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Charging strategy effect on lithium polymer battery capacity: A case study

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Abstract
Since the invention of lithium ion batteries, charging strategies have met great acknowledgment and research over the years. In this paper, a laptop with lithium polymer battery is monitored via three widely used tools, during various operational and charging loads. Several key values are obtained in order to evaluate the correlation between battery cycles, charging percentages and depth of discharge. Ultimately the results show that massive discharges and continuous operation with the device plugged should be avoided, though high load tasks require the AC charger to be connected. Ensuring that battery stays at safe temperature and charging ranges can expand cell life and state, as well as prevent lithium deposits inside the battery.

Keywords: Lithium; Battery; Cells; DoD; Discharge; cycles; Deposits; Laptop; Capacity; Polymer.

1. Introduction
Lithium ion batteries are the powerhouse of every modern application. They are used in microelectronics, like smartphones, laptops, cameras, alarms and electric vehicles, and basically everywhere a battery is needed. Developed by Akira Yoshino, based on Goodenough's team research [1], they soon became dominant in energy storage. The first massive commercial product was released by Sony Corporation, after massive attempts by researchers to reduce cost and make them safe for usage [2], because of major constructive issues like high flammability, oxidation and low charging cycles. They consist of a copper anode and an aluminum cathode (later on lithium oxide), separated with liquid electrolyte.
The working principal is simple, as shown in Figure 1. The movement of lithium ions creates free electrons in the anode, and thus a charge at the positive collector. The electrical current then flows through the load to the negative current collector. The separator blocks the flow of electrons inside the battery [3].
From then, their evolution has been enormous [4, 5] with tests of different elements to ensure decent energy density and cost savings [6].

2. Lithium Polymer Batteries
Even though li-ion batteries were adequate, the need to increase battery life and energy density turned research towards another form of li-ion battery: The lithium polymer or *Li-Po* battery. This type of battery

offers easy and cheap manufacturing, excellent thermal stability [7] and flexibility. It is also lightweight, safer and can be fitted at specialized equipment like microelectronics [8].
Using gel electrolyte and premium blending as stated at [9, 10] and demonstrated in Figure 2, supreme ionic conductivity, chemical firmness and mechanical strength are achieved, preventing massive deformation to enhance safety [11].

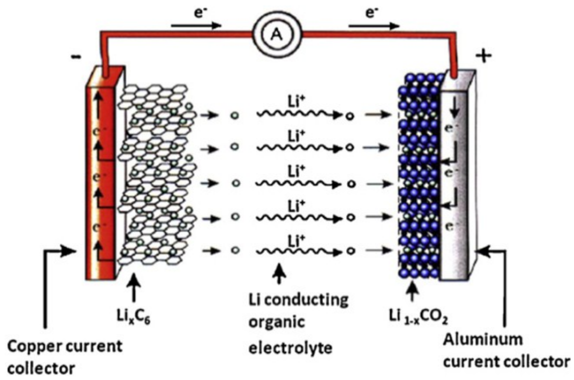

Figure 1. A typical ion battery as reproduced by Scrosati, B. and Garche, J. (2010) [3].

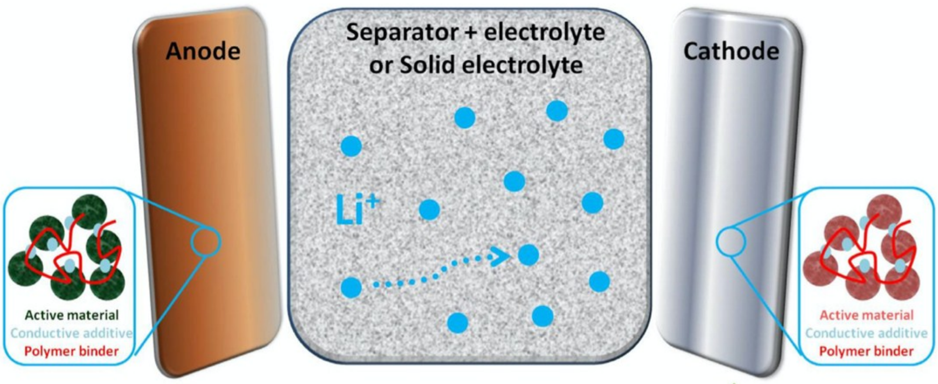

Figure 2. Lithium Polymer battery structure, by Costa et al. [10]

It is important to mention that the thickness of the plates and their ratio (Cathode-Anode) affect the electrochemical properties of the cell, in addition to performance, design and output energy [12]. That ratio alone under certain temperatures can accelerate aging, leading to increased internal resistance. Additionally, capacity is reduced as a result of lithium plating [13].

2.1 Charging Techniques

Because of the electrochemical model complexity of the Li-Po battery, multiple charging methods have been proposed:

a. Klein et al. [14] proposed a non-linear model predictive control (NMPC) based technique, where charging is dependent to cell and ambient temperature. It has many advantages over a simple CC/CV (Constant current-voltage) method, such as 50% faster charging time, but battery aging is also a consequence of this proposal.
b. Vo et al. [15] focused their research on charging time, state of charge, temperature and protection against overcharging, following the Taguchi method. It is a multi-stage charging method like Klein et al. [14] but tested on different capacity batteries with great results, as displayed in Table 1.
c. An algorithm-based approach was executed by Tolomin et al. [16], that calculated all available data from sensors, time and computer predictions, improving charging quality for LiFePO4 batteries.
d. Waldmann et al. [17] compared different charging strategies, eventually concluding that charging temperature is the most important factor, causing lithium deposition at the anode minimizing cell capacity and eventually battery life.

e. Another charging pattern using a buck DC-DC converter and multiple sensors is suggested by Hoang et al. [18], with improved charging time and energy efficiency. Additionally, three more methods are summarized and the results are presented in Table 2.

Table 1. Experimental results comparing two distinct charging methods [15].

LiPBs	Charging algorithm	Charged capacity (Ah)	Discharged capacity (Ah)	Energy eff. (%)	Charging time (s)	Temp. var. (°C)
B1 5.8 Ah	Proposed	5.75	5.66	96.22	3915	1.73
	CCCV	5.77	5.76	95.38	4838	3.4
B2 5.8 Ah	Proposed	5.55	5.49	95.39	3672	2.05
	CCCV	5.65	5.64	94.97	4768	3.27
B3 5.0 Ah	Proposed	4.74	4.64	95.57	3602	2.61
	CCCV	4.69	4.65	95.50	4561	3.18
B4 5.0 Ah	Proposed	4.76	4.66	94.30	3624	1.37
	CCCV	4.81	4.80	93.90	5162	3.21

Table 2. Side by side results of different charging methods [18].

Charging methods	CC-CV	Pulse current	Multistep current	Proposed method
Charging time [s]	3,607	3,038	1,485	1,702
Full charging capacity [Ah]	3.2	3.2	2.906	3.040
Full discharging capacity [Ah]	2.78	2.851	2.680	2.842
Energy efficiency	86.88%	89.1%	92.22%	93.5%

2.2 State of Charge

State of Charge (SOC) is a valuable battery characteristic. It is defined as the ratio of the current capacity of the battery, to the nominal capacity stated by the manufacturer [19], showing the maximum charge the battery can store. The SOC can be measured with different techniques, with later ones having more accurate approach. It is a crucial parameter for battery life.

Two new methods of SOC estimation have been released:

- Meng et al. [20] used an adaptive Kalman filter-based algorithm, testing both fast and slow charging profiles with an error of 2%, proving that the algorithm is accurate and feasible.
- Particle filter-based data fusion was selected by Zhou et al. [21] to estimate state of charge both battery voltage and output, as Figure 3 suggests. Linear and non-linear approaches are presented and computational speed is performed to minimize the error.

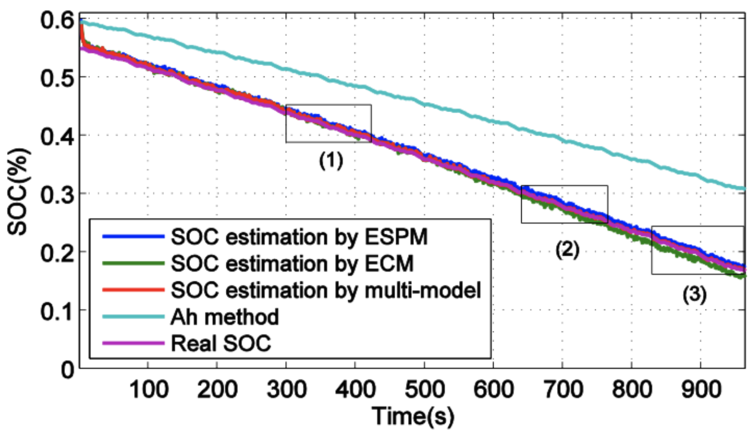

Figure 3. SOC estimation by [21].

State of Charge is also affecting lithium deposit formation at the conductive layers. According to Agubra et al. [22], changes at SOC levels lead to thick layer of deposits by side reactions. That contained lithium, shown in Figure 4, is practically lost and not available for usual electrochemical reaction, so charge transfer capability is decreased and consequently, useful battery capacity is lost.
Additionally, reducing the charge rate, thus the potential, results in dropped deposit thickness, with high cycling charge rate causing additional lithium trapped in the anode. Direct connection of captured lithium-layer thickness and capacity loss are formed and highlighted on Table 3 [23].

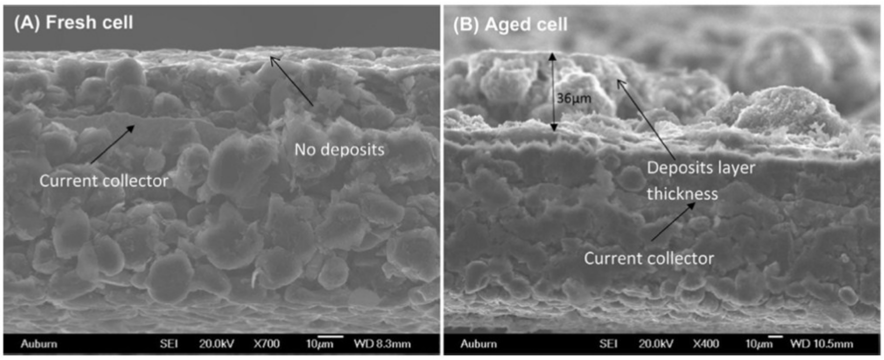

Figure 4. Deposit layer concentration taken by an anged anode electrode after 600 battery cycles as shown at [22].

Table 3. Connection between capacity decrease and Lithium layer thickness presented by [23].

State of Charge	Charging rate	Capacity Fade (%)	Deposit Layer thickness(μm)	Amount of Lithium Trapped (%)
25–90	4 C	17.8	56	8.1
5–70%		7.8	27	3.2
25–90	3 C	16.9	42	7.6
5–70%		5.3	15	2.5
25–90	2 C	15.7	37	3
5–70%		4.6	1	1.3

2.3 Discharge characteristics
Besides the fact that battery lifetime drops as cycles are increased, discharge cycles appear to damage the cells [24]. Hence is it essential to avoid using the battery below safe limits. Keeping the discharge values close to nominal value and current on maximum 2C rate, guarantees that the battery stays at normal temperature with slow discharge time [25].
Furthermore, charging voltage can be reduced slightly to improve useful cycles, at the expense of lower range, as reported by Grin Technologies portrayed in Figure 5 [26].

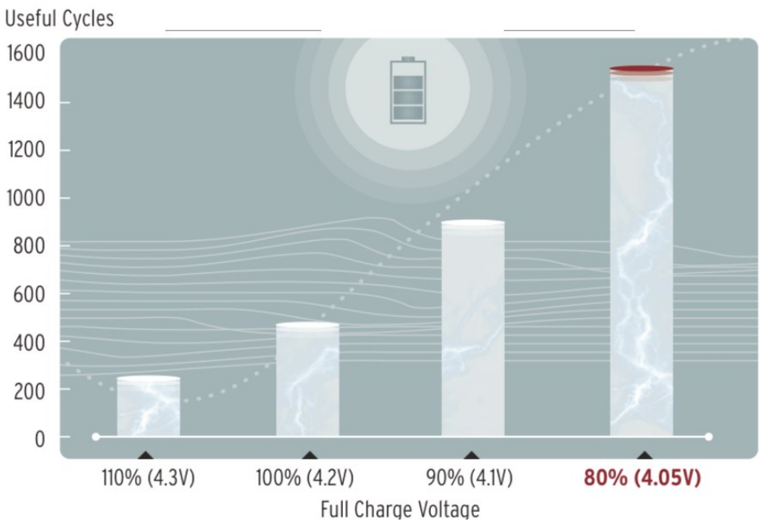

Figure 5. Useful cycles and charge voltage interaction as represented by [26].

3. Methodology

3.1 Objectives of Experiment

The aim of this paper is to test different charging techniques and patterns, based on battery changing range and cycle. With this approach, it is investigated how charging characteristics can affect battery capacity and what is the ideal usable range providing battery capacity endurance. Moreover, a mini battery calibration is executed (15% >> 100%), not only for data validation, but also to check battery calibration importance. This sequence is taking place via extensive laptop operation with AC adapter plugged in, while battery percentage is kept at full charge.

3.2 Selection of measured values and access

The monitored device is a 2018 Macbook Pro 13inch, A1989 Model with Touchbar, by Apple Inc. [27] with a built-in 58 Watt-hour Lithium Polymer battery and a 61W Charger. The device capacity is 97.8% at 125 battery cycles and it is mainly used for office work and browsing. The operating system installed during experimentation is macOS Catalina 10.15.2.

For this project, it has been decided to gather specific values that were easily obtainable through common software tools and applications. The reason of that call was to simplify readings and compare values that are easily understandable and widely available to everyone. So, the selected values are:

a. Battery capacity percentage
b. Battery capacity (mAh)
c. Battery cycles
d. Battery Voltage
e. Charging rate
f. Charging percentage

Those parameters were monitored after each charging session after the charger was plugged off. The required data is gathered by 3 widely utilized and renowned tools/applications introduced at Figure 6 below:

1. Apple integrated system information utility
2. *Coconut battery*, a notable application by coconut-flavour and
3. *Battery health application* from FIPLAB limited

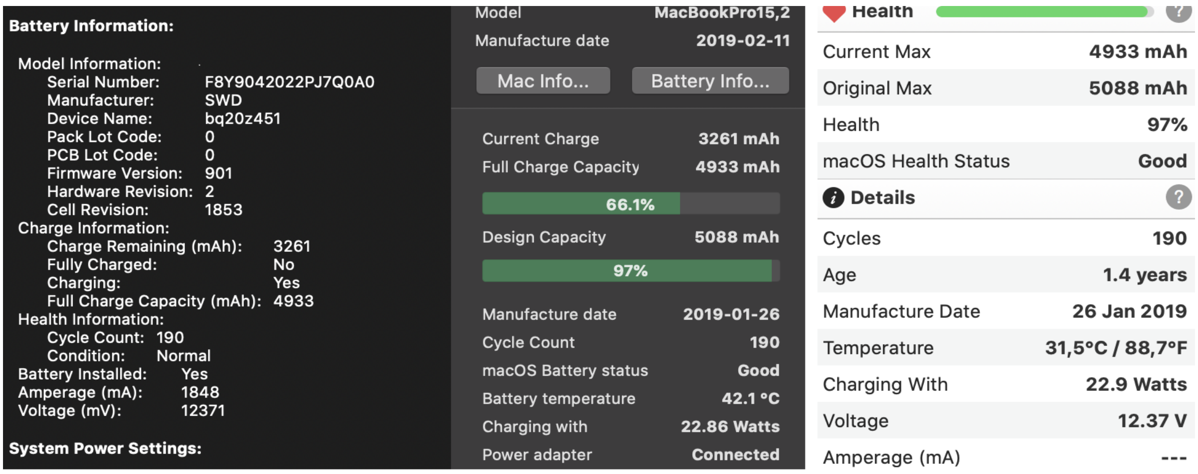

Figure 6. Software tools employed for experimentation. From left to right: Apple System Information, *Coconut battery* and *Battery Health*.

4. Experimentation and results

At the start of the project, initial capacity was 97.8% at 4,976mAh and 124 battery cycles. Temperature ranged between 26° to 40° degrees Celsius throughout the experiment as the laptop was charged inside our lab, thus no need for external cooling by pads or AC system was required. Total project duration is 4 and a half months that equals to 140 days.

During the experimentation, we retrieved battery capacity and percentage measurements that were directly compared with Apple Integrated Monitoring System (since all three tools monitor the same values) as a first validation of the system. The temperature was not recorded, but random checks with a thermal camera were performed for further validation.

4.1 Battery cycles – Battery capacity after charging

As depicted in Figure 7, battery cycles factor is not directly affecting the capacity as standalone. Capacity remains between 97.5 to 98.5 % but after 70 measurements it starts dropping, until it reaches the minimum of 93.8% that is a 5% reduction. After this point, capacity starts consistent fluctuations, finally reaching the maximum design capacity, 100% at 5,088mAh. Then a semi-calibration with 12% battery remaining and plugged in to charger makes it collapsing to 95.3%.

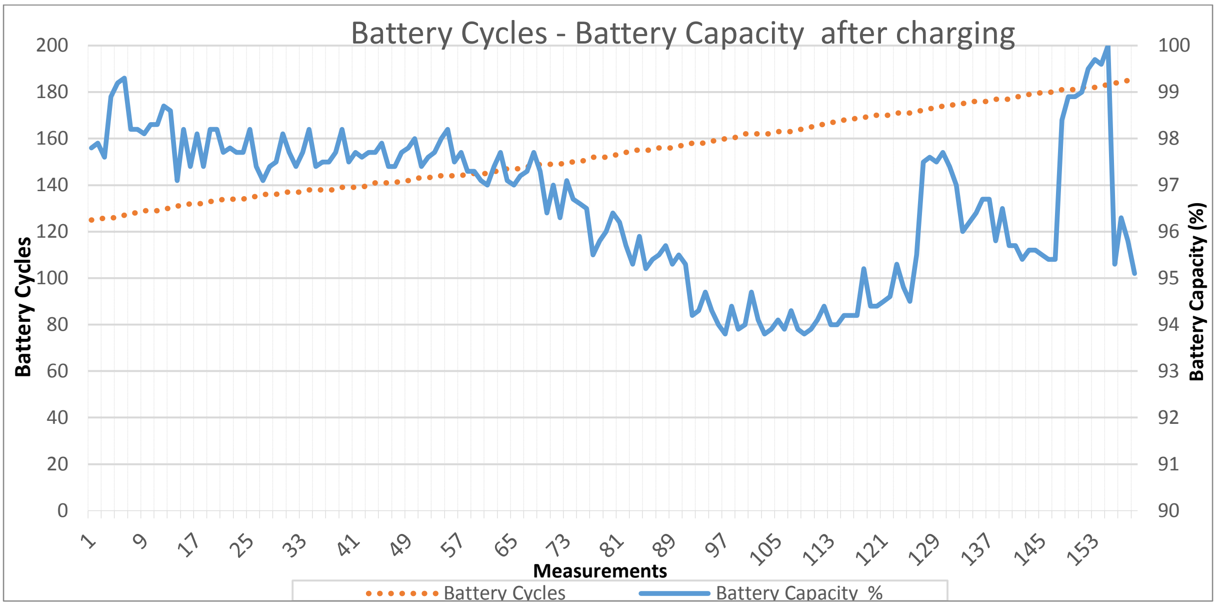

Figure 7. Battery capacity after charging to battery cycles comparison. Cycles follow a linear increase as expected whereas capacity ranges substantially.

4.2 Battery capacity – Battery Voltage

The next data analysis, shown at Figure 8, is about the two most important battery values: Capacity and Voltage. Even though a relation of these parameters is not clear enough, a small variation in inverse proportion has to be stated.

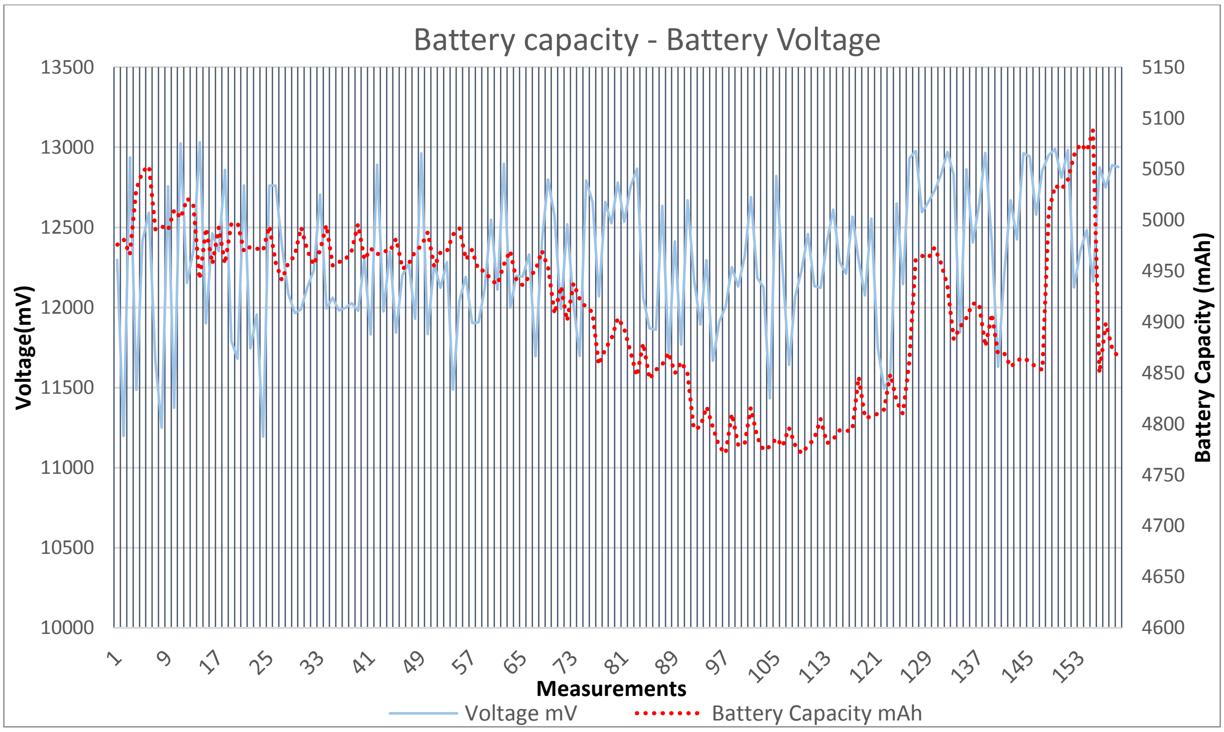

Figure 8. Battery capacity and Battery voltage contrast.

Having the device run at higher voltage, over 12.5 Volts, it needs less current to cover the necessary output wattage required by the workload. The battery then runs at lower temperatures which also boosts expected lifespan as heat can severely damage the cells.

4.3 Battery capacity – Charge Percentage

As portrayed in Figure 9, Battery charging technique is an immense factor affecting battery percentage. Major discharges/charges really decrease the ability of the battery to store charge and last as expected, due to manufacturer design. Small, quick charges at medium to high percentage really helps the battery function at low temperatures keeping the capacity as normal due to manufacturer specifications. Major charging sequences like No.71 or No.105, feature operation at high loads while charging. Those points confirm that the AC adapter needs to be plugged in for maximum device speed, avoiding extreme cells pressure, which also implies a slight battery capacity increase.

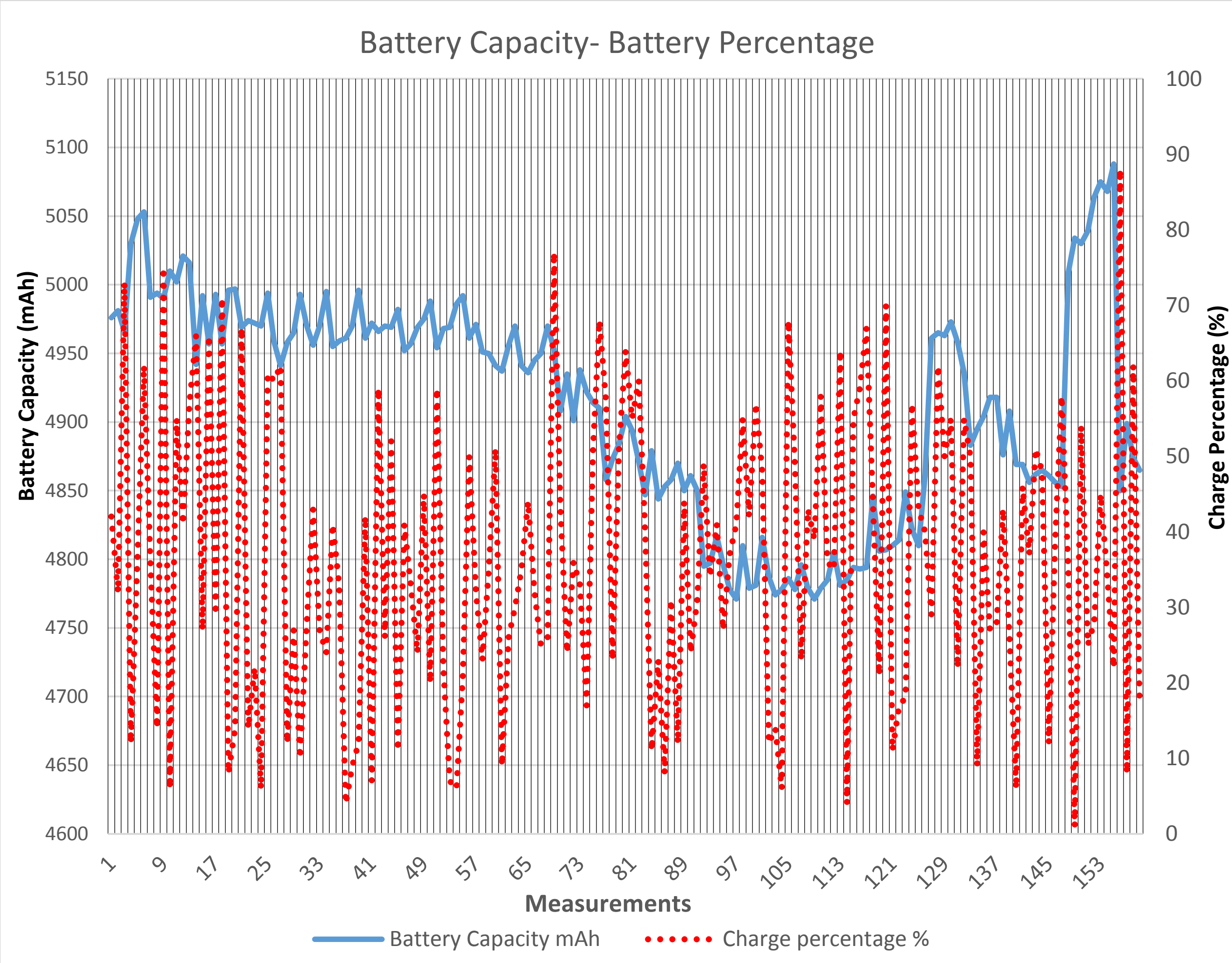

Figure 9. Battery capacity - charge percentage.

4.4 Battery voltage – Charge Percentage

Because battery voltage in millivolts would make presentation difficult and less understandable, that value is converted to Volts. Hence, illustrated in Figure 10, is the almost complete interrelation between battery charge percentage and voltage. Keeping the battery well charged, guarantees higher voltage leading to smoother operation.

4.5 Battery capacity – Charge start point

As depicted in Figure 11, maintaining the battery above 40% with small charges not greater than 40-45% is the ideal range for keeping a stable capacity or even increase it at a certain quantity. When heavy work load is needed, the charger must be plugged in. Thus, the battery does not reach operating limits which will lead to overheating and lithium deposition at the anode, as stated before [22]. Massive draining of the cells should be avoided, for the same purpose that can also prevent battery being pushed to safe mode due to immense stress.

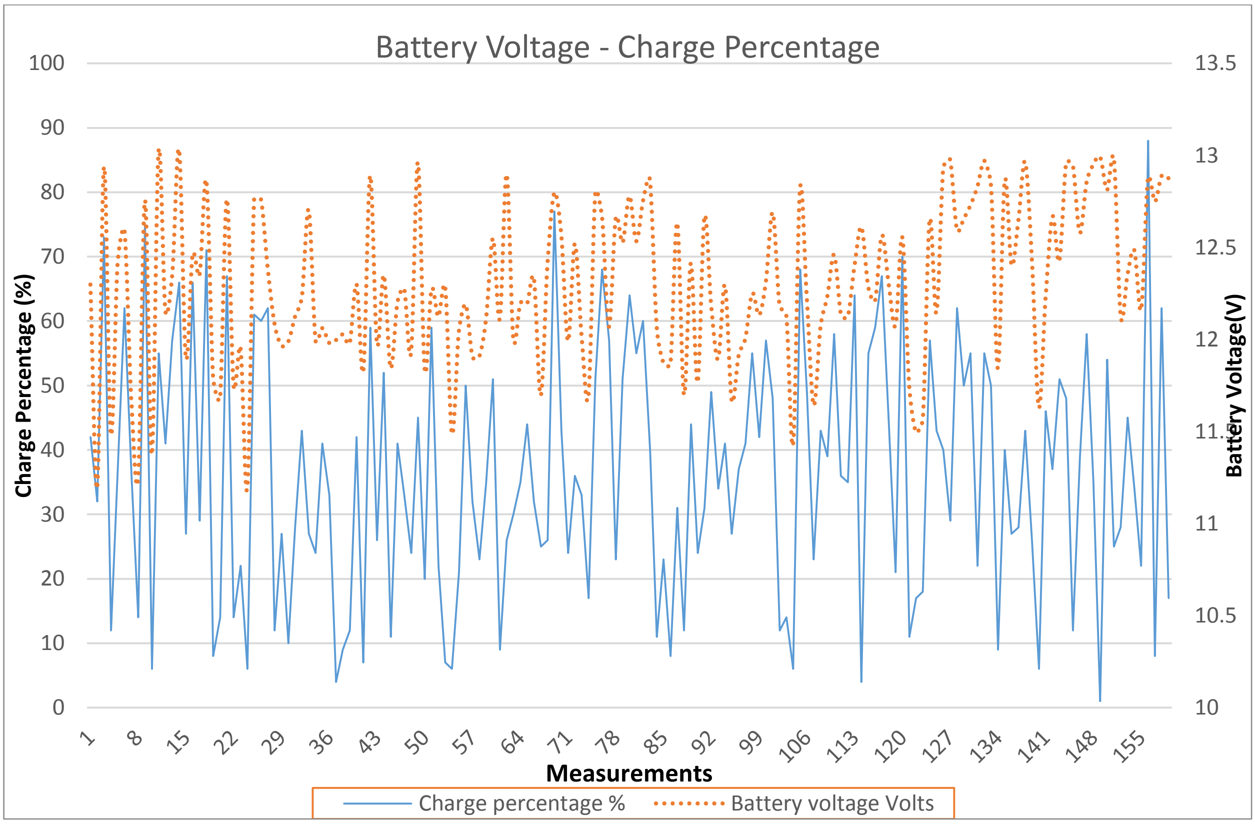

Figure 10. Battery percentage versus battery capacity in Volts.

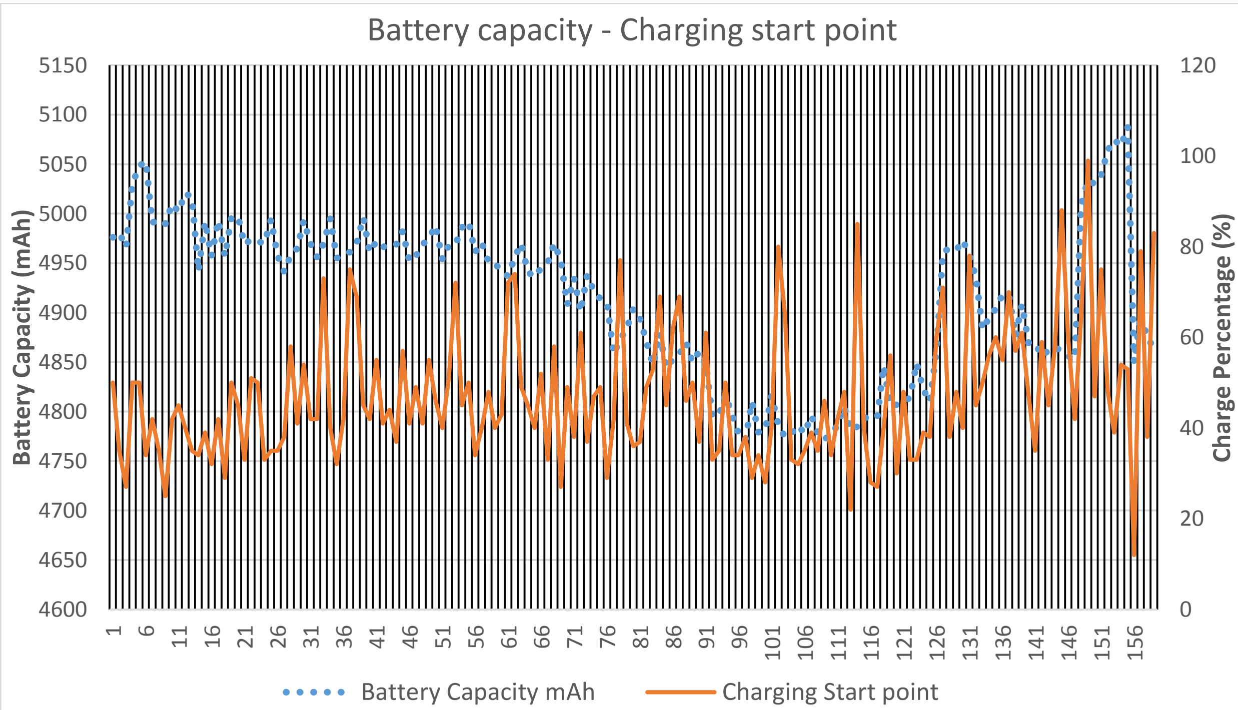

Figure 11. The effect partial discharges have on battery capacity.

5. Discussion

Battery cycle count is a very important battery life indication, but it also has limitations. Fluctuations occur as cycles increase but not in an insignificant matter. A range of 2-3% would be expected, but changes up to 5-6% at capacity are visible. Battery voltage has to be kept at high limits, operating plugged in during higher workload. Low capacity ranges should be avoided, so the device draws less current in order to produce the output power. It also has a decisive role on battery capacity, as the Energy management controller reads this low voltage and misjudges the value. Furthermore, immense discharges-charges and very low scores (like 10% battery left) are forbidden, so that voltage can be managed for safe and understandable reading.

However, for the typical end-users that is often not feasible. Typical laptop users could work all day until only 5-10% of battery capacity remains, then plug the devices in for a full charging session. Other users operate the laptops constantly connected on AC, in order to avoid cycles count increasing. That technique can be severe, because lithium deposition will gradually damage the cells, hence their ability to store charge and power up as expected.

Figure 11 is a clear guide for the right utilization of lithium polymer batteries. When battery is at medium ranges, small (15-25%) charges seem to form the ideal pattern for clever and long-term usage. Plugging the device in at 80% or above is not harmful either, but not really doable. Leaving the cells drop to ultra-low limits, can damage their structure leading to fast aging. That is also proved by [28-29], where partial discharges seem to be the best option for proper battery management (Table 4 and Figure 12).

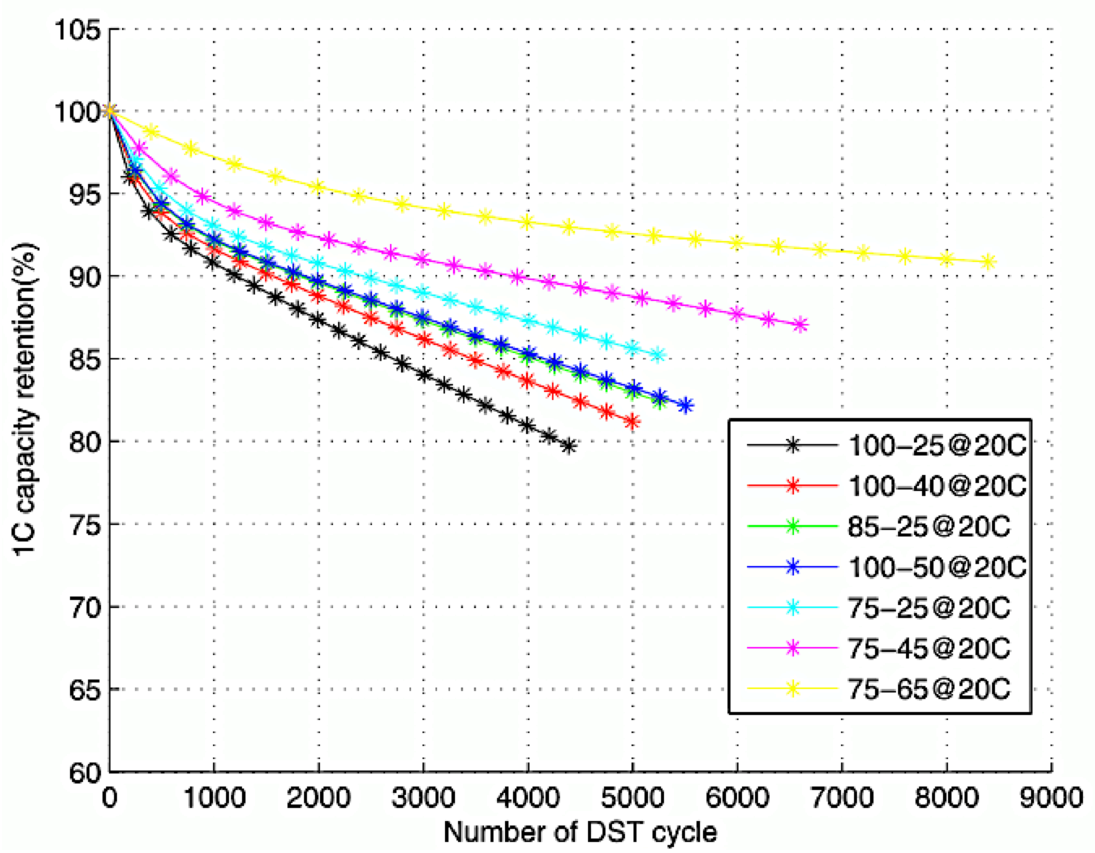

Figure 12. Reproduced Dynamic Stress test data comparison by Xu et al. [29]. This graph confirms the DoD technique declared at precious chapters.

Table 4. DoD effect on Lithium polymer battery. Major discharges shock the battery and reduce maximum capacity whereas low DoD increase it by a margin [28].

Depth of Discharge	LiFePO4 Battery
100%	~600
80%	~900
60%	~1500
40%	~3000
20%	~9000
10%	~15000

6. Conclusions

This paper suggests a simple and functional charging strategy for electronic devices with lithium polymer batteries. Crucial characteristics, such as State of Charge and Depth of Discharge, have been discussed along with the importance of each parameter. Since LiFePO4 batteries may suffer from lithium deposition, due to high temperatures and constant massive charging-discharging, an experiment has been executed to find the optimum way of using the battery without heavily damaging it. The chosen values to be retrieved (voltage, capacity, charge rate and battery cycles) were easily obtainable, with 3 software monitoring tools, and were practical enough to reveal a pattern.

Even though battery cycles are accepted as the leading factor to evaluate battery life and battery capacity, the drop is not as linear as the cycles are. Voltage has to be kept at high values so that operational hours increase, thus more work can be done at the same battery state. On the contrary, implementing minimal and frequent charges at high battery percentage -low Depth of Discharge- helps the capacity retention phenomenon. In conclusion, avoiding High DoD which will cause lithium deposits, hence quick battery aging, is what appears to be the best strategy for the end user.

Conflict of interest statement

Nothing declared.

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