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Determining the shortest charging time of batteries using SOC set point at constant current – constant voltage mode

***Abstract**. A method of determining the shortest charging time of 3 types of batteries: Lead Acid, Lithium Ion, Nickel metal hydride. Constant current (CC) and constant voltage (CV) charging modes are applied. Initially filled using the constant current method, the voltage and SOC increase over time. When reaching a certain SOC, as a set point, the voltage becomes constant and the charging current decreases until the battery is fully charged. The results show that the fastest charging time by for Li-Ion is 2.632 hours, Lead Acid is 4.619 hours, Ni-mH is 6.714 hours.*

***Streszczenie.** Opisano metodę określania najkrótszego czasu ładowania trzech typów baterii: ołowiowej, litowo-jonowej i niklowej. Rozpatrywano tryb stałego prądi I stałego napięcia. Po osiągnięciu pewnej wartości SOC (State of Cargin) pozostaje stałe napięcie a prąd stopniowo maleje. Otrzymano następujące rezultaty: liowo jonowe 2.6 godz, ołowiowe 4.6 godz I niklowe 6.7 godz. (**Badanie najkrótszego czasu ładowania baterii przy ładowaniu stałym prądem I stałym napięciem**)*

Keywords: Battery, Constant current (CC) mode, Constant voltage (CV) mode.
Słowa kluczowe: czas ładowania baterii, SOC – status of Charging

Introduction

The production and use of batteries as the primary source of energy has rapidly increased [1, 2] . The battery as the vehicle's primary source of energy [3, 4, 5] and the battery as a backup on the use of renewable electricity, such as the use of wind energy, PV to the use of marine current energy [6], including the use of batteries in data transmission systems [7]. The function of the battery in the use of renewable energy is also to maintain energy balance and improve power quality [8].

For each battery charging process, the efficiency of the charging process needs to be needed. Several studies have been carried out relating to battery charging, such as chargers designed to regulate voltage levels and charging. While research on the battery charging status (SOC) in the SOC estimation uses new improved coulomb counting method, the coulomb calculation algorithm, the universal SOC algorithm, and the Kalman filter algorithm. State of charge (SOC) describes how much charge is available in the battery relative to its capacity, expressed in percent (% SOC). [9, 10, 11, 12] .

Various simulation models for the testing and analysis of Lead Acid and Li-Ion batteries have been carried out. Simulation models were developed based on equivalent circuit models of lead batteries and 12V Li-ion batteries. The purpose of battery simulation is to study the battery operating system which consists of various battery models under various operating conditions [13]. When compared to lead-acid batteries, Ni-mH batteries are safer, more environmentally friendly, high specific energy and high specific power. To determine the state of the Ni-mH battery energy, a battery model is needed. The model used is very important to simulate the performance of the dynamic utilization of the battery [14]. Based on the advantages of each battery, it is necessary to design a circuit that compares the charge speed of each type of battery at the same current, voltage and capacity.

This research aims to find the shortest time to charge three types of batteries. The shortest time when charging a battery is very important to prevent the battery from being damaged in the form of bulging, smoky and exploding. Therefore, how to design a battery charging system that is able to show the shortest time when charging a battery by paying attention to the SOC, current and voltage. The system designed can show the results of three types of batteries used.

Battery characteristics

Batteries have been manufactured in many types of material and characteristics. Each battery has better capabilities under special operational requirements. The use of special designs is needed for safety and energy related to the safety of the battery itself. Therefore it is necessary to know the characteristics of each battery.
Generally, the battery circuit model is shown in Fig 1 [15]:

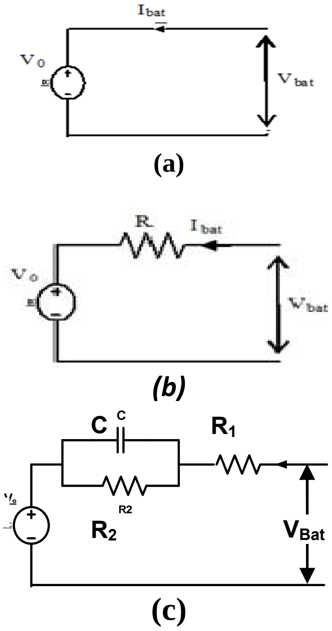

Fig.1. Batteries model; (a) Ideal, (b) Linear, (c) Thevenin

Based on the circuit image in Fig. 1, the voltage value using the ideal model uses the equation:

(1) $$V_{bat}(t) = V_0$$

Where V_{bat} is the battery voltage at time t, and V_0 is the battery initial voltage. Voltage values in linear models using the equation:

(2) $$V_{bat}(t) = R.I_{bat} + V_0$$

Whereas in the Thevenin model, voltage values are obtained using :

(3) $$V_{bat}(t) = R_2.I_{bat} + R_1.I_{bat}(1 - e^{\frac{-t}{R_1.C}}) + V_0$$

where: Vbat is battery voltage, V. V_0 is initial voltage, V. t is time, s. R is resistance, Ω. R_1 is resistance 1, Ω. R_2 is resistance 2,Ω. I_{bat} is current of battery, A. V_{bat} is the battery voltage at time t, V. V_0 is the battery initial voltage, V. C is capacitance, C.

Lead acid

Lead Acid battery is a type of battery that contains lead, lead dioxide and sulfuric acid. This battery is a type of battery that can be re-charged. Lead acid batteries are an effective energy storage technology. Also low cost, good recycling, and favorable electrochemical characteristics so that most electric vehicles use Lead acid batteries. However, the disadvantages of lead acid batteries are low performance, low durability and environmental problems due to the use of lead.

The Lead acid battery charge voltage equation follows as [16]:

(4) $$V_{bat}(t) = V_0 - R.I_{bat} - K\left(\frac{Q_{max}}{Q_{max} - Q}\right)(Q + i^*) + V_{exp}(t)$$

(5) $$V_{Dc,Bat} = E_0 - Ri_{Bat} - K\left(\frac{Q_{max}}{Q_{max}-Q}\right)(Q + i^*) + V_{exp}(t)$$

Lithium Ion (Li-Ion)

Some of the advantages of lithium-ion batteries are long life, energy density, safety, low cost and charging speed. Another advantage of this battery is the non-flammable electrolyte field. [17].

Li-Ion has the disadvantage of being very sensitive to overcharging and if connected in series, an imbalance in battery capacity can occur. If both of these occur then it can cause a decrease in the performance of the battery. Therefore, special methods are needed to recharge the battery. The voltage and current relationship as in equation [18]:

(6) $$V_{bat}(t) = V_0 - R.I_{bat} - KQ_{max}\left(\frac{1}{Q - 0.1Q_{max}} i^* - \frac{1}{Q_{max} - Q}\right) + Ae^{-BQ}$$

Natrium metal Hidrid (Ni-mH)

Ni-mH battery technology is a cadmium free battery, which is a successor to rechargeable and portable Ni-Cd (nickel cadmium) batteries. This battery uses a metal hydride alloy for negative electrodes. Ni-mH battery is high power batteries in small size because the power density is very high. The disadvantage of this battery is that it has a high self-discharge. The voltage and current relationship as in equation [19].

(7) $$V_{bat}(t) = V_0 - RI_{bat} - K\frac{Q_{max}}{Q_{max} - Q}(Q + i^*) + A(t)$$

To get an idea of what needs to be considered in the use of batteries it is necessary to know the advantages and disadvantages of each. The following are the advantages and disadvantages of the three types of batteries table 1.

Tabel 1 The advantages and disadvantages of battery

Batteries	Advantages	Disadvantages
Lead Acid	- varied designs - mature, reliable and well-understood technology - Capable of high discharge rates. - the best in terms of reliability and workability - able to deal with conditions of slow, fast and excessive power charging - able to survive inactivity in the long run without electrolyte solution	- Low capability and cycle life (50–500 cycles) - Limited energy density—typically 30–40 Wh/kg - Transportation restrictions on flooded - Thermal runaway can occur if improperly charged. - There are environmental concerns regarding spillage.
Lithium-Ion	- Has no memory effect - Very high energy density - Small self-discharge - More twisted than other batteries - Quite a lot of cycles which is around 400-1200 cycles	- flammable - Short life time - Cobalt material used is rare - the main material, lithium, is an alkali metal that is highly reactive - Very sensitive to high temperatures
Nickel metal Hidrid	- Higher energy density compared to NiCd - Does not contain hazardous materials - The construction is closed so that it does not require maintenance - Long life cycle - Long shelf life in each SOC - Environmentally friendly, even the toxin it contains is light.	- High self-discharge - Low internal resistance - High-rate of performance is not good - Poor charge retention - Do not absorb overcharge properly, trickle charge must remain low - limited service life, deep discharge - The cost of negative electrodes is higher

Capacity and state of charge (soc)

Capacity is the amount of charge stored in a battery, usually expressed in units of Ah (Ampere-hours). The international unit for capacity is Coulomb, but in battery technology, Ah units are used more often. If 1 C = 1 ampere-second, then 1 ampere-hour (Ah) = 3600 C. Battery capacity is also the maximum energy that can be extracted from a battery under certain conditions. Large battery capacity (Q) is expressed in the equation:

(8) $$Q = \int i_{bat}\, dt$$

State Of Charge (SOC) shows the state of the battery at a certain time. SOC becomes very important so that energy management control becomes effective and efficient. Observation of the SOC is also to determine the percentage of remaining battery capacity. To state the percentage of available (remaining) battery capacity expressed as the state of charge (SOC) stated in the following equation:

(9) $$SOC(t) = 100 * \left(1 - \frac{Q}{Q_{max}}\right)$$

Q_{max} is the maximum capacity owned by the battery. When the battery is fully charged, we can say that this SOC Battery is 100%. SOC can be used to evaluate the way the battery is fully charged.

Methodology

Three common methods for charging a battery: constant current, constant voltage, and constant current-constant voltage combination (CC-CV). Constant current is a simple form of battery charging. A relatively long charging time can cause the battery be overheat. Constant voltage allows the full current of the charger to flow into the battery until the power supply reaches a predetermined voltage. The battery can be left connected to the charger until it is ready to use and will remain at "floating voltage".

The principle of data collection follows the pattern shown in Fig 2:

The constant current-constant voltage (CC-CV) mode is a combination of the constant current and constant voltage methods. The characteristic of changing CC to CV is shown in Fig. 3.

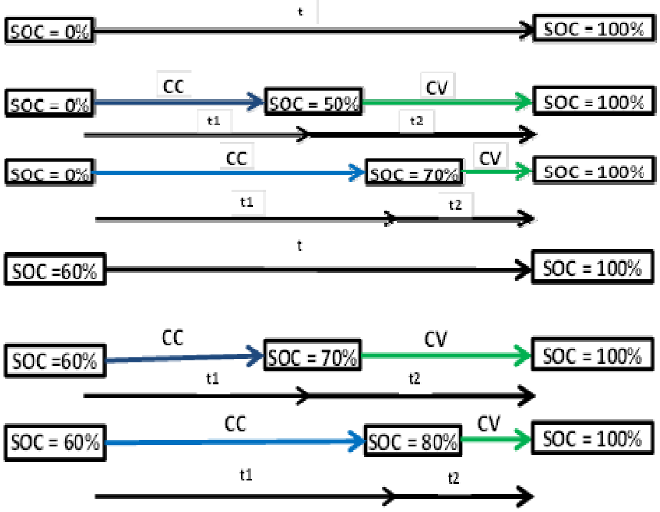

Fig. 2. The pattern of recording time when CC and CV

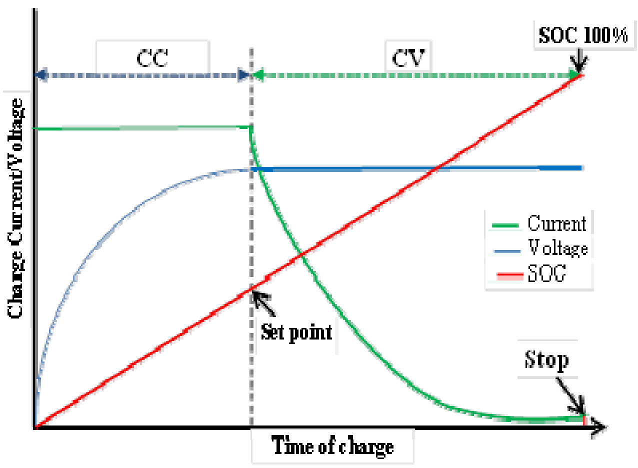

Fig. 3. Charge characteristics using CCCV mode

The charge path starts at the input voltage and current into the charge circuit. Voltage input values are based on the value of the voltage range required for each battery. The input current value is set at 20 A, as shown in Fig 3. The input voltage is connected to the switch and to the battery. Input The current is connected to another switch and the battery. During charge, the two switches work alternately based on set point (% SOC) settings.

The purpose of charging the battery using CC-CV mode is to limit the charging current because the charging current will reduce the battery life Following the in Fig. 2, then designed the circuit as Fig. 4, and data collection is obtained by inputting a current of 20 A and the voltage according to the voltage range in each type of battery as listed in table II.

In Fig. 4, the two inputs, voltage and current, are connected to the battery and the switch. One side of the voltage and current is connected to the (-) side of the battery, the other side is connected to a switch (regulating on-off to the current or voltage) which is then connected to the (+) side of the battery.

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The three outputs on the battery charge are current, voltage and SOC. SOC output as a set point on the change from constant current (CC) to constant voltage (CV). Set point is set in the range of SOC = 10% to SOC = 95%. Changes in SOC values, time, and voltage are recorded to be made in graphical form.

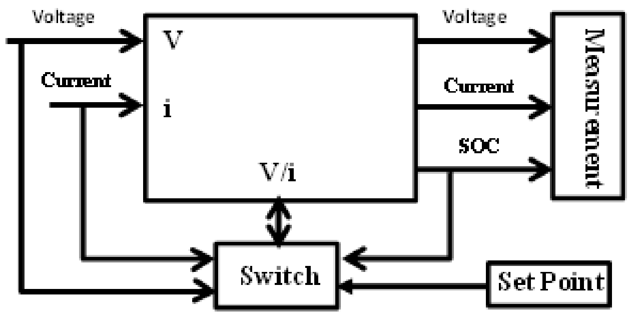


Fig. 4 Circuit battery charging design

The three steps taken at battery charging are::

1. At the beginning, the initial current is conditioned constant. The switch is connected to the current input (switch 1 is On) and switch 2 is connected to the opened voltage (switch 2 is Off). The other side of the current meter is connected to the battery. Likewise the other side of the voltage gauge is connected to the battery.
2. The next step is the constant voltage (CV) condition. A constant voltage occurs when the SOC set point reaches a certain point. Set points based on SOC in the range SOC = 0% to SOC = 95%. When reaching a certain set of SOC, the switch that connects the voltage is closed (switch 2 ON) and the switch that is connected to the current is Off. This process is also called the transition from CC to CV (CC-CV).
3. The last stage is the present cessation when the battery is full (100 percent SOC). Complete charging occurs when a threshold voltage is reached by the battery, and the current will drop to 3% of the measured current. Also, if the current level stops or cannot be even lower, the battery is considered fully charged.

Voltage settings are adjusted to the type of battery. Lead acid batteries use Lead Acid input voltages of 12.9 V - 13.56 V, Li-Ion at 13V - 13.2 V, and Ni-MH at 13.339883 V. While the inputs used for the three batteries are the same, which is 20 A.

Set point settings based on the desired SOC value to change from constant current (CC) to constant voltage (CV). The role of SOC is very important to determine the time of CC change to CV. When changing CC to CV is a transition period that can affect the performance of the main battery when the battery is being used.

The use of two switches can trigger a spark on the current. So that the spark does not occur, then the inductor must be installed before entering the battery.

Table 2 the parameter values for each battery

Parameter	Lead acid	Li-Ion	Ni-mH
E_0 (V)	12	12	12
Nominal capacity,Ah	100	100	100
Charging voltage, V	12.9-13.56	13-13.2	13.39883
Charging current, A	20	20	20
Internal resistance, R (Ω)	0.0012	0.0012	0.0012
K (Ω)	0.003573	0.00089	0.0012605
A (V)	0.81645	1.0077	1.1127
B $(AH)^{-1}$	9	0.61062	0.15
Respon time (s)	1	1	1

Results and discussion

The battery parameters used to charge three types of batteries are presented in table II. Data are obtained from the initial charge process and the specifications of each battery in the Matlab Simulink program.

Current profile with respect to SOC

Simulation results are presented in the interaction of current and SOC in the initial SOC state of 50%, change in CC to CV when the SOC is 70% and change in CC to CV when the SOC is 95% as shown in Fig. 5. Initial SOC 50% means the battery starts charging at SOC = 50%. 70% SOC CCCV means that there is a change from CC to CV when the battery is 70% (SOC = 70%).

As shown in Fig. 5, the charge current on the Lead Acid battery decreases linearly after changing from CC to CV. Decrease in the current looks very slow. The current required by a Lead Acid battery when full (SOC = 100%) is 5.7 A.

While the current in the LI-Ion battery decreases gradually, the current changes rapidly when charging SOC = 95% to the full, from current 11.24 A to 0.095 A. In the SOC profile of current for Ni-mH batteries, the change in charge current is very fast, from 20 A (SOC = 70%) to 5.91 A (75%). The increase in SOC is only 5%. The current required by a Ni-mH battery when fully (SOC = 100%) is 1 A.

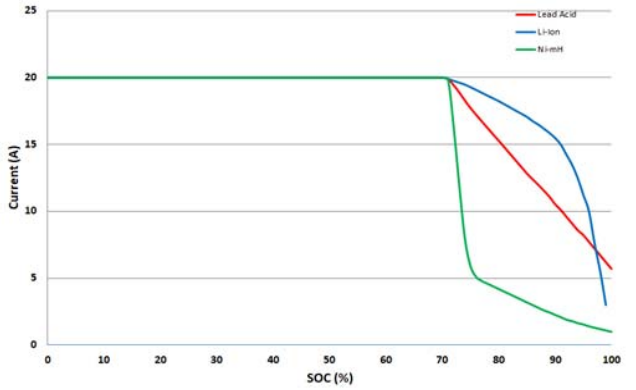


Fig. 5. Changes in current with increasing SOC SOC=50%, set point SOC= 70%

The results of the comparison are shown in Fig. 6. The current profile for SOC on Lead Acid and Li-Ion batteries looks the same. Charging the Lead Acid battery fully (SOC = 100%) requires a current of 1,294 A. While Li-Ion is fully charged only up to SOC = 98% and requires a current of 5,011 A.

Charging Ni-MH batteries look slow and the current needed to reach full are higher than Lead Acid and Li-Ion batteries. The current required for a full Ni-MH battery is 9.5 A.

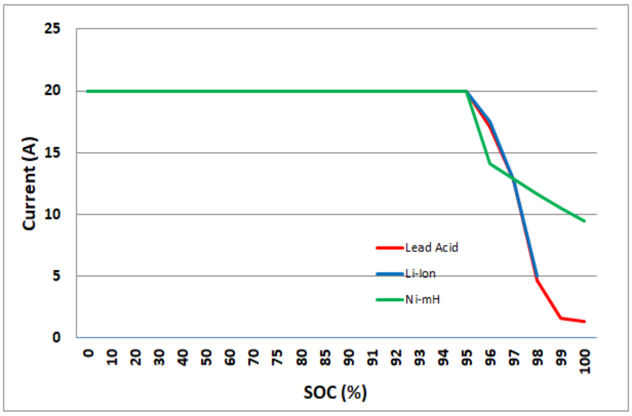


Fig. 6. Changes in current with increasing SOC SOC=50%, set point SOC= 95%

SOC Set Point profile with respect to time

The charge characteristics of each type of battery are based on changes in CC to CV each time starting from SOC = 0% to SOC = 100% presented in Figs 7a, 7b and 7c. In this section what is observed is the time required for each battery to be fully charged at SOC = 0%, SOC = 30% and SOC = 50%. Change of CC to CV is set point at SOC = 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90% and 95%.

As can be seen in the graph in Figure 7a, if the initial Lead Acid SOC battery charge = 0%, set point SOC = 55%, the time required to be fully charged is 14,056 hours. If the SOC set point is at 95%, the time required until fully charged is 7,277 hours. If the initial Lead Acid SOC battery charge = 30%, set point SOC = 55%, the time required to be fully charged is 12,528 hours. If the SOC set point is at 95%, the time required until fully charged is 5.682 hours. If the initial Lead Acid SOC battery charge = 50%, set point SOC = 55%, the time required to be fully charged is 11.531 hours. If the SOC set point is at 95%, the time required until fully charged is 4.619 hours.

On the Li-Ion charge chart in Figure 7b, where the chart pattern tends to be the same. If the initial Li-Ion SOC battery charge = 0%, set point SOC = 55%, the time required to be fully charged is 5.92 hours. If the SOC set point is at 95%, the time required until fully charged is 5.136 hours. If the initial Li-Ion SOC battery charge = 30%, set point SOC = 55%, the time required to be fully charged is 4.399 hours. If the SOC set point is at 95%, the time required until fully charged is 3.613 hours. If the initial Lead Acid SOC battery charge = 50%, set point SOC = 55%, the time required to be fully charged is 3.398 hours. If the SOC set point is at 95%, the time required until fully charged is 2.632 hours.

On the Li-Ion charge chart in Fig. 7c, where the chart pattern at each SOC set point shows a long charge time. The longest charge time if the battery starts charging at SOC = 0% and the set point SOC = 55% is 18.538 hours. The shortest charge time of this battery is if the battery starts charging at SOC = 50% and the set point SOC = 95% is 6.714 hours.

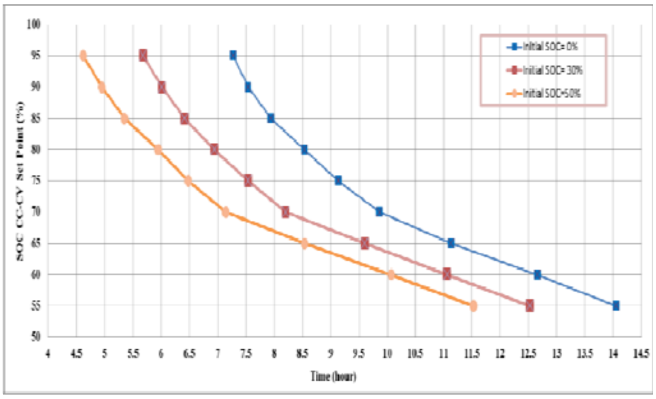
SOC set point profile with respect to time

The timely process of the CC and CV will determine the length of the charging process. The duration of CC and CV for the initial SOC (0%, 30%, 50% and 80%) until the battery is fully charged (SOC = 100%) is summarized in Table III.

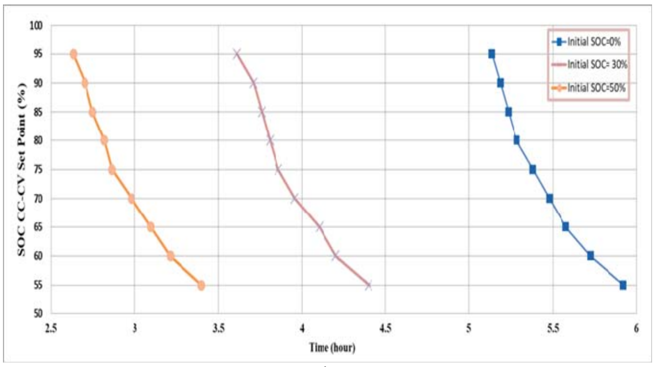
Tabel 3. The duration time (hour) of CC and CV at set point SOC = 95% in each initial condition of the battery.

Battery	0%		30%		50%		80%	
	CC hour	CV hour	CC hour	CV hour	CC hour	CV hour	CC hour	CV hour
Lead Acid	4.95	2.33	3.40	2.28	2.35	2.27	0.77	2.32
Li-Ion	4.74	0.39	3.27	0.34	2.26	0.37	0.75	0.37
Ni-mH	5.12	4.26	3.51	4.28	2.64	1.87	0.97	1.60

Graphical form of change of CC to CV when the initial charge SOC = 50%, set point SOC = 95% on the three types of batteries presented in Fig. 8



7a



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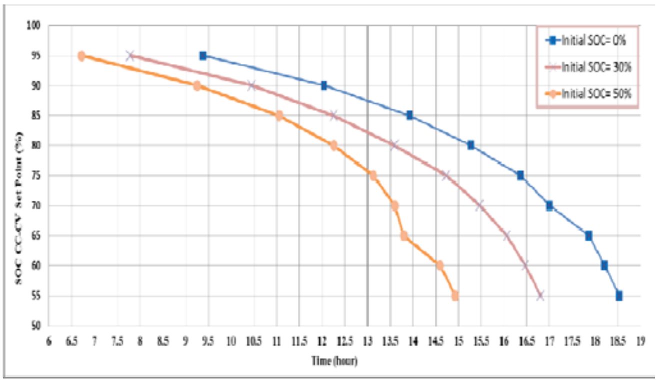

7c

Fig.7. Comparison of % SOC CC-CV to time based on the initial capacity of (a) Lead Acid batteries, (b) Li-Ion, (c) Ni-mH

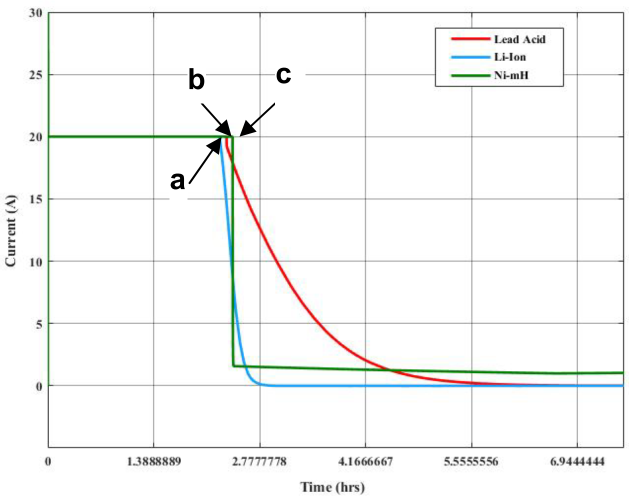

Fig.8 Change CC to CV,initial SOC = 50%, set point SOC = 95%, a-2.06; b= 2.10; c= 2.17

The fastest charging time

When charging the battery in a condition of current drop and voltage is constant, then the current levels are off and can not go further down, a battery is considered fully charged. Based on the simulation results as shown in Fig. 9, that the Lithium Ion charged at the SOC 55% - 95% set point shows the fastest battery to charge compared to leading Acid and Ni-mH. The fastest time achieved by Li-Ion to fully (SOC = 98%) is 2,632 hours. The charge occurs at the 95% set point where the initial SOC is 50%.

If the charge on the three batteries is continued at the set point SOC = 96% to SOC = 98%, the time taken for each battery to be fully charged is still the same. Therefore, the high s Li-ion batteries do not need to be fully charged as is the case with lead acid and Ni-mH, even better not to charge fully because a voltage higher than the maximum voltage will stress the battery. Therefore Choosing a lower voltage threshold or eliminating charge saturation will completely extend battery life and prevent the battery from rising battery temperature so damage occurs.et point chosen is SOC = 95%.

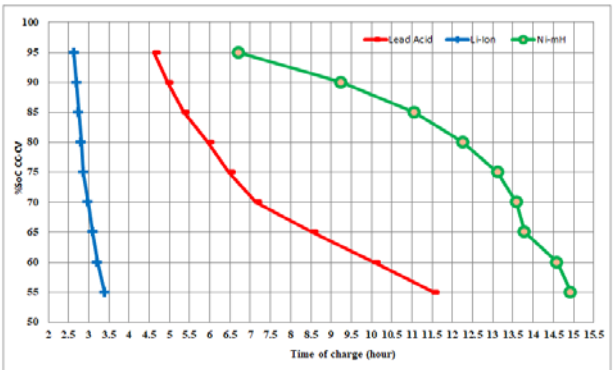

Fig.9 The fastest and best of battery charge

Conclusion

Simulation and analysis to find the shortest charging time for 12 V/ 100 Ah of Li-Ion, Lead acid and Ni-mH batteries was presented in this paper. Firstly, the batteries were charged from empty, or the State of Charge (SOC) at 0% using Constant Current charging mode. Then, a Constant Voltage (CV) mode was applied to replace the CC mode at a certain SOC (set point), until the baateries were fully charged. The sortest charging time was obtained by Lion battery at 2.632 hours when the set point was at 95%.

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