Automatic Battery Charging Algorithms for Hybrid Electric Vehicles

F.Vijay Amirtha Raj

Abstract— Battery-charging algorithms can be used for either single or multiple-battery chemistries. Single-chemistry chargers have some advantages than multi chemistry chargers because of its simplicity and reliability. On the other hand, multi chemistry chargers, or "universal battery chargers," provide a practical option for multi chemistry battery systems, particularly for portable appliances, but they have some limitations. This paper proposes the design of a single chemistry intelligent battery charger that can be used for major batteries, i.e. Nickel-Metal-Hydride and Lithium-Ion batteries for use in Hybrid Electric Vehicles (HEV). The design is implemented using MATLAB Simulation Tool which monitors the battery status and parameters and controls the charging operation. This ensures complete, fast, and safe charging of the battery pack.

Index Terms— Constant current (CC), constant voltage (CV), inflection point, open-circuit voltage (OCV), pulse charging, state of charge (SOC), trickle charging, voltage drop.

I. INTRODUCTION

BATTERIES play a crucial role as emergency backup power in various industrial applications. For example, in the case of power supply failure, batteries provide emergency power in uninterrupted power supply (UPS) systems, alarm systems, emergency lighting, telecommunication systems, etc.

A battery charger is expected to charge batteries at an optimized charging rate and terminate the charging procedure when the battery is fully charged. The charger design thus strongly relies on a reliable charge termination method adopted. Each battery cell has its own composition and therefore charging curve/characteristics. The battery charger should be knowledgeable enough to comply with such battery specific requirements. Another challenging aspect in the design of a battery charger is to automatically handle large variety of batteries with different configuration and capacity.

Battery charging is the most substantial issue in battery management systems. Basically A charger performs three functions: 1) delivering charge to the battery; 2) optimizing the charge rate; and 3) terminating the charge. The charge can be delivered to the battery through different charging schemes, depending on the battery chemistry. For example, nickel batteries require only constant current (CC), whereas Li-ion batteries require constant current/constant voltage (CC/CV). The charge rate can be optimized if the capacity and state of charge (SOC) are given. As an example, a completely discharged or a fully charged battery must be trickle charged with a very low current (a fraction of the capacity rate) to extend the battery life when it is completely discharged and to sustain the full charge in the battery when it is fully charged. In addition to CC and CC/CV charging schemes, pulse charging, which uses a pulse current for up to 1 sec, followed by a rest period and a discharge pulse for milliseconds, is claimed to be optimal, because it improves the charging speed and efficiency. With regard to the charge termination, different techniques are used, such as the voltage drop and temperature rise in nickel batteries or the inflection point (the point at which the sign of the second derivative of the voltage–time curve changes or the point at which the first derivative of the voltage–time curve is zero) in both nickel and lithium batteries. This paper proposes the design of an intelligent battery charger capable of charging NiMH or Li-Ion batteries, which can be used for Hybrid Electric Vehicles. The organization of this paper is as follows. Section II introduces and explains the terminology used in single chemistry battery charging applications and the functioning details of the battery charger and operation. Section III details the developed simulation logic and the experimental results of the developed prototype, along with its performance characteristics. Finally section IV summarizes the conclusions and outlines the future work.

II. CHARGING RATE AND CHARGING TERMINATION

The NiMH and Li-Ion batteries are high energy/power density, life-cycles batteries and can be rapidly charged in 1 to 2 hours with the usage of proper charging method. However, it is necessary to closely monitor the allowed operating conditions so that they are not violated. To discuss the battery charging performance some charging tests were performed on commercial NiCd, NiMH, and Li-ion single cells with capacities of 1200,1000, and 1100 mAh, respectively. The cells were completely discharged and then completely charged. Fig. 1 shows the results.

A. Charging Process

*1).Charging Method***:** The charging techniques used in single chemistry algorithm are trickle charging, CC, and CC/CV. Trickle charging uses a very low current of a magnitude around 0.1 C to pre-charge a completely discharged battery or to sustain the charge in a fully charged battery. A discharged battery is normally trickle charged for a short time to extend its life. On the other hand, CC and CC/CV are usually used for bulk charging. NiCd and NiMH batteries require only CC, whereas Li-ion batteries require CC until the battery voltage reaches a predefined safety limit at which CV begins. CV charging is used in Li-ion batteries to limit the current and thus prevent the battery from overcharge.

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Results in Fig. 1 show CC charging [see Fig. 1(a) and (b)] and CC/CV charging [see Fig. 1(c)].

*2).Temperature Control***:** The chemical reactions that occur inside the battery during charging produce heat. This heat increases the pressure and the temperature of the battery pack. The charger keeps monitoring the temperature during charging, and if the temperature deviates from a predefined range, the charger will either switch from fast charging to trickle charging or show a "fault" statement until the normal temperature range resumes.

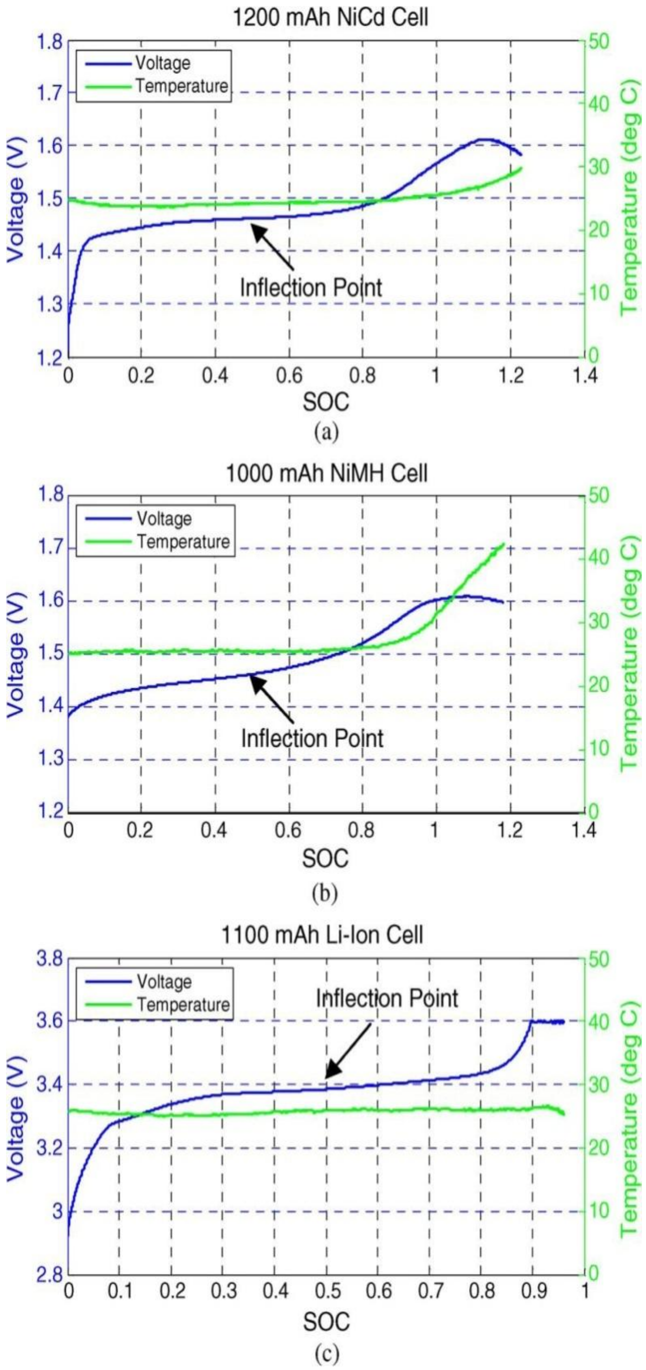

Fig.1. Voltage and temperature profiles for charging.(a) NiCd, (b) NiMH, and(c).Li-ion cells.

*3) SOC Estimation***:** The initial SOC was predicted based on the value of the OCV. If a good estimation of the initial SOC was obtained, the performance of the charger can be improved. In practice, the accuracy of the SOC estimation from the OCV value is not guaranteed, unless the battery relaxes for a long time. Furthermore, even if the battery relaxes for a long time, its OCV will not converge to its true value (at a certain SOC) due to the hysteresis, which means that the cell voltage relaxes to a value greater than the OCV for a given SOC after charging, and relaxes to a value that is less than the OCV of that SOC after discharging. In advanced battery management systems such as electric vehicle (EV) batteries, the estimation of the SOC is substantial and must be very accurate as opposed to portable appliances, for example. If an accurate SOC estimation is required by an application, some techniques can be used, e.g., the Kalman filter, if an accurate battery model is provided.

B. Termination Techniques

As the charging rate increases, the possibility of battery damage due to overcharging increases. Therefore, it is important to accurately terminate the fast charging of the battery when it is fully charged. The charger periodically monitors the battery parameters; voltage, current and temperature; calculates the voltage and temperature gradient; for precise measurement and control of battery charging.

*1).Voltage Drop***:** The voltage drop that occurs in nickel batteries, which is more obvious in NiCd, is due to the drop in the battery internal resistance when it becomes fully charged. In Fig. 1(a) and (b), the charging was terminated when a voltage drop of 30 mV occurred in the NiCd cell and 10 mV in the NiMH cell. In NiCd and NiMH batteries, the detection of a predefined voltage drop can be used as an indication to terminate charging, however, using this method alone is not recommended, because it will certainly overcharge the battery. Fig. 1(a) and (b) shows that the SOC was around 120% when the voltage drop was detected. This case can significantly reduce the battery lifetime.

*2).Inflection Point***:** The concept of the inflection point is sometimes used as an indication that the battery is almost half charged. In Fig. 1(a)–(c), the inflection point occurred when the SOC approached 50%. In [4], the charger switches to trickle charging when the inflection point is detected. This method requires very stable charging conditions such as CC and temperature to precisely allocate the inflection point to avoid overcharging or partially charging the battery.

*3).Temperature Rise***:** In the tests in Fig. 1, the temperature rise was 6° C for the NiCd cell (from 24° C to 30° C) and 17° C for the NiMH cell (from 25° C to 42 ° C). For the Li-ion cell, the results show almost a constant temperature during the entire range of SOC. The sudden rise in temperature, which is more obvious in NiMH cells, is a result of the undesired gases that were produced when the battery became fully charged. This unique phenomenon in NiMH batteries is employed to terminate charging. If a temperature rise is detected, the charger switches to the trickle charging mode until the battery is removed from the charger. This simple technique can save the battery life, at the cost of extending the charging time.

*4).Timing***:** As a safety procedure, some chargers add a timer to terminate charging if a predefined timeout is reached.

This method is very simple but can be advantageous if the charger did not detect a full charge status. However, this method cannot be used without the support of other methods.

III. BATTERY CHARGER DESIGN

Single-chemistry chargers are very common and are used in most battery systems. In this section, the charging algorithms for single-battery chemistries that were implemented in MATLAB simulation have been discussed.

A. Simulation Logic

It is expected of the charger to boost charge the batteries of HEV without physically damaging them or reducing its life because of overheating or excessive charging while striving to minimize the charging time. This requires an accurate and reliable algorithm and a corresponding hardware design to effectively control the charging rate and the charging time.

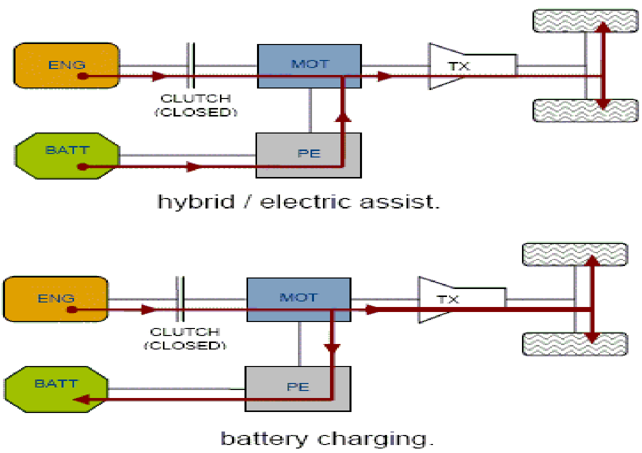

Fig.2 Charging and discharging method of NiMH/Li-Ion battery used in HEV

The charging process of 50Ahr NiMH/Li-ion battery was simulated by controlling the charging current/voltage through the power electronic converter. For charging, the electrical power was supplied from the generator. Fig.2 shows the module of charging method of battery which can be used in HEV.

Hybrid Electric Vehicles (HEVs), combines an internal combustion engine and one or more electric motors. The required power for electric motor was supplied by high capacity battery. The user powers a generator while driving the vehicle. This is converted into electricity and can be fed directly to the motor and also to charge a battery. The motor draws power from the battery and must be able to deliver the full mechanical torque required. The control circuitry is needed for charging the battery and delivering charge to electric motor

The battery charger is designed in MATLAB Simulation tool. It charges the 50Ahr NiMH/Li-Ion battery by 10KWh generator through the power electronic converter. The power electronic converter was a Buck Converter, which is operated at 20 KHz frequency (see fig.3)

B).Charging Procedure

1) *NiMH Battery*

Because NiCd and NiMH single cells have the same cut-off voltages and the two battery types share almost the same performance during charging, they can be charged with the same charger. However, the charge termination method might be different for these batteries. A CC is used during charging until an inflection point is detected. Once an inflection point is detected, the charger switches to trickle charging to prevent overcharging the battery. Other charge termination techniques are also implemented in this algorithm, e.g., voltage drop, temperature rise, and timing, to improve the charger performance.

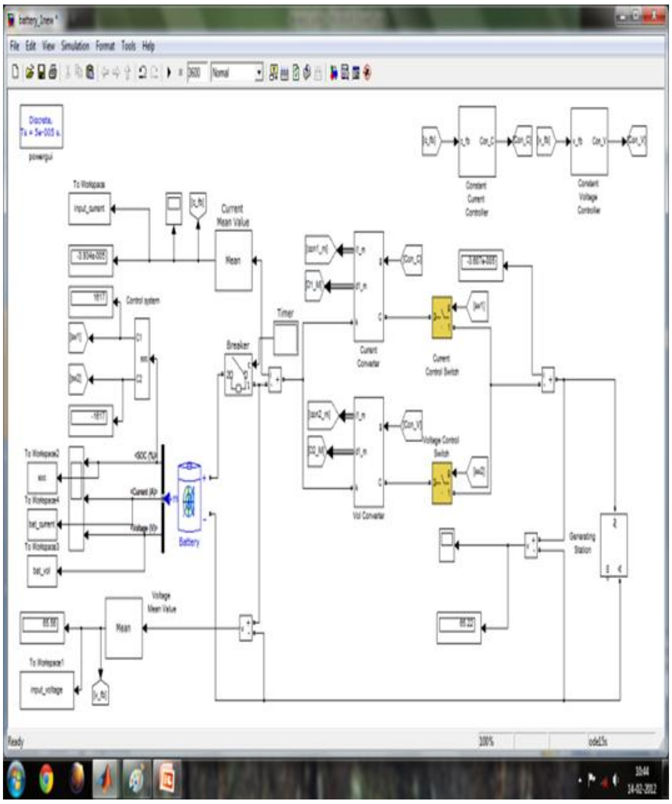

Fig. 3 Simulation diagram of 50Ah NiMH/Li-Ion Battery charging algorithm

Charging starts by sensing the initial open-circuit voltage (OCV) to determine the battery SOC. Initially the timer is set to 1600 sec. Fig. 3, shows the charging method of NiMH battery. The charger measures the battery voltage, current, and temperature during charging. In the first case, where the OCV is below 1 V/cell, the charger will inject a current of 0.1 C (C represents the capacity of the battery in ampere-hours) to charge the battery for 5 min. After the injection of the 5-min 0.1-C current, if the battery voltage is below 1.25 V/cell, the battery will be interpreted as damaged, and the charging will end. If the voltage was more than 1.25 V/cell after the 5-min 2.8C current injection, a fast charging current will charge the battery until it becomes fully charged. In the second case, if the OCV was more than 1 V/cell, then, depending on this value, the battery will be in one of the following three states: 1) fully charged (SOC >80%); 2) half charged (10% ≤ SOC ≤ 80%); or 3) discharged (SOC <10%).

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If the battery was discharged, it will initially be trickle charged to avoid damaging it with a high current. If the battery was half charged, it will initially be discharged and then charged to protect the battery from memory effect.

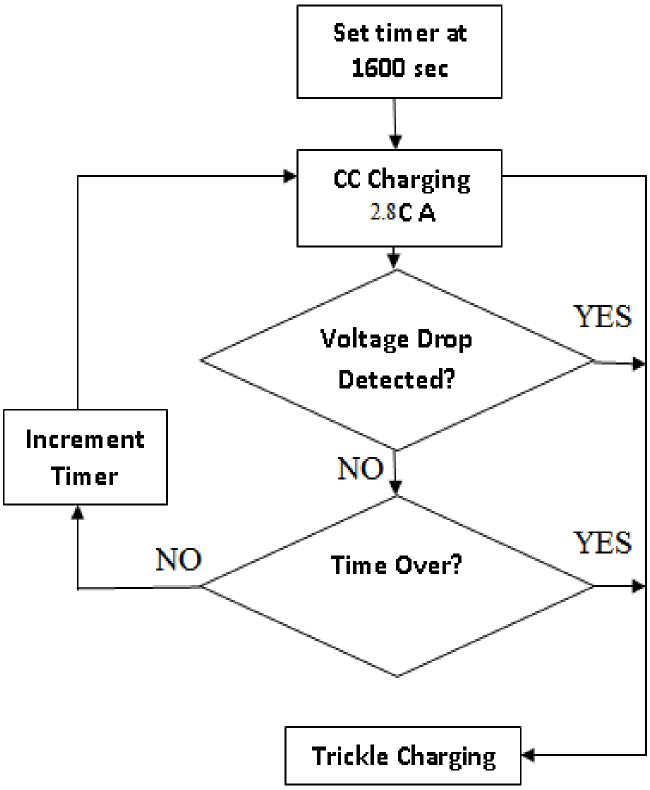


Fig. 4 Flow chart for charging algorithm of 50 Ahr NiMH batteries

The Simulation result of charging characteristics of NiMH battery is shown in Fig 5. Battery is fully charged in 1300 sec by Constant Current of 2.8 C. When the voltage reaches the predefined safety limit, battery switches to trickle charging at the rate of 0.1C until the battery is removed from the charger.

2).Li-Ion Battery

Li-ion batteries have very critical charging requirements that must be met during charging to ensure preventing overheating and overcharging these batteries. Li-ion batteries are charged with a CV with a current limiter to prevent overheating in the initial stage of the charging. One special requirement for Li-ion chargers is to monitor the voltage across each cell when more than one cell is in a string (connected in series) to ensure charge balance and voltage equalization of the cells. A protection circuit is usually added to the charger circuit to handle these functions.

In Li-ion battery-charging algorithm, Charging starts by measuring the initial OCV of the battery (see fig. 6). If the value was between 2.9 V/cell and 4.2 V/cell, charging with a current of 2.8 C will hold until the upper voltage limit or a timeout is reached. Then, the CV mode starts until either the current drops below a threshold value or a timeout is reached. If the initial OCV was below 2.9 V/cell, charging with trickle current will sustain until the OCV reaches 3 V/cell, at which fast charging current of 2.8 C will be applied. If the temperature during charging deviates from a certain range, the battery will be disconnected until its temperature returns to the defined range

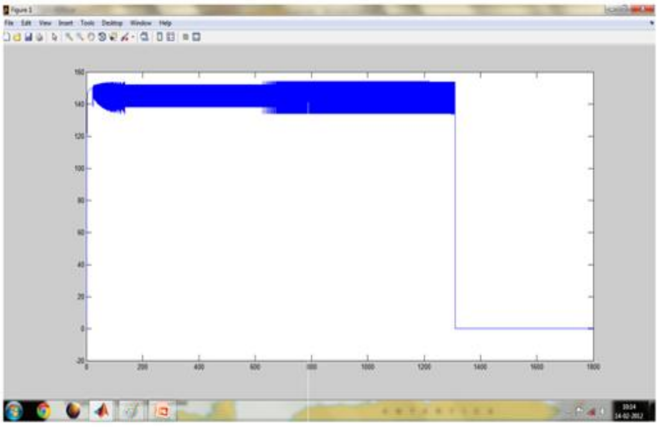


Fig. 5 (a) Charging Characteristics of NiMH battery (time vs Input Current)

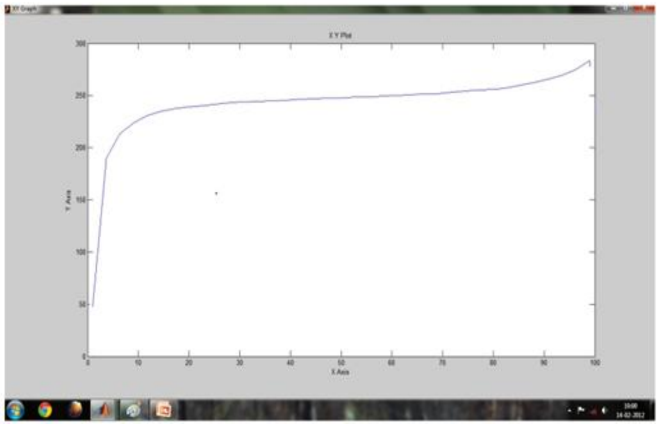


Fig. 5 (b) Charging Characteristics of NiMH battery (Soc vs Battery Voltage)

The Simulation results of charging characteristics of Li-ion battery were shown in fig 7. Initially the OCV of the battery pack is sensed to check whether the battery is fully charged. CC Charging will start when cell voltage is between 2.9V and 4.2V until the upper safety voltage limit is reached. Then the CV mode will start until the current drops to a threshold value at which charging will be terminated. During charging, if the voltage or time escaped the normal range, charging will be interrupted, and this condition will be interpreted as an error.

C). Summary

A good charger must extend the battery lifetime by properly charging it. In applications where a crude SOC prediction is acceptable, e.g., in portable electronics, a simple charger with the trickle–CC–CV charging scheme is sufficient to maintain a proper operation. In this battery charger design only voltage termination is considered. In outdoor environments where the ambient temperature can widely change, the charger must accommodate these variations in temperature while ensuring a proper operation.

In environments where temperatures and charging rates are unexpected and can considerably change in a short time, e.g., in EVs and solar-powered chargers, more advanced techniques must be used along with the above charging techniques. The EV environment is extremely harsh. Temperatures can change from -30°C to 50°C, and different charging rates are usually used.

The large amount of heat that is generated inside the battery during charging is an indication of a poor charging efficiency, which can reduce the battery capacity and lifetime. The charging efficiency can be increased by addressing the chemical reactions inside the battery, e.g., the pulse charging method. Hence, improving charging methods according to the thermo chemical behavior of the battery results in an increased efficiency, this, as a result, improves the charging speed and extends the battery lifetime.

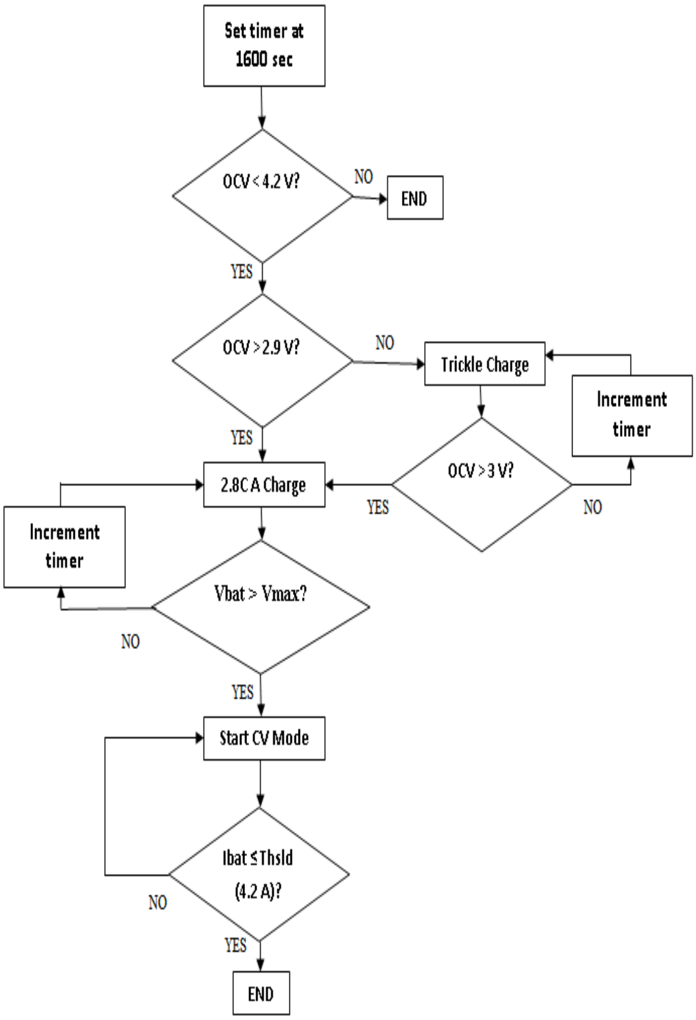
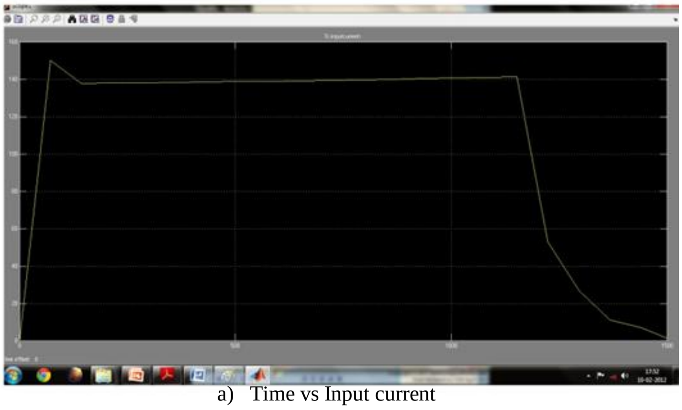
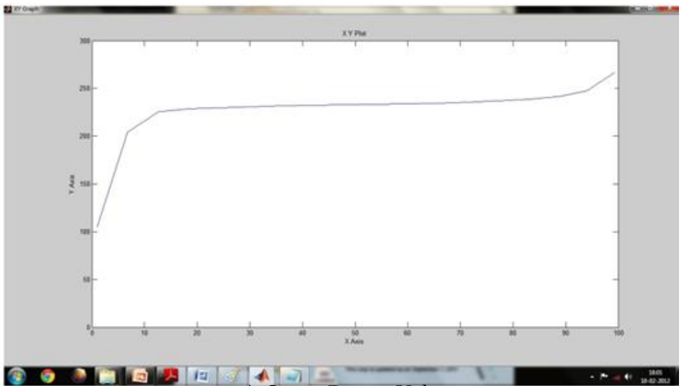


Fig. 6 Flow chart for charging algorithm of 50 Ahr Li-Ion batteries



a) Time vs Input current

b). Time vs voltage (V)



c). Soc vs Battery Voltage

Fig. 7 Charging Characteristics of Li-Ion battery

IV. CONCLUSION

Battery-charging systems have been intensively researched and developed since rechargeable batteries have been invented. However, due to the increasing demand on energy storage systems in recent applications, battery management systems have opened new doors for research and development to meet all battery system requirements. This paper has presented a review of recent charging algorithms for nickel and lithium batteries. These algorithms, which can accommodate a wide range of applications, were evaluated through some real tests on commercial battery cells.

This evaluation showed the strengths and weaknesses of these algorithms, with an experimental verification, and proposed some directions for further improvement.

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