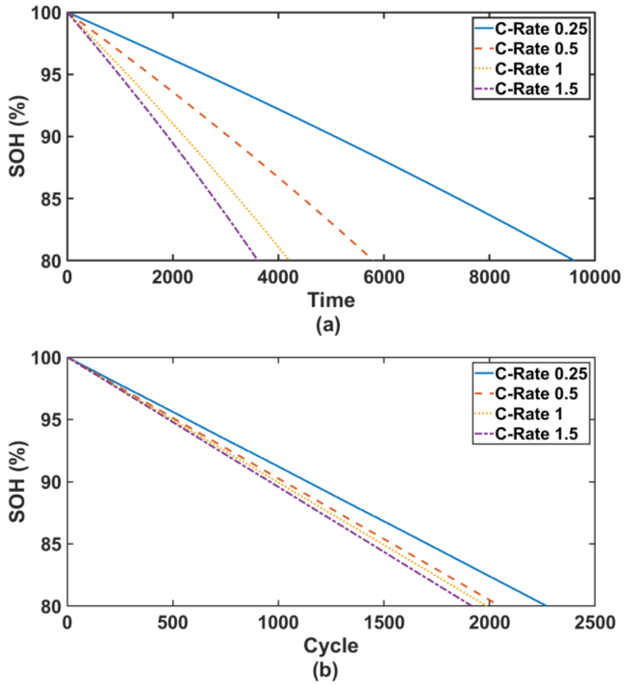

Fig. 4 a. Effect of C-Rate on battery usage time, b. Effect of C-Rate on battery cycle

6. Conclusions

The relationship between DoD, C-Rate, battery degradation, and lifetime is complex and multifaceted. These parameters play pivotal roles in determining how a battery performs and how long it lasts, making them crucial considerations for a wide range of applications, from consumer electronics to electric vehicles and renewable energy storage systems.

DoD directly impacts a battery's degradation and lifetime. Deeper discharges, characterized by higher DoD levels, increase the stress experienced by the battery during each charge-discharge cycle. This elevated stress leads to more significant chemical reactions, heat generation, mechanical stress, capacity fade, and reduced cycle life. Balancing the trade-off between maximizing energy usage and extending battery life remains a central challenge in battery management.

On the other hand, the C-Rate, representing the rate at which a battery is charged or discharged concerning its capacity, also plays a vital role in battery performance and degradation. Higher C-Rates accelerate chemical reactions, increase heat generation, elevate internal resistance, and can contribute to capacity loss and shorter cycle lives. Managing C-Rates effectively is essential for optimizing battery performance while preserving its health.

Moreover, the interplay between DoD and C-Rate is critical in real-world applications. Different usage patterns, such as frequent deep discharges or rapid charging, can interact to influence battery performance and longevity. Careful consideration of these parameters is necessary to meet specific application requirements and extend battery lifespan. As emphasized in the study, optimizing battery usage through a deeper understanding of the relationship between DoD and C-Rate will remain essential for achieving more efficient and sustainable energy storage solutions. By this knowledge being applied, longer-lasting and more reliable batteries can be strived for, meeting the demands of our increasingly battery-dependent world while minimizing environmental impact.

7. References

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