ANALYSIS OF CHEMICAL CELLS IN DIFFERENT ASPECTS FOR OFF-GRID ENERGY SYSTEMS

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Abstract - *Different battery chemistries fit different applications, and certain battery types stand out as preferable for stationary storage in off-grid systems. Rechargeable batteries have widely varying efficiencies, charging characteristics, life cycles, and costs. This paper compares these aspects between the lead-acid and lithium ion battery, the two primary options for stationary energy storage. The various properties and characteristics are summarized specifically for the valve regulated lead-acid battery (VRLA) and lithium iron phosphate (LFP) lithium ion battery. The charging process, efficiency, and life cycle are discussed for each battery type. Through cost analysis specifically, lithium ion batteries are shown to be a cost-effective alternative to lead- acid batteries when the length of operational life – total number of charge/discharge cycles – is considered. Finally, applications for off-grid applications and specifically developing world microgrids are discussed.*

Key Words: Batteries, Lithium Batteries, Lead-Acid Batteries, Energy Storage, Microgrids, Valve Regulated

Lead-Acid (VRLA).

1. INTRODUCTION

The rechargeable electric battery is the most common and widespread device used to store electrochemical energy for power systems. Fundamentally, a battery is a combination of electrodes soaked in an electrolyte substance that enables an ion exchange to happen so as to conduct electricity. Recent years have seen continuous improvements in battery technology, and improvements continue in the fields of battery safety, reliability, performance, efficiency, cost and capacity. Two major types of battery technology are used in power applications: lead-acid and lithium ion (Li-ion). In off-grid power systems, distinct base load and peaking power plants are generally unavailable. Generation sources are generally few and increasingly sporadic given the recent propagation of intermittent renewables like solar and wind.

If backup or reserve generation is available at all, the options off the grid are generally expensive and/or oil-burning, e.g. diesel generators. Stationary storage can eliminate the need for such backup options and provides a renewable alternative to burning fuel. Banks of lead-acid batteries are used most commonly for off-grid stationary energy storage. Li-ion batteries work longer in operation (more charge-discharge cycles than lead-acid) but are often avoided in budget-constrained systems off-grid because Li-ion are more expensive per kWh of storage capacity.

Lead-acid batteries, being the older technology, are widely used and comparatively big and bulky. They are easy to install and have low upfront and maintenance costs. Performance of lead-acid batteries is depends largely on ambient temperature and the discharge rate, which is controlled by a system's power electronics. Lead-acid batteries are made up of plates of lead and plates of lead dioxide, all immersed in an electrolyte solution of sulfuric acid and water. When discharging the process involves electrodes turning into lead sulphate, whereas the electrolyte that is sulphuric acid becomes primarily water. A single cell of lead-acid is capable of producing 2.15V [2], [3]. Two types of lead-acid batteries dominate the market – flooded and valve regulated lead-acid (VRLA). This paper focuses primarily on VRLA since – by contrast with flooded – this type has a lower chance of cell failure and does not require addition of handling acid or water. Furthermore, degradation from hydrogen evolution during float is lower in VRLA than in flooded lead-acid by a factor of 10 [4].

Li-ion batteries rely on newer chemistry that improves on lead-acid and other batteries previously available on the market. Li-ion batteries are mainly used in portable electronics because of their durability, compact and lightweight form factor, fast charge/discharge rate, long life, and higher efficiency than lead-acid. The downside, though, is that the cost per unit energy (kWh) is typically at least twice as high for Li-ion batteries as for lead-acid. Li-ion uses the transfer of lithium ions from anode to cathode when storing energy (charging) and the reverse direction when discharging. The two primary chemistries available for Li-ion are lithium iron phosphate ($LiFePO4$, i.e. LFP), nickel cobalt manganese (NCM), and lithium titanate oxide (LTO). For our comparative review of lead-acid and Li-ion, we focus on LFP rather than LTO, as LFP has a lower cost per kWh [2], [3], [5].

Many factors are important to consider when choosing which battery type is best for a specific application. This paper is a review of prior work describing several such factors as they differ between lead-acid and Li-ion batteries. Section II gives an overview of lead-acid batteries, section III does the same for Li-ion batteries, and section IV focuses on key differentiators that show which battery type is preferable in off-grid applications with different conditions. Section V describes the implications of storage in developing world power systems, e.g. rural microgrids.

2. LEAD-ACID BATTERY CHARACTERISTICS

Lead-acid batteries are still the most common option worldwide for stationary energy storage, and they are designed to perform a deep discharge when required. Performance of a battery can be determined by its behavior in different current rate (C-rate) conditions. Lead-acid battery C-rates from 0.25 to 4 are plotted in the charging performance of a lead-acid battery is shown in the upper plot of with a constant-current/constant-voltage (CC/CV). Charging method, which describes the voltage rise pattern in a VRLA battery.

Charging is slow and limited to 0.25C, which is one drawback of the VRLA. Another drawback is that over many charge-discharge cycles the battery capacity drops, a phenomenon that varies in extremity between different battery types but is significant in lead-acid.

2.1. Charging properties

Basic techniques to charge a battery include Constant Voltage (CV), Constant Current (CC) and the pulse method [6].The pulse method involves periodically sending pulsed current to the battery followed by a short deep discharge, then a waiting period. This repeats until the battery is fully charged. This method is used in EV applications but has poor efficiency [7]. The most common lead-acid battery uses CC/CV charge method. Traditional charging methods CC, CV, and CC/CV have drawbacks that include high gas evolution from electrolyte decomposition, which degrades battery performance. Graphically depict the customary charging algorithm implemented with power electronics for charging lead-acid batteries is given.

A newer technique is the intermittent charging method – charging to full capacity over a short period of time and then keeping the battery open. Another recent method is Interrupted Charge Control, which is similar to intermittent charging but also ensures the full charge return by supplying charging. Both of these methods reduce grid corrosion, ensure full recharge, have no thermal runways, and increase battery life [6], [9], [10]. A battery's charging method significantly affects its life cycle and discharge capabilities. The method should therefore be chosen carefully according to usage patterns, and robust power electronics are needed to reliably implement the chosen method.

2.2. Life Cycle

A Lead-acid batteries lifetime typically depends on the frequency with which it is charged and discharged, the C-rates for charging and discharging, and the ambient temperature. When properly maintained, a VRLA battery can last 10 years at an ambient temperature of 25 °C but the life often falls below half the rated lifetime at 35°C ambient or hotter [11]. Overcharging and undercharging also reduce battery lifetime.

VRLA battery usage causes decrease of both float life and cycle life. Float life is defined as the expected lifetime in hours of a battery operated in float charging. A float charge setup has the battery and load wired in parallel to a DC charging source, so the battery powers the load even when

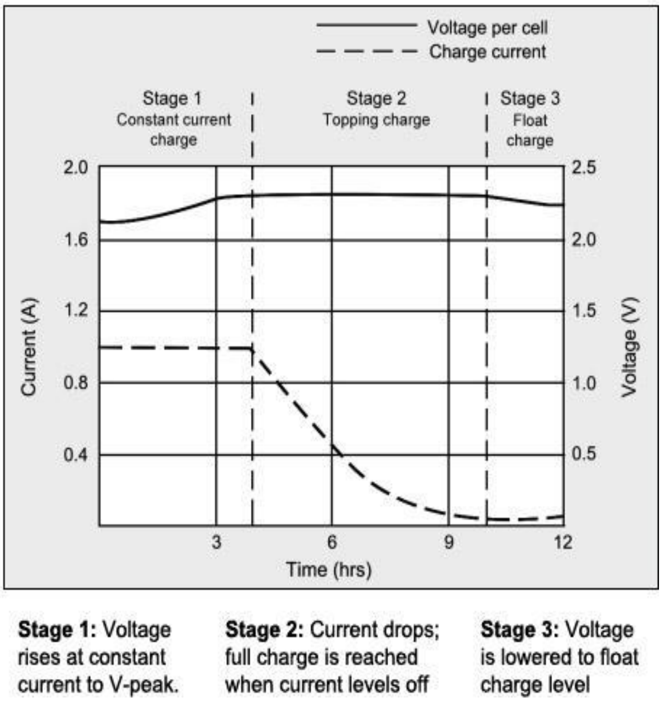

Fig-1: Charge stages of a lead-acid battery [8]

The charger fails. The main cause of float life degradation is deterioration in the positive plate [10].Cycle life is defined as the number of charge/discharge cycles a battery will complete before its operating capacity falls lower than 80% of its initial capacity. Reduction in cycle life results from the unavoidable loss of active material from the positive plate, which is caused by the plate expanding and shrinking with repeated discharge and charge cycles. Figure 4 shows cycle life drop in relation to Depth of Discharge (DOD), the percentage of discharging capacity of a fully charged battery. The discharge current here is 0.17C, charging current is 0.09C, charging volume 125% of discharged capacity, and ambient temperature 20- 25oC [11].

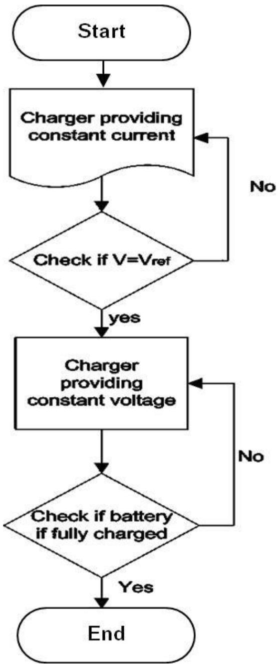

Fig-2: Flow chart of lead-acid battery charging [6]

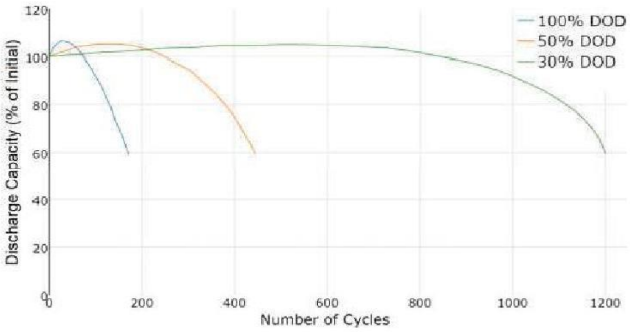

Fig-3: Cycle service life of VRLA at different DOD [11]

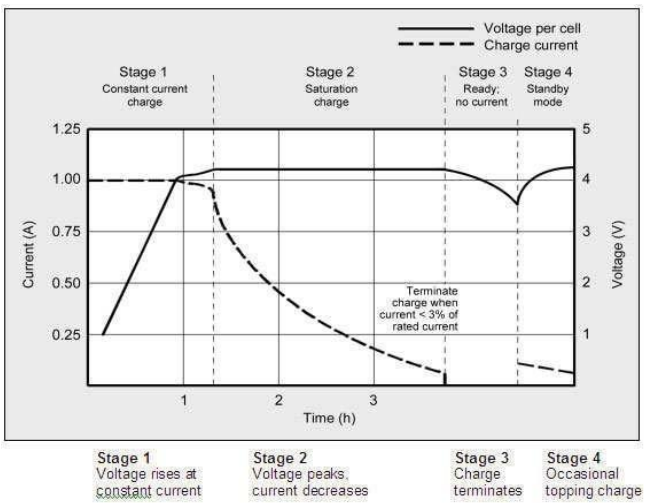

Fig- 4: Charging stages for Li-ion batteries [8]

For a better life expectancy from a lead-acid, two factors are considered: lower DOD and higher SOC (State of Charge), the amount of energy left in the battery to avoid overcharge.

3. LI-ION BATTERY CHARACTERISTICS

Performance

Li-Ion batteries have the highest energy to weight and energy to space ratios of modern rechargeable batteries. They are one the most efficient options in battery family. Li-ion batteries work on the principle of reversible insertion (extraction) of the ions towards two porous electrodes, which are separated by a foil that prevents electrical contact. The electrodes and separator foil are immersed by electrolyte solution containing charged species of Li+ ions [13].Battery performance is highly dependent on both the charge and discharge current. One advantage of LFP over VRLA is that the former can be charged at much higher C-rates. With high discharge current, Li-ion batteries can provide high levels of power in short time as compared to others, with a very slight variation in efficiency. Temperature at both extremes adversely affects the performance of the Li-ion battery. Shows discharge capacity as it varies across different ambient temperatures [14].

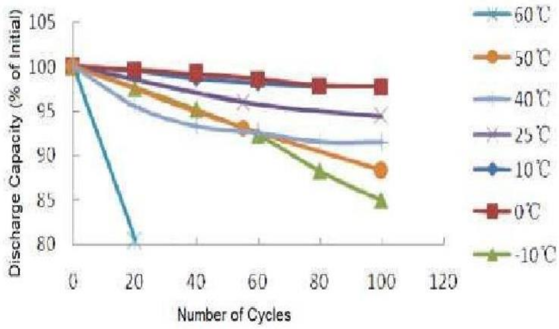

Fig-5: Discharge capacity curves at different temperatures for Li-ion batteries [20]

Charging Properties

Li-ion batteries at full charge reach up to 4.20V per cell, greater than a lead-acid battery cell. While charging the Li-ion battery, the energy stored depends on the difference in the energy states of the intercalated Li+ ion between the cell's positive and negative electrodes [15]. The most common charging method for Li-ion battery is the CC/CV charging algorithm shown in figure 8. The reason for the selection of this method is due to its simplicity and easy implementation. In this method the battery is charged via constant current until a predefined battery voltage (Vpre set) is reached after that a constant charging voltage is supplied, accordingly charging current is reduced exponentially. The charging is completed when the charging current reaches a preset small value. Different charge stages and the CC/CV process are depicted. This CC/CV charging method generally takes 1-2.5 hours to fully charge the cell. Charging with lower currents is generally better for efficiency and long battery life, but this also slows charging. Other common charging methods are variants of CC/CV charging algorithms, multistage current charging algorithm and Pulse charge, they are newer, faster and efficient methods of charging but are complicated then the more common CC/CV method.

Life-Cycle

Battery performance reduce with the repeated use and age, that is capacity is affected which is the ability to repeatedly store and release electric charge, decreases. This phenomenon is often referred as battery aging [16]. This capacity reduction/fading in aging mechanism is generally due to the following factors:

- Loss balance between electrodes
- Loss of electrode area
- Loss of electrode material/conductivity

The bulk material properties of anode and cathode don't vary significantly across Li-ion batteries, but more variation can be seen in mechanical structure and electrochemical properties of the surface [18], [19], [20]. These properties that show significant variations include SEI formation and reformation, contamination, lithium plating, corrosion, gassing, and migration of reaction products. Battery life is tested with different methods including accelerated testing, calendar aging, standardized cycles, and cycle life evaluation [21]. A typical Li-ion battery by A123 Systems can go up to 20,000 cycles with a discharge rate of 1C before losing its optimum capacity [20].

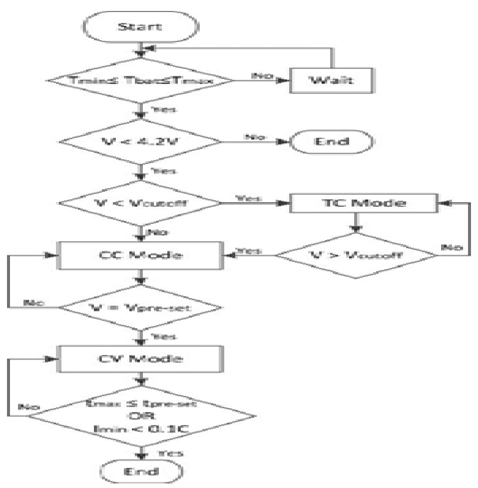

Fig-6: Flow chart of CC/CV charger for Li-ion batteries, where 4.2V corresponds to the maximum cell voltage [17]

4. COMPARISON OF LEAD-ACID AND LI-ION BATTERIES

Lead-acid and Li-ion batteries are the most widely used battery types for stationary storage in power system applications because each is reliable and has unique desired qualities. Since each type has both pros and cons, the decision between battery chemistries is dependent on the specific application and on the funding available. This section compares lead-acid and Li-ion batteries in four aspects: efficiency, life cycle, charging/discharging performance and cost analysis.

Efficiency

A battery's energy efficiency is defined as ˉthe ratio between discharge energy and charge energy‖ [2]. As graphed in figure 10 from capacity measurements, Li-ion batteries are nearly 100% efficient at low C-rates, as shown for both LFT and LTO types. By contrast, the efficiency of VRLA battery peaks at 75% and falls to 55% at a C-rate of 4. Li-ion batteries showing a very slight variation in their efficiency whereas lead-acid being the least efficient [2].

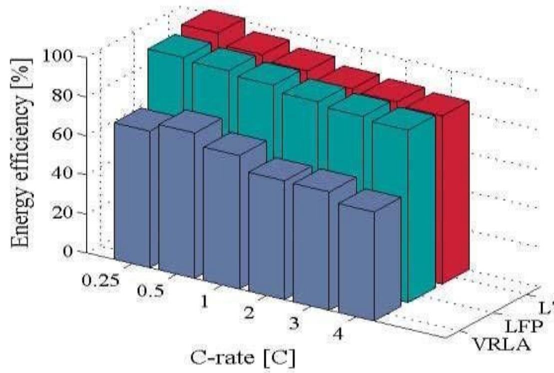

Fig-7: Efficiency of different batteries across C-rates at 25oC [2]

Life cycle

When the life cycle (number of charge/discharge cycles) is considered, Li-ion batteries beat lead-acid by a factor greater than 2 for all DOD VRLA batteries typically operate for 2 to 5 years. Lifetime varies significantly with SOC of the battery, at 50% SOC and 25oC Li-ion can operate for 20-25 years, while at 100% SOC it drops to 12- 16 years [23].

Charging/Discharging Performance

Lead-acid and Li-ion batteries behave differently while charging/discharging depending on factors that include temperature and C rate. The Li-ion battery (LFP) doesn't show near the variation of lead-acid (VRLA). VRLA batteries show a dramatic change in performance when the discharge current rate is increased, but the LFP is minimally affected. In other words, Li-ion batteries can undergo discharge at faster current rates with the similar efficiency as compared to lead-acid batteries, which makes them better with comparison.

In charging, lead-acid batteries are slower (around 0.25 C) whereas Li-ion batteries can be charged at a much higher rate (0.25-4C).One key scenario where lead-acid batteries are superior to Li-ion is when charging at low temperatures. Lead-acid batteries can safely be charged in ambient temperatures as low as -20oC, provided the charge rate is kept at or below 0.3C [21]. Li-ion batteries, on the other hand, cannot be safely charged below 0oC. At freezing temperatures, irreversible plating of liquid lithium develops on the anode while charging Li-ion cells.

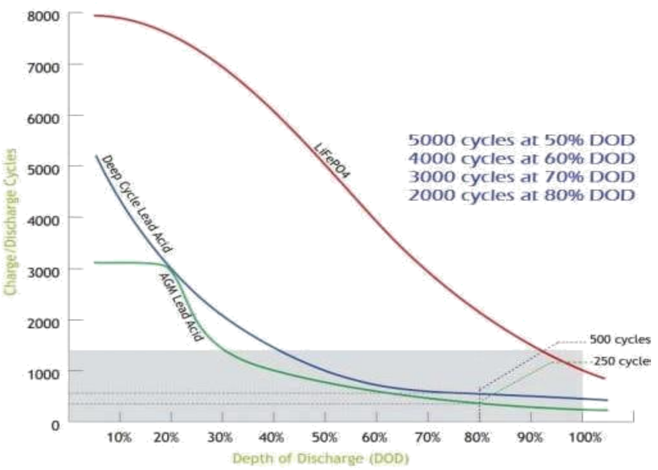

Fig-8: Battery life cycle based on DOD, with discharge current of 0.5C [23]

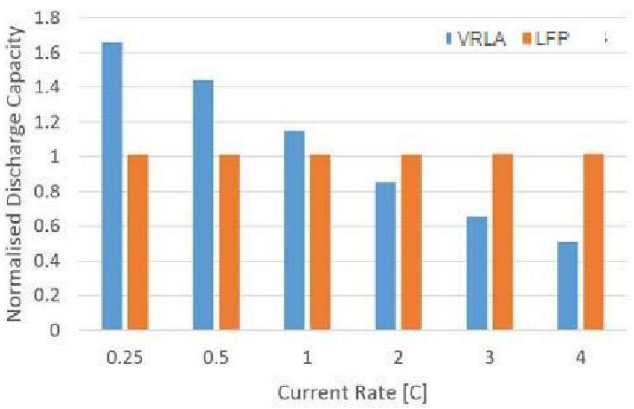

Fig- 9: Normalized discharged capacity versus current rates at a working temperature of 35° C [2]

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When sub-zero charging is done repeatedly, the plating can make the battery unsafe, causing a thermal runaway which destroys the battery with flame as well as burning surrounding objects. Failure by thermal runaway also occurs in Li-ion batteries when their protection circuit is faulty or degraded (e.g. by a faulty charger) [21]. Overcharging causes plating of liquid lithium as described above, which leads to thermal runaways, so precise and robust power electronics (to cut off the charge current at full charge) are essential for safety in Li-ion batteries [8]. Lead-acid batteries, with chemistry more stable than lithium, do not require such a protection circuit though they can still experience thermal runaway when improperly charged [20]. Under sub-freezing charging conditions, however, lead-acid batteries still prove safer than Li-ion.

Cost analysis

In practice, Li-ion batteries are often dismissed for stationary storage projects with significant budget constraints because the lower price for lead-acid batteries translates to a lower cost per unit energy stored on a charge. Looking at energy stored throughout the expected lifetime, however, Li-ion batteries provide cheaper energy than lead-acid. In other words, by dividing the upfront cost over the energy stored times expected operational lifetime (number of charge- discharge cycles), the price of energy is often several times cheaper for Li-ion than lead-acid batteries.

5. OFF-GRID APPLICATIONS IN DEVELOPING COUNTRIES

Especially in the developing world, extending the utility grid to electrify new customers is expensive and often prohibitively so. Bringing power to the poorest citizens also falls low on the priority list for many governments with significant social, health, and infrastructure needs. Off-grid power systems, e.g. microgrids for rural communities, provide a more affordable alternative than grid extension [1]. Reliance on limited and often intermittent generation resources makes energy storage important for reliable service. Given the developing world communities without electricity also lack electric vehicles, uninterrupted power supply (UPS) systems, and more expensive storage options like pumped hydro, stationary storage and specifically battery banks are the best option.

With limited funding these poor communities in need of power and power storage typically purchase lead-acid batteries for communal or building-specific battery backup. The findings in the cost analysis above argue that funds for storage (e.g. outside donations and government grants or subsidies) would be better spent on Li-ion rather than lead-acid batteries. Banks of Li-ion batteries will run for more cycles and at higher efficiency, which means the cost per unit energy provided over the life of the batteries is lower. While raising funds for such a storage system falls outside the scope of this paper, a Li-ion battery bank is a better investment which serves the users longer for lower incremental cost.

6. CONCLUSIONS

Batteries are a widely used and increasingly important component of stationary energy systems. Many different factors show advantages of Li-ion over lead-acid batteries for stationary storage applications. The comparative study reviews major factors that differentiate the two for better planning of energy storage installations. The comparison shows Li-ion to have higher efficiency and 5-10 times the life cycle of lead-acid. On charging and discharging, Li-ion outperforms lead-acid with wide margins. Cost analysis is less straightforward since lead-acid has a drastically lower upfront cost. The results and discussion here presented ultimately find that Li-ion batteries can even be preferable in terms of price when upfront cost is divided over the entire operational lifetime.

Li-ion batteries have higher efficiency, longer lifetimes, faster charging capabilities, and lower incremental cost for energy supplied throughout their lifetime. For these reasons they are deemed preferable for off-grid stationary storage applications except in low temperature locations where lead-acid proves safer. Specifically for off-grid communities in tropical and semi-tropical developing countries, or any location where charging in freezing temperatures is not required, Li-ion batteries are a better long term investment than lead-acid

REFERENCES

[1] J. Thornburg, T. S. Ustun, and B. Krogh, ˉSmart Microgrid Operation Simulator for Management and Electrification Planning, || IEEE PES PowerAfrica, July 2016.

[2] A. I. Stan, M. Swierczynski, D. I. Stroe, R. Teodorescu, S. J. Andreasen and K. Moth, "A comparative study of lithium ion to lead acid batteries for use in UPS applications," 2014 IEEE 36th International Telecommunications Energy Conference (INTELEC), Vancouver, BC, 2014, pp. 1-8.

[3] 3. I. Buchmann, ˉ BU-403: Charging Lead Acid||, Battery University (website), May 2017. http://batteryuniversity.com/learn/article/charging_the_ lead_acid_battery.

[4] W. Rusch, K. Vassallo, and G. Hart, ˉFlooded (Vla), Sealed (Vrla), Gel, Agm Type, Flat Plate, Tubular Plate: The When, Where, And Why. How Does The End User Decide On The Best Solution?||, 2006.

[5] A. I. Stan, M. Swierczynski, D. I. Stroe, R. Teodorescu and S. J. Andreasen, "Li-ion battery chemistries from renewable energy storage to automotive and back-up power applications — An overview," 2014 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Bran, 2014, pp. 713-720.

[6] P. G. Horkos, E. Yammine and N. Karami, "Review on different charging techniques of lead-acid batteries," Technological Advances in Electrical, Electronics and Computer Engineering (TAEECE), 2015 Third International Conference on, Beirut, 2015, pp. 27-32.

[7] C. C. Hua and M. Y. Lin, "A study of charging control of lead-acid battery for electric vehicles," in IEEE International Symp. on Proceedings of the 2000 Industrial Electronics, Cholula, Puebla, 2000, vol. 1, pp.135-140.

[8] I. Buchmann, ˉBU-409: Charging Lithium ion||, Battery University (website), 2016.

[9] X. Muneret, M. Coux, and P. Lenain, "Analysis of the partial charge reactions within a standby VRLA battery leading to an understanding of intermittent charging techniques," in Telecommunications Energy Conf., Phoenix, AZ, 2000, pp. 293-298.

[10] C. Alaoui, and Z. M. Salameh," Experiments in fast charging lead-acid electric vehicle batteries," in Vehicular Technology Conference, 2003, vol 5, pp. 3326-3331.

[11] ˉLead Acid Battery Working – Lifetime Study||, Power thru.https://www.scribd.com/doc/305243921/The-Truth-About-Batteries-POWERTHRU-White-Paper

[12] K. Yabuta, T. Matsushita and T.bu Tsujikawa, "Examination of the cycle life of valve regulated lead-acid batteries," INTELEC 07 - 29th International Telecommunications Energy Conference, Rome, 2007, pp. 97-101.

[13] M. Yoshio, R. J. Brodd, A. Kozawa, ˉLithium-Ion Batteries: Sciences and Technologies||, Springer, pp. XV, 2010.

[14] Jiexun Liu, Dawei Gao and Jianhua Cao, "Study on the effects of on LiFePO4 battery life," 2012 IEEE Vehicle Power and Propulsion Conference, Seoul, 2012, pp. 1436-1440.

[15] H. J. Bergveld, W. S. Kruijt, H. L. N. Peter, ˉBattery management systems||, Springer, 2002, pp. 185.

[16] A. A. Hussein and I. Batarseh, ˉA review of charging algorithms for nickel and lithium battery chargers,IEEE Transactions on Vehicle Technology, vol. 60, no. 3, pp. 830-838, March 2011.

[17] Weixiang Shen, Thanh Tu Vo and A. Kapoor, "Charging algorithms of lithium-ion batteries: An overview," 2012 7th IEEE Conference on Industrial Electronics and Applications (ICIEA), Singapore, 2012, pp. 1567-1572.

[18] Blanchard, S. Herreyre, K. Nechev, R.J. Staniewicz, ¨Main aging mechanisms in Li ion batteries‖, Journal of Power Sources 146, 2005, pp. 90–96.

[19] J. Vetter, P. Novák, M.R. Wagner, C. Veit, K-C. Möller, J.O. Besenhard, M. Winter, M. Wohlfahrt-Mehrens, C. Vogler, A. Hammouche,"Ageing mechanisms in lithium-ion batteries", Journal of Power Sources 147, 2005, pp. 269–281.

[20] B. Markovsky, A. Rodkin, Y.S. Cohen, O. Palchik, E. Levi, D. Aurbach, H-J. Kim, M. Schmidt, ¨The study of capacity fading processes of Li-ion batteries: major factors that play a role‖, Journal of Power Sources, 2003, vol. 119–121, pp. 504–510.

[21] J. Groot, ¨State-of-Health Estimation of Li-ion Batteries: Cycle Life Test Methods‖, Chalmers University of Technology, Department of Energy and Environment , Division of Electric Power Engineering, 2012.