Development of Lithium Ion Battery with Overcharge and Deep Discharge Protection

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Abstract: This paper mainly represents a design of constant current chargers with overcharge and deep discharge protection for lithium ion and lithium polymer based batteries. Analysis of different battery chemistries was carried out to investigate the batteries availability to consumers for low voltage energy storage system. Lithium ion and lithium polymer batteries were chosen as their robust construction and ease of use greatly improve their appeal in use for small form factor power storage system in different electronic devices. The objective was to design an inexpensive and efficient lithium ion or lithium polymer battery charger which will create appeal to the cost-minded customers. The charger circuit must charge the battery to full capacity while minimizing over charging for extended battery life for complete battery utilization.

Keywords: Discharge,Electrolyte, Impedance, Overcharge,Threshold, Charge rate, Cut off, Lithium ion,State of Charge

I. INTRODUCTION

The word 'Battery'comes from an Old French word 'Baterie' means 'action of beating' relating to a group of cannons in battle. In the endeavor to find an energy storage device, scientists in the 1700s adopted the term 'Battery' to represent multiple electrochemical cells connected together.Battery charger is a device used to put energy in cell by forcing an electric current through it. The number of portable telecommunication systems such as smartphones and laptops has grown explosively. These developments have resulted in massive demand for batteries. Secondary batteries are often used in these equipments because they are cost-effective over the lifetime of product. Widely used secondary batteries such as NiCd and NiMH are not satisfying people's requirements due to lack of high energy capacity and bulky size. As there are many advantages like no memory effect, high operation voltage and high energy density forward; lithium ion (Li–ion) battery is becoming the acceptable battery for portable electronic system. The performance of Li-ion battery depends to a large extent on the quality of their chargers.

In this paper, the construction of constant current charger with over voltage and deep discharge protection for Li-ion and Li-polymer batteries have been represented. The target was to design such a charger which is versatile and cost-effective. Also overcharge and deep discharge protection to prolong the battery life was implemented.

II. BATTERY TECHNOLOGY

Li-ion battery is a member of rechargeable battery types in which Li-ions move from negative to positive electrode during discharge and back when charging. The electrolyte, which allows for ionic movement and two electrodes are constituent components of Li-ion battery cell.It is important to note, rather than using lithium metal for battery technologies, manufacturers commonly use lithium carbonate/hydroxide. So there are many types of Li-ion battery.The differences withLi-ion charger and lead acid system is that Li-ion creates higher voltage per cell, tighter voltage tolerances and absence of trickle/float charge at full charge. While lead acid offers some flexibility in terms of voltage cut off,manufacturers of Li-ion cells are very strict on the correct setting because Li-ion cannot accept overcharge.Li-ion is a 'clean' system and only takes what it can absorb.

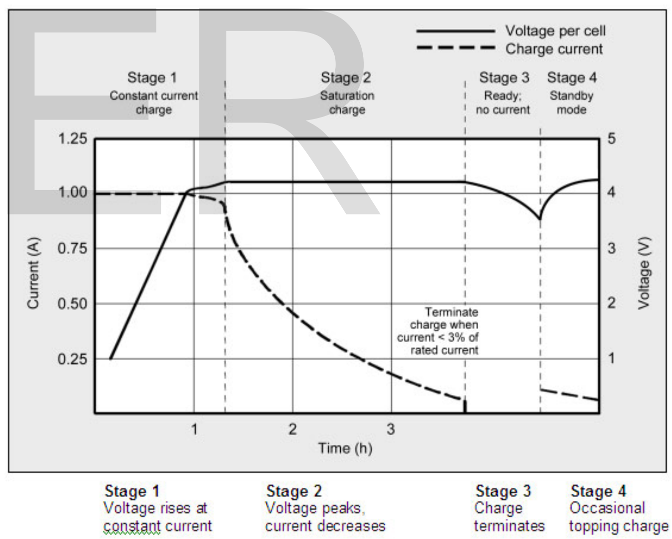

Figure 1: Charge stages of lithium ions [1]

Li-ion with cathode materials of cobalt, nickel and aluminum typically charge to 4.2V/cell. The tolerance is +/–50mV/cell. Some nickel based batteries charge to 4.1V/cell, high capacity Li-ion may go to 4.3V/cell. Boostingthe voltage increases capacity but going beyond specification stresses battery and compromises safety. Protective circuits built into the pack do not allow exceeding set voltage.Li-ion is fully charged when current drops to set level. Chargers for non-cobalt based Li-ions are not compatible with regular 3.6V Li-ion. Provision must be made to identify systems and provide correct voltage charging.When battery is put on charge, voltage shoots up quickly. This behavior can be compared to lifting weight with a rubber band, causing lag. The capacity will catch up when

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battery is almost fully charged as shown in figure 2. The higher charge current is larger the rubber band effect will be. Cold temperature or charging cell with high internal resistance amplifies the effect.

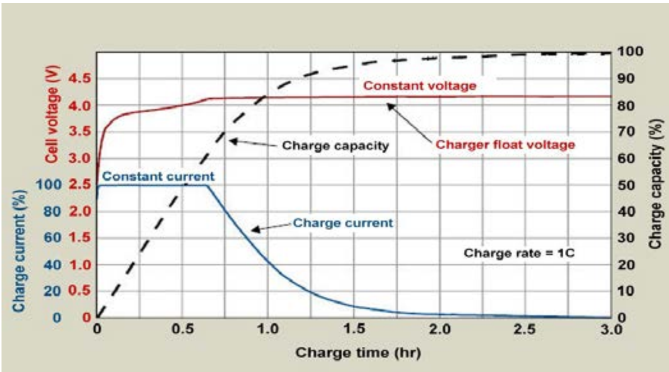

Figure 2: Voltage/capacity vs time when charging Li-ion [1]

Li-ion operates safely within designated operating voltage. But battery becomes unstable if inadvertently charged to higher than specified voltage. Prolonged charging above 4.3V on Li-ion designed for 4.2V/cell will plate metallic lithium on anode. The cathode material becomes an oxidizing agent, loses stability and produces Carbon Dioxide (CO2). Cell pressure rises and if the charge is allowed to continue, Current Interrupt Device (CID) responsible for cell safety disconnects at 1000-1380kPa. Should the pressure rise further, the safety membrane on some Li-ion bursts open at about 3450kPa and cell might vent with flame.Venting with flame is connected with elevated temperature. A fully charged battery has lower thermal runaway temperature and will vent sooner than that is partially charged. This is why authorities will mandate air shipment of Li-ion at 30% state-of-charge rather thanat full charge.The threshold for Li-cobalt at full charge is 130-150ºC, Nickel-Manganese-Cobalt (NMC) is 170-180ºC and Li-manganese is about 250ºC. Li-phosphate has better temperature stabilities than manganese.Li-ion is not the only battery that poses a safety hazard if overcharged, Lead and nickel-based batteries also melt down and cause fire if improperly handled. Properly designed charging equipment is paramount for all batteries and temperature sensing is a reliable watchman.

III. CHARGING PROTECTION

The charging scheme is combination of charging-termination methods. During fast charging it is possible to pump electrical energy into battery faster than chemical process. The chemical action cannot take place instantaneously and there will be a reaction gradient in the bulk of electrolyte between electrodes with electrolyte nearest to electrodes being charged before electrolyte further away. This is particularly noticeable in high capacity cells which contain large volume of electrolyte. Battery charging process has at least three characteristic time constants associated with achieving complete conversion of active chemicals which depend on both chemicals employed and on cell construction.

A. Charge Discharge Hysteresis

The time constants and phenomena give rise to hysteresis in battery. During chargingthe chemical reaction lags behind application of charging voltage and similarly when load is applied to battery to discharge it, there is a delay before full current can be delivered through load. As with magnetic hysteresis, energy is lost during charge discharge cycle due to chemical hysteresis effect.Allowing rest periods during charge-discharge processes to accommodate chemical reaction times will tend to reduce but not eliminate the voltage difference due to hysteresis. The true battery voltage at any State of Charge (SoC) when the battery is in its quiescent condition will be somewhere between charge-discharge curves. During charging the measured cell voltage in rest period will migrate slowly downwards towards quiescent condition as the chemical transformation in cell stabilizes. Similarly, during discharging, the measured cell voltage in rest period will migrate upwards towards the quiescent condition. Fast charging also causes increased joule heating of cell because ofhigher currents involved and higher temperature in turn causes an increase in the rate of chemical conversion processes.

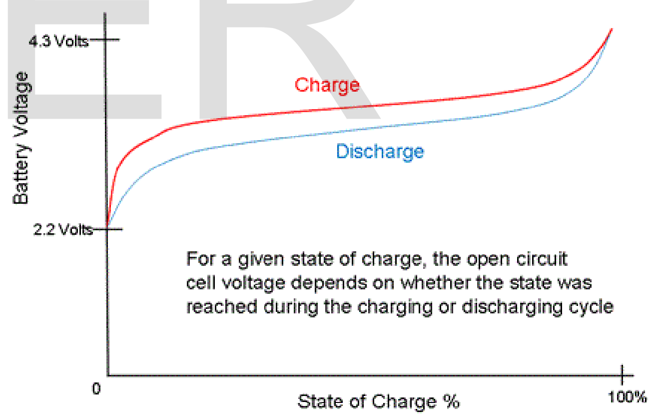

Figure 3: Charge-discharge profile [2]

B. Charging Termination Methods

Batteries can be charged at different rates depending on chemistries and requirements for different types ofchargers.

Table 1: Charger characteristics with charge termination [3]

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C. Cell Protection Systems

Cell protection can be external or internal to battery and this is one of the prime functions of Battery Management System (BMS). Different applications and different cell chemistries require different degrees of protection. Lithium batteries in particular need special protection and control circuits to keep them within their predefined operating limits. Cell protection should address undesirable conditions like; excessive current, short circuit, overcharging, high ambient temperature, overheating, inside cell pressure and system isolation.Most protection circuits therefore incorporate a thermal fuse which will permanently shut down the battery if its temperature exceeds predetermined limit. On the other hand, a resettable fuse provides on-battery over-current protection. It has similar function to thermal fuse but after opening it will reset automatically once the fault conditions have been removed and after it has cooled down again to normal state.

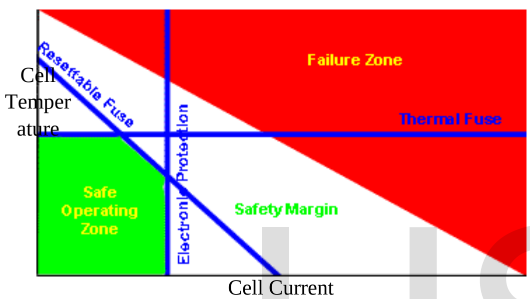


Figure 4: Cell over-current and temperature protection [4]

Over-current protection is normally provided by current sensing device to detect the upper current limit of battery. Since current is difficult to measure, the usual method of current sensing is by measuring voltage across low ohmic value, high precision, series, sense resistor in current path. When the specified current limit has been reached, the sensing circuit will trigger a switch which will break the current path. The switch may be semiconductor device or relay. Once fault conditions have been removed, the circuit would normally be reconnected automatically.

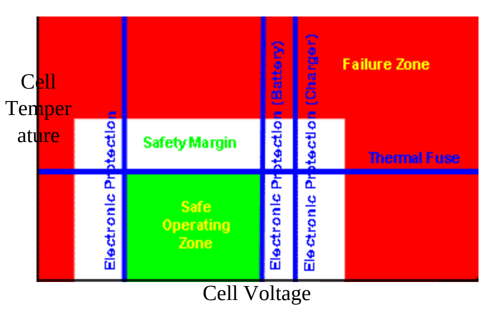


Figure 5: Cell over and under-voltage protection scheme [4]

Batteries can be damaged both by over-voltage which can occur during charging and under-voltage due to excessive discharging. By providing the charger with inputs from voltage and temperature sensors in the battery, the charger can be cut off when the battery reaches predetermined control limits. The

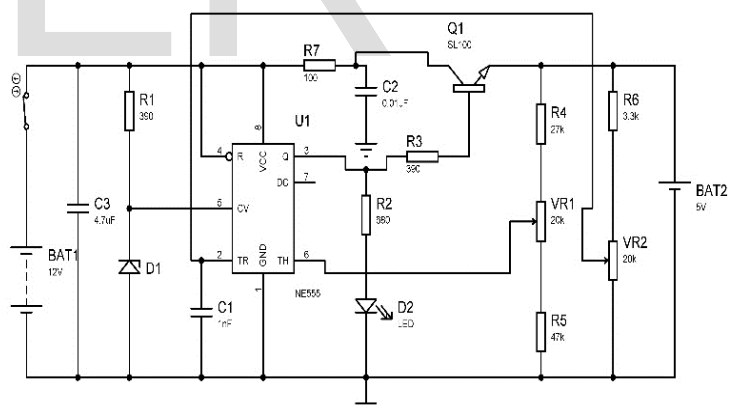
Type	Chem	C-rate	Time	Temp	Termination
Slow	NiCd, Lead acid	0.1C	14hr	0ºC-45ºC	Overcharged; remove battery when charged.
Rapid	NiCd, NiMH, Li-ion	0.3C-0.5C	3hr-6hr	10ºC-45ºC	Senses battery by volt, current and temp.
Fast	NiCd, NiMH, Li-ion	1C	1hr	10ºC-45ºC	Same as rapid charger with faster service.

figure 5 above shows a single voltage cut off from the charger. It should be noted that for each of the protection devices added into the main current path will increase the effective internal impedance of the battery, as much as doubling it in the case of single cell batteries. This adversely affects the battery's capability of delivering peak power [4].

IV. DESIGNANALYSIS

A. Li-ion Battery Charger usingTimer

The objective of this hardware isto provide a range of 180-290mA current, monitoring voltage level of battery and automatically cut-off charging when output terminal voltage increases above the predetermined voltage level.



Charging (percentage)	Time (minute)
25	38
50	79
75	131
100	186

Figure 6: Circuit diagram for battery charger with 555 timer

A 555timer is used to charge and monitor voltage level of battery. Pin5 is provided with reference of 5.6Volt by zener diode. Threshold pin6 is supplied with voltage set by VR1=20K pot. Trigger pin2 is supplied with voltage set by VR2=20K pot. When battery is fully charged output terminal voltage increases voltage at pin2 of 555timer above trigger point threshold. This

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switches of flip-flop andoutput goes low to terminatecharging process. Threshold pin6 of 555timer is referenced at (2/3rd) of Vcc set by VR1. Transistor SL100 used to enhance charging current. Value of R3=39Ω is critical in providing required current for charging. With given value 39Ω, charging current is around 180mA.

Table 2: Charging time for 555 timer based circuit

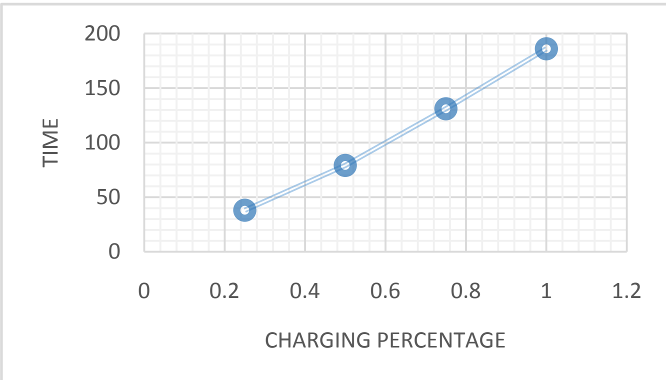

Figure 7: Time/charging curve for 555 timer circuit

For calibrating cut off voltage level, variable DC power source is used. By adjusting VR1 in middle position and slowly adjusting VR2 until LED goes off indicating low output; LED should turn on when voltage of variable power supply reduces below 5V.

B. Overcharge and Deep Discharge Protection

The objective of this design is to monitor voltage level of battery, automatically cut off charging, over charge protection, complete drain out protection and current rating up to 1A.

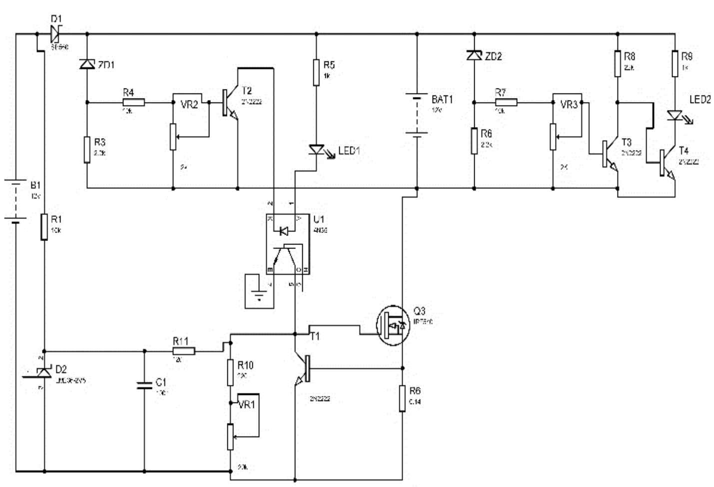

Figure 8: Circuit diagram for batterywith protection scheme

Constant current source is built around IRF540, transistor T1, diodes D1, D2, resistors R1, R2, R10, R11 and potentiometer VR1.D2 is low temperature coefficient, highly stable reference diode LM236-5. It can be used with reducing temperature range.Gate-Source voltage VR1 is slightly above 4V. By setting it, charging current can be fixed depending on battery capacity. First decide charging current (1/10th of battery's Ah capacity) and calculate nearest standard value of R2 as R2=0.7/safe fault current. R2 and T1 limit charging current if something fails or terminals get short circuited accidentally.To set charging current while multimeter is connected in series with battery and source is present adjusting VR1 slowly until charging current reaches its needed value.For overcharge protection, zener diode ZD1 starts conducting afterits breakdown voltage is reached. By adjusting VR2 when battery is fully charged (say 14V in case of 12V) VGS of IRF540 is set to 0and current stops flowing. LED1 glows to indicate that battery is fully charged. Internal LED of opt coupler also glows and internal transistor conducts, resulting VGS of IRF540 to 0 and stops charging.For deep discharge protection,zener diode ZD2 conducts to divide transistor T3 into conduction and make T4 cut off. If battery terminal voltage drops(say 11V in case of 12V) by adjusting VR3 suchthat T3 is cut off and T4 conducts. LED2 will glow to show that battery voltage is low.

Table 3: Charging time for charger with protection scheme

Charging (percentage)	Time (minute)
25	33
50	70
75	109
100	154

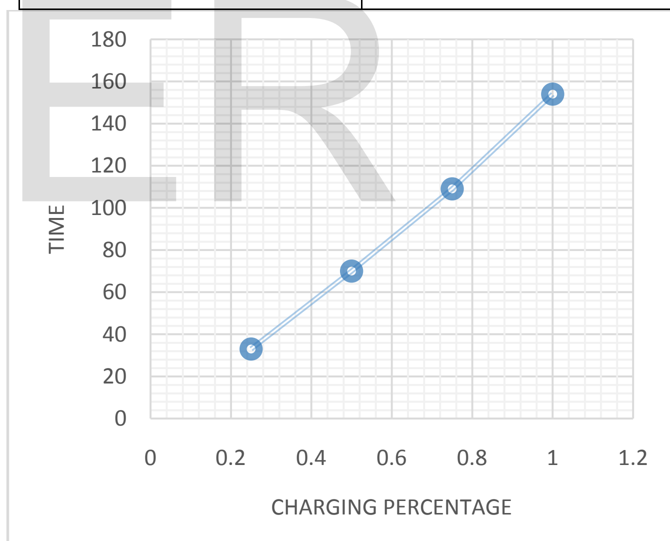

Figure 9: Time/charging curve for circuit with protection

If required charging current is 5A,then it can be gained by putting another LM235-5 in series with D2, changing value of R11 to 1K, replacing D1 with two SB560 device in parallel and providing a good heat sign for IRF540 to the circuit.

V. CONCLUSION

It was asuccessful design for producing two charging circuits and implementationof protection schemes that can prevent overcharge or deep discharge damage for Li-ion or Li-polymer batteries. These circuits were developed using readily available and inexpensive components which makes them easy to construct and produce in large quantities as well as obtaining charging time became possible which is competitive with available chargers. Inclusion of protection circuitry to avoid damage and increase battery lifetime also makes them appeal to consumers to use.

Implementation of a microcontroller would enable charger to monitor temperature, regulate voltage and change charging algorithm. So, with proper addition of microcontroller system, charging circuits developed in this research paper can be turned into Universal Chargers.

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