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Comparison of Characteristics - Lead Acid, Nickel Based, Lead Crystal and Lithium Based Batteries

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***Abstract*—Rapid growth and improvement has been witnessed in the field of batteries usage in recent years. Batteries are vital part of our everyday life. Batteries are energy storage devices that have applications in everything from small portable electronics, covering solar energy usage up to aircraft and space vehicles. Various types of batteries are available in market however all the types are application specific and they have their own characteristics in terms of technology implemented or reliability or cost. We present in this paper a comparison of various batteries types, characteristics and charging methods. We finally arrive at a proposal highlighting their suitability with respect to usage domains, especially for renewable energy solutions.**

Keywords–renewable energy; battery; types of batteries; batteries characteristics; charging techniques; batteries applications;

I. Introduction

Batteries are energy storage devices consisting of electrochemical cells that convert chemical energy into Electrical Energy. Batteries are being used everywhere but there are some misconceptions at consumer level which lead to selection of inappropriate battery type in an application which is one basic reason for poor reliability in batteries applications. Industries and researchers have been providing consumers with battery characteristics analysis along-with provision of a lot of techniques and methods to ensure longer battery life but they have not compiled all the content related to all the battery types with their best applications in one piece. Moreover, two aspects that have been mixed in earlier publications are battery life reliability and battery maximum discharging time with fine efficiency as long as load is connected and battery is in working condition. In this paper we have critically analysed types of batteries and their characteristics staying application specific. We have also discussed charging methods for different battery types in order to ensure efficient charging that will result in durability of batteries. After analysis we come with some results and comparison that will assist consumers to select and buy most suitable batteries for their applications. Analysis of charging methods will assist us to achieve reliability and consumers will have batteries that will last for significantly longer period of time.

II. Battery Generic Applications

In this section, we discuss batteries with the most common applications. The most common type of battery being used is used for engine starting known as Start, Light and Ignition (SLI) battery which provides a large amplitude current of a small interval to the starter motor resulting in rotation of crankshaft of internal combustion engine. Secondly, there are applications and industries in which batteries need to stay on stand by for a very long duration. Such batteries are supposed to provide backup power in case of electricity failure which happens once in long time span. Thirdly, the battery can provide much of its power several times, possibly on a daily basis known as Deep Cycle Batteries. Batteries used in electrical vehicle (EV) applications face most strenuous discharges for EV application is a combination of SLI and deep cycle. Batteries are sometimes required to pull high amperage for starting or climbing and it may work on normal amperage capacity on plain routes at constant speeds. While analysing batteries on basis of their characteristics, durability and performance we obtain pretty varying results for one obvious reason that is different types of batteries are being manufactured in industry and all of these types are installed in different applications on large scale. Therefore, there is a need to cover all battery types while doing this kind of detailed analysis as mentioned above.

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III. Battery Classification, Types and Characteristics

A brief explanation to each battery type has been given below in order to provide understanding of the issues and concerns regarding different types of batteries that need to be addressed.

A. Primary Cell/Batteries

Mostly discarded after first use, these are non-rechargeable batteries. These batteries are usually made up of carbon zinc and are least expensive batteries which found their application in low power applications such as electronic portable devices of common use like remote controls.

B. Secondary Cell/Batteries

These can be easily recharged after first use to their original pre-discharge. Main focus of our study will revolve around Secondary Batteries.

1) Lead Acid Battery: A lead-acid battery is manufactured using lead based electrodes and grids. Calcium may be added as an additive to provide mechanical strength. Active ingredient formulation is some lead oxide. For optimize performance, the battery manufacturers have their own proprietary formulation. Electrolyte is a dilute solution of sulphuric acid (H_2SO_4). Active materials that participate in electrochemical charge/discharge include the electrolyte, positive and negative electrodes. Negative electrode of fully charged battery is sponge lead (Pb) and positive electrode is lead oxide (PbO_2). There are several types of lead-acid batteries and a selected set of these is discussed below:

a. Flooded: Flooded type is the traditional engine start and traction style battery which consist of liquid formed electrolyte. Upon drying out, users can easily approach the individual cells and can add distilled water.

b. Sealed: Differentiating from flooded type, sealed batteries do not allow user access to individual cells though internal structure is basically the same as flooded battery and may include number of different constructions including only slight modifications. The manufacturer has to ensure sufficient amount of acid in the battery cell compartments so that the battery may tolerate chemical reactions under normal use.

c. VRLA (Valve Regulated Lead Acid): VRLA batteries offer a valve regulation feature, allowing a safer escape of hydrogen and oxygen gasses during charging.

d. AGM (Absorbed Glass Matte): Electrolyte is suspended very close to the plate's active material in AGM type batteries, theoretically enhancing charge-discharge efficiency. These batteries, actually a variant of sealed VRLA batteries, have become very popular in many engine starts and power sports.

e. GEL: Gel cell batteries are considered to be drier than AGM batteries but have the same style because, both consist of a suspended electrolyte. Electrolyte in a GEL cell has a silica additive that causes it to set up or stiffen, first like Jell-O, then after subsequent discharge/charge cycles more like peanut brittle. Micro cracks form in the gelled electrolyte that provides paths for the oxygen recombination reactions between positive and negative plates. The recharge voltages on this type of cell are lower than the other forms of lead acid battery. This is probably the most sensitive cell in terms of adverse reactions to over-voltage charging.

While discussing battery characteristics, we discuss their thermal characteristics. Thermal characteristics of batteries are of prime interest when we talk about maintenance and reliability of a battery. Lead acid batteries are the most common used batteries in Uninterrupted Power Supply (UPS) industry. Thermal concerns are taken into account because these batteries are often subjected to enclosed environments. Due to recombination phenomenon of VRLA and gelled type lead acid batteries, there is a need to make sure that there is a sustainable thermal management system by studying their properties. With the aim of modelling a thermal management system to minimize heat input and maximize heat transfer, Authors in [2] have conducted an experimental study that included a constant voltage float test in order to determine heat generation rates for different types of batteries. Standard gelled and AGM batteries were subjected to this experimental test in an oven set at varying temperatures for 72 hours. In order to determine the effect of batteries surface area to volume ratio on heat transfer rate, the batteries packing orientation was rearranged in the oven. Heat generated by batteries can be evaluated using:

$$\text{Heat Input (W)} = \text{Voltage (V)} * \text{Current (I)} \quad (1)$$

Float voltage range is usually specified by battery manufacturers and set by user. The acceptance current is very much temperature dependent. In [2], Graph 1 shows the acceptance current as a function of battery temperature. From the construction of VRLA in comparison with flooded battery and the graphical result clearly shows that VRLA batteries draw more current and are more subjected to heat due to property of recombination which is an exothermic reaction. Another factor that plays its role in varying current acceptance is the float voltage. Authors in [2] have shown response and values of current acceptance for Gelled and AGM batteries at 2.30V/^{o}C and 2.40V/^{o}C. Reduction in heat input can be achieved by keeping the float voltage to minimum levels. Positive grid alloy has a significant effect on current acceptance. A comparison of AGM batteries with calcium versus Antimonial positive grid alloy is presented in [2] and graphical results evidently show that calcium system offers lower current acceptance consequently decreasing heat input. Heat transfer properties are second vital component of thermal characteristics of a battery system. Battery with high heat capacity and heat transfer is generally more stable and this is presented in [2]. This is the reason that gelled and flooded batteries are less sensitive to temperature changes because of the additional electrolyte present in them as compared to AGM battery which has less amount of electrolyte surrounding the internal components of a battery. The electrolyte high heat capacity and higher weight fraction makes it a good agent to make battery thermally stable. Table I reflects the above mentioned facts. We have taken average of the Heat Capacities and Heat Transfer Coefficients of Gel, AGM and Wet Batteries from [2], and have enlisted them in Table I, as follows:

TABLE I: HEAT CAPACITIES AND TRANSFER COEFFICIENTS

Battery Type	Average Heat Capacity cal/g-^{o}c	Avg. Heat Transfer Coef.
AGM	0.192	4.6
Gel	0.212	5.2
Wet	0.224	6.8

It is pertinent to mention that heat transfer co-efficient mentioned above are based on single batteries subjected in open air. In case of packed batteries and forced air environment heat transfer co-efficient decreases. From above results it is evident that, Gelled, AGM and VRLA batteries are temperature sensitive as compared to traditional flooded types which have lower heat generation and higher heat transfer rate. Although thermal stability is influenced by battery type, charging parameters and optimizing heat transfer rate.

2) Nickel-based Batteries: Next, we discuss two subtypes of Nickel based Batteries.

a. Nickel Cadmium (NiCd): Invented in 1989, Nickel Cadmium battery was made by depositing active material inside a porous nickel plated electrode. Further improvements were made subsequently by absorbing gases generated during discharge which offered several advantages over lead acid. This also led to modern sealed NiCd battery which was obtained by packing more active material into the cell that increased its capacity by 60% but had high internal resistance and shorter cycle. NiCd became the best battery for the portable electronic equipment in its days.

b. Nickel Metal Hydride (NiMH): In early days when researchers started working on NiMH they did not find it suitable due to the instabilities of metal hydride and as a result NiH was developed which is mainly used in satellites. After discovery of new hydride alloys which provided better stability NiMH were developed and they offered considerable higher specific energy. And another advantage over NiCd is that it is environmental friendly with no presence of toxic metals in it.

C. Lithium Based Batteries

In this subsection, e discuss lithium based batteries, their sub-types and characteristics in this section.

a. Lithium Ion Battery : In the 1990s, Lithium ion batteries went commercial. They do not even suffer from the Memory Effect for their higher energy and power densities as compared to lead acid and nickel cadmium batteries. Memory Effect is the term that is used to define the degradation in the battery capacity when it is partially charged and discharged [13]. These batteries find their vast application in the consumer electronics since then due to their characteristics such as higher efficiency and longer life [14].

b. Lithium Polymer Battery: Lithium polymer battery or lithium ion polymer battery is a rechargeable battery which followed lithium-ion technology made in lighter and soft packaging. Having high energy to weight ratio along-with higher discharge rate these batteries offer a variety of advantages over other battery types. Lithium polymer battery comes with rated voltage of 3.7V per cell. As compared to NiMH it has pretty low self-discharge rate. Considering battery characteristics in this sub-type, Lithium ion battery offers wide range of advantages over Ni based batteries and the prominent ones among them are mass, volume, cost and extended life time [6]. Mass reduction has been one of the most major factor since the battery needs to be placed in satellites where mass is a big concern. Li-ion battery life characteristics for the space applications is [6] where the authors have approached major manufacturers of Li-ion battery and has provided nice comparison of Li-ion battery produced by different manufacturers. In geo-synchronous earth orbit (GEO), battery supplies 1200-2400 cycles for 15 years if DOD (Depth of Discharge) is up to 60% and 35000 cycles over duration of 7 years for a low earth orbit (LEO) satellite with DOD set up to 25% [6]. In addition to that, this battery can be stored on ground for many years if not subjected to use. Like many crucial fields such as space, Li-ion battery did fit in automotive industry as well in order to assist production of efficient Hybrid Vehicles. It is essential to study the design considerations of Li-ion battery for automotive applications. There are number of factors affecting the Li-ion battery usage in automotive industry such as their electronic controls, operating temperature, thermal management environmental impact, durability and cost [7]. All of the above factors specifically addresses lithium ion battery usage in hybrid vehicles [7].

- Monitoring is one major thing that is required in EV especially for sophisticated technology like Lithium ion battery. There is a need of constant cell monitoring and balancing in order to ensure reliability of battery. The need of provision of fine control software along-with electronic hardware with communication system so that battery status can be monitored.
- [7] lists the minimum model output requirements with respect to battery performance and thermal behaviour using MATLAB modelling.

Li-ion batteries are studied in [8] these batteries are found to be the best for space applications. They proposed a scheme that constitute solid state conducting polymer electrolyte which allowed the use of lithium ion battery production along-with use of thinner electrodes and electrolyte. They predicted energy densities up to 250 watt-hours per kg with 1000 charge/discharge cycle.

- In order to obtain optimized performance results, various thermal management approaches could be adopted. A liquid coolant (anti-freeze/water) is the most common approach which is easy to carry out by consumer and it ensures maximum thermal efficiency. But it must be noted that implementation of this technique requires engineering design considerations [7].
- There is need to ensure the maximum battery operating temperature range in transportation applications. Operating temperature range of EV (Electric Vehicle) is -30 to +60^{o}C. Extreme climates may affect battery life if it thermal management system gets over burdened.
- Reliability is one factor that is influenced by environmental exposure.

D. Lead Crystal Batteries

Another modern, highly improved and robust version of lead based battery is in the market i.e., Lead Crystal (LC) Battery. It is claimed that lead crystal batteries perform better than all the other batteries existing when it comes to different battery performance parameters compromising only cost factor for lead crystal is one high priced battery due to fine results. [16] [17] have shown different Battery Performances. LC batteries perform best when kept between 15^{o}C-20^{o}C temperatures. The LC batteries can with stand operation in extreme temperatures too. But it is always advised for the best performance of the battery, to keep the temperature of the environment properly air conditioned [16].

IV. Comparative Battery characteristics

There are variations in behaviour and characteristics of batteries which depend on climate to which they are subjected, application and maintenance levels. Therefore, in order to study battery characteristics, we must set specific parameters for each battery. Lead Acid, Lithium Based and Nickel based batteries have been discussed for their use and applications found at consumer, research as well as industrial level, e.g., in [1],[3], [4], [5], [6], [7].

A. Battery Characteristics with respect to Temperature Variations

It is a general perception that battery life decreases with extreme climate conditions. If we set maintenance factor identical for two different climates for a low and good quality battery, we can study overall battery quality as well. On basis of climate NiCd battery variants have already been analysed in [1]. The study shows that NiCd performance is better than Lead Acid Battery in cold (where maintenance is adequate) as well as hot climate (typically in developing country climate) [1]. By taking high quality lead acid, low quality lead acid and nickel cadmium batteries under observation, [1] has discussed battery response for a hot and fairly pleasant climate for photovoltaic (PV) applications. It is concluded that High Quality Lead Acid is designed for PV applications based on a traction battery with low antimony alloy plates while Low Quality Lead Acid is not designed for PV applications and usually has lead calcium plates. Performance analysis of lead-acid, gel-based, lead-crystal, Nickel-Cadmium and lithium batteries for their operating temperatures, environmental characteristics, and high current discharge are studied in [15] and the results are presented in Table II below:

TABLE II: PERFORMANCE ANALYSIS OF BATTERIES

Item	**Lead Acid**	**Lead-Gel**	**Lead Crystal**	**Lithium**
Operating temperature	18^{o}C to + 45^{o}C	-18^{o}C to + 50^{o}C	-40^{o}C to + 65^{o}C	20^{o}C to + 65^{o}C
Environment	Damaging	Damaging	Safer	Damaging
Safety Transportation	Not Good	Normal	Good	Good
Cycles at 80% DOD	450	500	1000	1000
High Current Discharge	Not Advisable	Not Advisable	Most sustainable	Sustainable
Usage Life	2-3 Years	3-4 Years	7-10 Years	5-6 Years
Performance	Average	Average	Very Good	Good
Recyclability	Good	Good	Very Good	Poor
Size	Average	Average	Average	Small

V. Charging Methods

This section is devoted to various charging methods which is helpful in drawing the final conclusion.

A. Constant Voltage Charging

In constant voltage charging method, voltage across battery terminals are kept constant throughout charging process [11]. Initially, in this process current flows towards battery from power source/charging source is relatively higher than flow in the latter hours. This is mainly due to charge accumulation in battery and reduction in potential difference between voltage levels of battery and charging source.

B. Constant Voltage-Constant Current Charging

In constant voltage - constant current charging methods as discussed in [11], both voltage across and current the battery terminals is kept constant, throughout charging process. Proper charging time mainly depends on discharge rate of a battery.

C. Two Step Constant Voltage Charging

In two step constant voltage charging, as presented in [11], two step constant voltage charging method uses two paths for charging the battery. The method consists of two charging voltage levels. Firstly the battery is charged at a high voltage level. When the battery voltage reaches to a specific/desired potential level, charging voltage is reduced to a lower level and is then charged for a longer time.

D. Trickle Charging

In trickle charging method, small current is constantly supplied to a battery with a small duty cycle [11]. This type of charging is required for those batteries that are used for backup when the normal power supply gets cut. The small current is just used to compensate the self-discharge that occurs in batteries.

E. Float Charging

In float charging, batteries are connected in parallel with load and power supply [11]. The power supply provides load with required voltage and current ratings and at the same time, some of the voltages and currents are consumed by the batteries. Just as the main power supply gets interrupted, the batteries supply power to the load.

VI. Comparative Analysis Results

Hence from [11] and [12], Figure 1 has been concluded in the light of the discussion and the two references as mentioned above.

VII. Our Experiment

We first study lead crystal battery for its charging and discharging cycles under extreme environments. Here, it is pertinent to mention that we present battery classification based on our study and literature review presented in the preceding sections, e.g., [10]. Our classification is presented in Fig. 1 below:

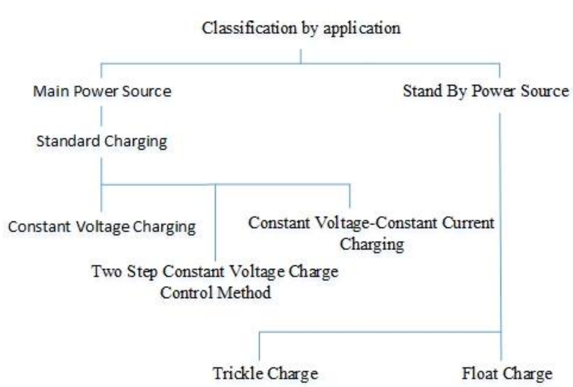

Fig. 1: Battery Classification

To verify if lead crystal battery has better characteristics over lead acid battery, lead acid batteries were exposed to same environments as lead crystal batteries. First of all, 12-V 4-Ah lead acid battery was put under observation. Its charging and discharging curves were plotted and compared with a higher capacity lead acid and lead crystal battery. Battery was exposed to 40% DOD and after 2 to 3 cycles battery died. Then valve regulated lead acid and lead crystal batteries of same capacity were put under observation while charging and discharging. For charging the batteries, two Solar Panels one of 40W and the other of 36W, were connected in parallel combination. In order to obtain discharging curves, same load was connected to both batteries one after the other.

A. Discussion

The load was 12V DC fan. Fig. 2 and Fig. 3 show charging and discharging curves of lead crystal battery. Figure 2 shows an increase in the lead crystal battery voltage. It can be seen that the increase in terminal voltage with respect to time is almost a linear one.

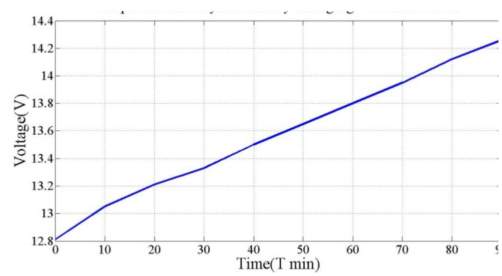

Fig. 2: Charging of Lead Crystal Batter via Solar Panel

Figure 3 shows discharging voltage (red line) and current (green line) of lead crystal battery. It can be seen that current level remains almost constant, throughout, with a very negligible decrease in its level. Providing load with a constant current throughout is always beneficial and improves overall performance of the system.

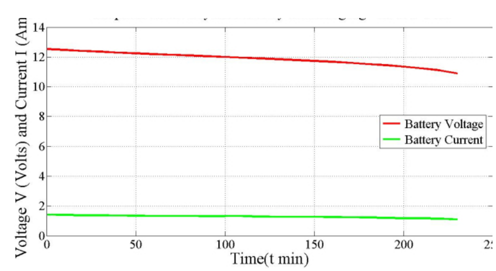

Fig. 3: Discharging Curve of Lead Crystal Battery

The voltage experiences a decrease in the voltage level with respect to time, but the decrease is almost constant, again, benefiting the overall system's performance. Figure 3 and Figure 4 show charging and discharging curves of valve regulated lead acid battery. Figure 4 shows charging curve of VRLA battery.

TABLE III: COMPARATIVE ANALYSIS

Battery / Parameter	Lead Acid	Lithium Based	Nickel Based
Cost	Cheap	Average	Expensive
Maintenance Required	High	Moderate	Low
Estimated Life Time (Years)	Short	Long	Longer
Energy Density (Wh/Kg)	60-110	110-160	45-120
Best Application	Solar Power Storage.	Space Vehicles, Cell Phones, Laptops	Aircraft Applications, Emergency lightening
Depth of Discharge (Apprx)	20% for 500 cycles	20% for 3000 cycles	20% for 2500 cycles
Best Charging Technique	Constant Current-Constant Voltage	Constant Current-Constant Voltage	Constant Current
Hot Climate	Severe Effect	Great Sustainability	Moderate Effect

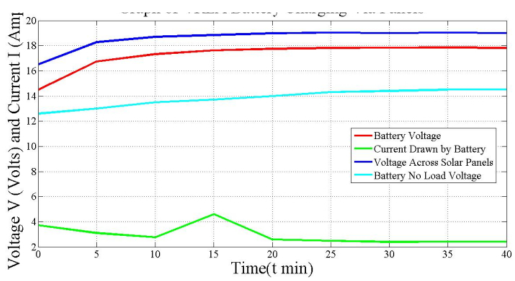

Fig. 4: Charging Curve of VRLA Battery

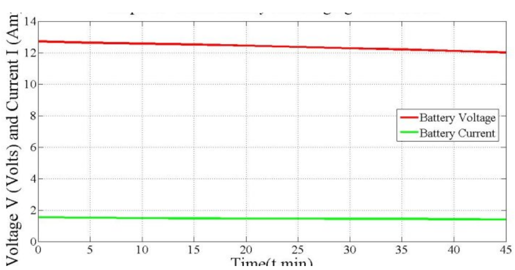

Fig. 5: Discharging Curve of VRLA Battery

Finally, Fig. 5 shows discharging lines of VRLA Battery using a DC fan. Comparing figure 4 with figure 2, it can be noted that VRLA battery lasts shorter than Lead Acid battery. As both the figures show that the Lead Acid battery was subjected to load for approximately 230 Minutes and still maintains its terminal voltage of almost 11V. Also, the current remains almost constant as the terminal voltage of battery decreases from 12.2 V to 11 V. While in case of VRLA battery (figure 5), the battery goes below 12 V right after 45 mints.

B. Observations and Results

Following were the observations made from the charging and discharging curves for VRLA and Lead Crystal Combined.

- While discharging, current oscillations are frequent in lead acid based battery. From 12.20 V, current started from 1.40 but kept oscillating between 1.37 A to 1.32 A. Whereas lead crystal battery is quite stable in terms of providing current and voltages.
- It is evident from the results that Lead Acid based battery cannot resist effectively the large DODs (more than 15%) as compared to Lead Crystal Battery.

VIII. Recommendations

We have covered a wide range of the most commonly used battery types. We have noticed that a battery operation is a battery management system (BMS) there are factors due to which a BMS can affect a battery's life and performance. While providing recommendations for the right BMS, we consider charging techniques as well. We take lead from prior checks and recommendations, defined in [9], that have a direct impact on battery maintenance and battery life. They are:

- End Application: battery performance differs as per its usage so does the charging mechanism. Therefore, in order to obtain optimal battery performance, BMS should be designed application specific.
- Regulation: The charger should maintain output voltage of battery charger to within +, - 1 % maximum because excessive voltage causes overcharge which consequently gives rise to battery temperature and reduces battery efficiency.
- Voltage Settings: Each battery needs to be charged on a specific voltage. This voltage varies with each battery type. To obtain optimum performance out of any battery, they need to be fully charged without overcharging.
- Load and No Load Voltage: There is a difference between battery load and no load voltage which needs to be determined. Load voltage is the voltage of battery when it is connected to the load while no load voltage is battery voltage when its terminals are open.
- Battery Intrinsic Resistance: No real batteries constitute materials which have zero resistance which is known as Internal Resistance (r). For a battery, the voltage source (an emf source) is connected in series with the Internal Resistance. The relation between battery voltage and internal resistance is $V = \xi - Ir$.

- Negative Temperature Compensation: When battery is used in an area where temperature varies, there needs to be an in-built feature in the charger which makes sure that for every degree change in temperature it varies supply voltage to battery in order to ensure longer battery life and improved efficiency.
- Charger Sizing: Each battery needs a proper sized battery charger for an efficient charging. A low capacity charger is not suitable for a big battery because low capacity battery cannot charge a big battery with enough energy needed. Small charger will keep on charging it on a trickle charge which means provision of inadequate electron flow to battery. For most industrial applications, charger size needs to be of 10% of battery AH capacity. In case of relatively larger charger, care should be taken that too much current should not be forced in discharged battery. As suggested [9] standard rule of thumb is not to provide more than 25% of battery AH capacity.
- Power Source Analysis: For different power sources, BMS designs needs different electronics and control. It also depends on the magnitude of power sources. For example, in high power applications in PV (photovoltaic), BMS needs to be an intelligent maximum power point tracking controller involving complex power electronics to avoid huge power loses [17]. While in case of low power applications, a PWM charger can serve the purpose.

Charging techniques play a vital in improving many factors like reducing battery charging time, enhancing battery performance and increasing battery life.

IX. CONCLUSIONS

Concluding our discussion on selected parameters including extent of discharge, deep discharge cycle life, charging efficiency and energy range and energy density, we report that while comparing extent of discharge, lead acid batteries undergo more damage as compared to Nickel Cadmium batteries. We also conclude that deep discharge cycle and nickel cadmium batteries life time is better as compared to low quality Lead acid batteries. However, high quality LA and high quality batteries stand approximately equal to nickel cadmium batteries. Discussing charging efficiency, low and high quality Lead acid batteries over take the Nickel Cadmium batteries. Comparing Energy Range, Lead Acid batteries lag behind Nickel Cadmium batteries, while in context of Energy Density, Lead Acid Batteries are more feasible to use. Considering VRLA and Lead Crystal Batteries, lead crystal batteries have proven to be more reliable and have greater percentage of DOD (Depth of Discharge). If price is not users concern and battery is to be used in a sophisticated application like large power distributed generation systems and deep cycle applications, lead crystal batteries will prove to be a better choice in terms of longer life span and better performance.

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